Contrib. Mineral. Petrol. 73, 207–220 (1980)

Contributions to Mineralogy and Petrology

Zircon and Granite Petrology

J.P. Pupin

E.R. "Stabilité et Réactivité des Minéraux", Laboratoire de Pétrologie-Minéralogie, Faculté des Sciences, Parc Valrose, F-06034 Nice Cedex, France

Abstract. The typologic study of zircon populations from granitic rocks lead to the proposition of a genetic classification with three main divisions: (1) granites of crustal or mainly crustal origin [(sub) autochthonous and aluminous granites)]; (2) granites of crustal + mantle origin, hybrid granites (calc-alkaline and sub-alkaline series granites); (3) granites of mantle or mainly mantle origin (alkaline and tholeiitic series granites). In detail, there are many petrogenetic variants of each of the following granitic rocks: granodiorite, monzogranite and alkaline granite. The variations observed with zircon typology are accompanied petrographically by modifications of associations of other main and accessory minerals, and on the field by the presence or absence of basic microgranular xenoliths, associated microgranites, rhyolites or basic rocks. In the typologic diagram, some endogenous non granitic rocks (i.e. migmatites, tonalites, rhyolites ...) show a logical distribution with regard to different genetic stocks of granitic rocks.

Introduction

Geologists all over the world have well accepted the concept of *"granite and granite"* introduced by Read in 1957; apparently similar granite bodies may have entirely different geneses, and the genetic evolution of each one is usually not evident from the observed relative proportions of the constituent minerals. Although granitic petrographic nomenclature was an important subject at the 1974 I.U.G.S. Congress, yet no internationally accepted petrogenetic classification of granites exist today. A consequence of the absence of a widely accepted petrogenetic classification for granites is that confusion invariably arises in the application of results of studies of distribution of elements in one kind type of a granite to granitic rocks of entirely different origin. This is particularly true as for example Pupin (1976) has shown that there are petrogenetic variants of each of the following granitic rocks: alkaline granites, monzogranites and granodiorites; in the similar sense, there are, for example, petrogenetically different biotite-muscovite monzogranites and biotite granodiorites. Scientific progress in this field will be retarded as long as the petrogenetic differences between granitic rocks are not discernible by simple tests that are easily applicable by most geologists.

Apart from the fact that each granitic unit is a peculiar entity, some granites are in addition liable to considerable secondarily transformation by deuteric processes which could appreciably alter their chemical as well as mineralogical compositions (e.g., Lameyre 1975). To be effective and widely applicable, a petrogenetic classification must be, at least partially, beyond the influence or control of such secondary phenomena or factors.

The polygenetic concept already developed has shown that granites could originate either from (i) the sialic crust – with a diversity of compositions – or (ii) from the mantle or (iii) as is more often the case, from the blending of (i) and (ii) above (e.g., Bonin 1975), in which case the initial Sr isotopic ratios do not always yield satisfactory results.

In this work, a method which is based on the careful study of the morphology of zircons is proposed for the petrogenetic classification of granites. Although it is not claimed that the proposed method will solve all the intriguing and difficult granite problems, yet this method, which is based on more than ten years of study and observations, is considered capable of crystallizing an acceptable consensus from the various current theories and hypotheses on the subject.

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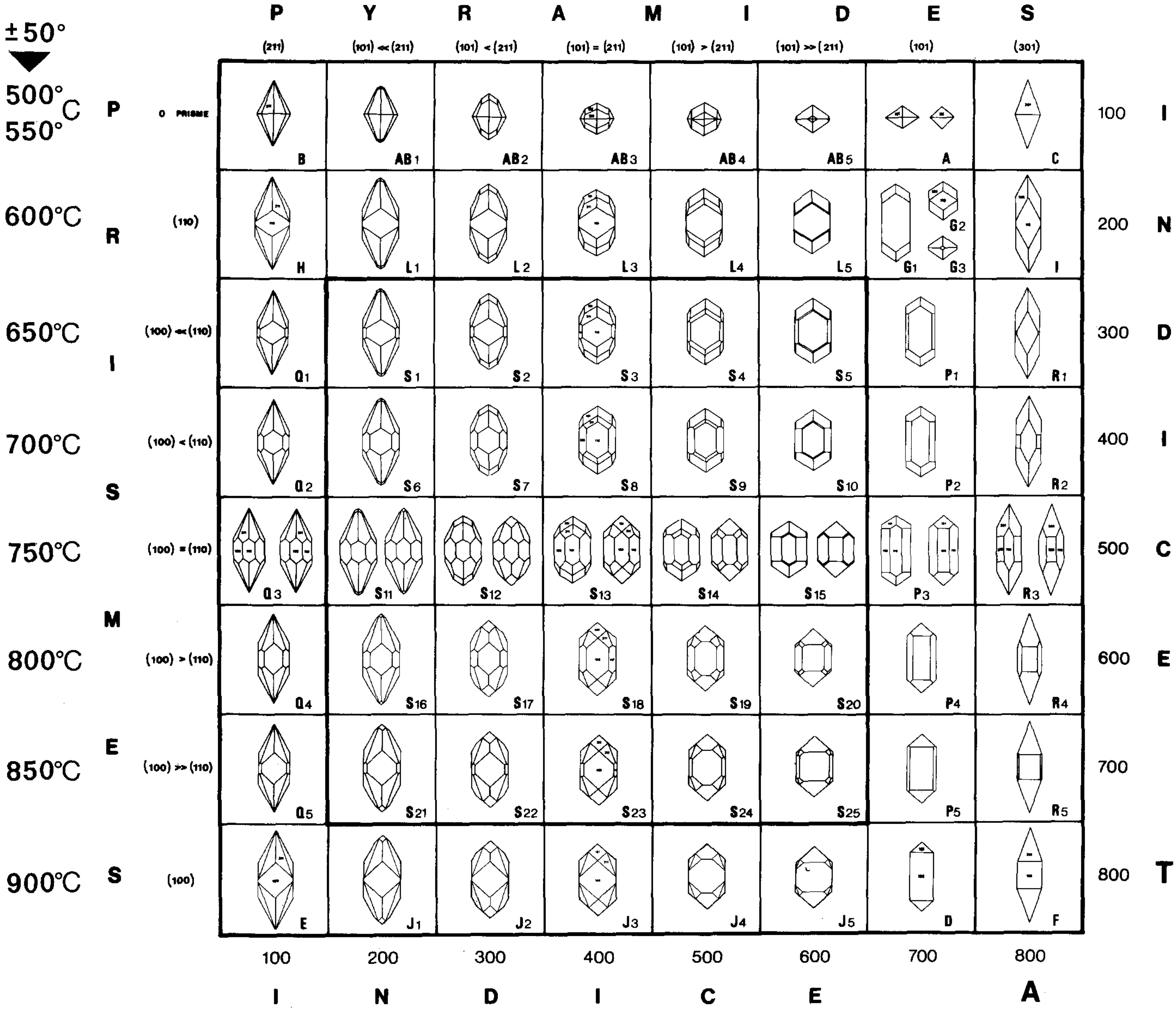

Fig. 1. Main types and subtypes of the typologic classification and corresponding geothermometric scale. The approximative temperature scale proposed (Pupin and Turco 1972c) was calibrated from the confrontation of the typology zircon data with the temperatures normally accepted in literature for crystallization of pluto-volcanic rocks and minerals. In this work, we have particularly considered: The limit of stability of the minerals (i.e., the muscovite in granitic and metamorphic rocks); – the geothermometric data obtained with other methods (i.e., on pyroxenes from charnockitic and volcanic rocks; on vitreous inclusions); – the temperature ranges for gneiss anatexy; – the temperature ranges for the beginning and the end of the magmatic crystallization in granites, diorites, gabbros and effusive equivalents; – the temperatures of formation of minerals with which zircon syncrystallized (i.e., fluorite, late-magmatic quartz)

The Typology Method

The use of zircon as a possible clue to the problem of the origin of granite had been proposed by Poldervaart since 1950; the idea, though further developed by Poldervaart and his collaborators (Poldervaart 1956; Larsen and Poldervaart 1957; Alper and Poldervaart 1957), did not receive wide acceptance because the proposed criteria of dimensional crystal statistics, criticised by Pupin (1976, pp. 314–317), did not produce the desired solution.

The fundamental basis of population study in zircons had been given in an earlier publication (Pupin and Turco 1972a). An arrangement of given prismatic and pyramidal crystal faces constitute a population type. The abundance of zircon crystals related to certain types has led to the setting up, in those particular cases, of more or less numerous subtypes (1 to 25).

Table 1. Main and secondary types and subtypes of the typologic classification of zircon

Prisms	Pyramids	Main types	Subtypes	Supplementary pyramids: secondary types and subtypes					Pinacoïd
				+{301}	+{112}	+{321}	+{311}	+{511}	+{001}
0	1 {101}	A	–	AC	Add	Add	Add	Add	Add
	{211}	B	–	BC					
	{301}	C	–	–	Z	Y	W	X	an
0	2 {101} – {211}	AB	5 (AB_1 à AB_5)	$ABC_{1\text{ à }5}$	to the	to the	to the	to the	asterisk
1 {100}	1 {101}	D	–	K	main	main	main	main	to the
	{211}	E	–	EC					
	{301}	F	–	–	type:	type:	type:	type:	type:
1 {110}	1 {101}	G	3 (G_1 à G_3)	$M_{1\text{ à }3}$	AZ, BZ, ...	AY, BY, ..	AW, BW, ...	AX, BX, ...	A*, B*, ...
	{211}	H	–	HC					
	{301}	I	–	–					
1 {100}	2 {101} – {211}	J	5 (J_1 à J_5)	$N_{1\text{ à }5}$					
1 {110}	2 {101} – {211}	L	5 (L_1 à L_5)	$O_{1\text{ à }5}$					
2 {100} – {110}	1 {101}	P	5 (P_1 à P_5)	$T_{1\text{ à }1_5}$					
	{211}	Q	5 (Q_1 à Q_5)	$OC_{1\text{ à }5}$					
	{301}	R	5 (R_1 à R_5)	–					
2 {100} – {110}	2 {101} – {211}	S	25 (S_1 à S_{25})	V_1 à $_{25}$		SY = V			

$\longrightarrow$

Decreasing frequency of Pyramids in nature

So, that rocks with comparable percentages of the same zircon type can then be easily separated – significantly – provided that their subtypes distribution is known.

The main types show 0, 1 or 2 prisms, i.e. {100}, {110} in combination with either one of the three pyramids {101}, {211} or {301}, or the arrangement {101} + {211}. Main types and subtypes can be related on a square board with two variables (Fig. 1), depending upon the relative development of the crystalline faces. The initial typologic diagram design was entirely based on the relative natural abundances of zircon types and subtypes. S type, which is the most abundant habitus that can be found in endogenous and exogenous rocks, forms, then, the diagram's main point, the other main types logically arranged around. Some main types stay purely theoretical (i.e.: C, I, R, F): their emplacement was suggested at the diagram right part (Fig. 1) as *T* and *K* types are mainly linked with the *P* and *D* types in alkaline rocks.

The secondary types have been derived from the above main types from which they can be deduced by adding one or more extra pyramids, with usually a minor development. The secondary types appellation can be found in Table 1.

Regarding the more complex cases where a crystal shows a great number of different pyramidal forms, the nomenclature can yet be used. A bipyramidal crystal {100} {110} with four pyramids {101} {211} {112} {311} would be labelled SWZ, the W and Z letters listed by alphabetical order (corresponding to the supplementary pyramids {311} and {112}) with respect to the S principal type; the relative developments of {100} {110} prisms and {101} {211} pyramids allow the subtype characterization (SWZ_1 to SWZ_{25}) as for a common S type.

Up to now, we have listed some thirty natural types, out of whose eight only are frequent (D, G, J, L, N, P, S, U).

It is also very important to point out that crystal elongation is not at all taken into account in our proposed typology.

Analytical Techniques

Zircon crystals (populations) are separated from rocks by well known routine procedure: moderate crushing and sieving followed by densimetric (bromoform and methylene iodide), magnetic and electromagnetic separations of the heavy minerals fraction; only the 0.050–0.160 mm fraction, where most of the granites zircons generally are, have been here studied. The separated populations are then mounted on microscope glass slides with Canada balsam and studied at 250× magnification. For each of the 200 granitic rock samples studied up to date, the typologic distribution has been determined on the basis of the examination of 100 to 150 unbroken zircon crystals whenever possible, and the coordinates ($I.\bar{A}$ and $I.\bar{T}$) computed (Pupin and Turco 1972b) (Fig. 2). Typo-

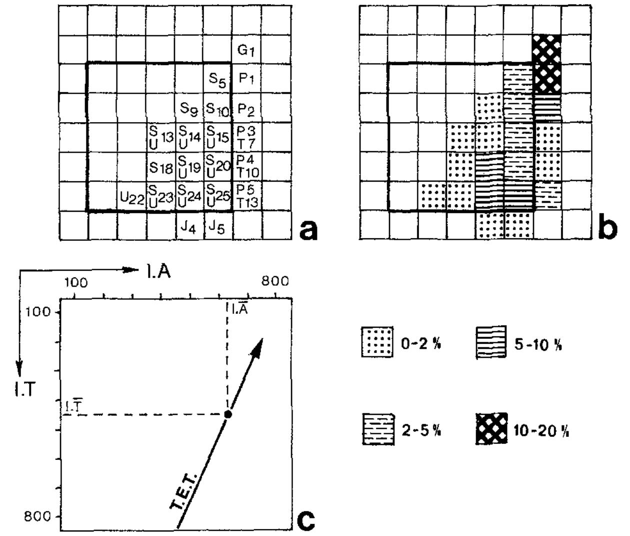

Fig. 2a–c. Zircon population representation: **a** subtypes observed; **b** typologic frequency distribution of the population; **c** mean point (I.Ā, I.T̄) in the (I.A, I.T) diagram and calculated "Typological Evolutionary Trend" (T.E.T.) of the population **c**. – The determinations of I.Ā and I.T̄ indices are made with the following formulas:

$$\bar{\mathrm{I.A}} = \sum_{\mathrm{I.A}=100}^{800} \mathrm{I.A} \times n_{\mathrm{I.A}} \qquad \bar{\mathrm{I.T}} = \sum_{\mathrm{I.T}=100}^{800} \mathrm{I.T} \times n_{\mathrm{I.T}}$$

where $n_{\mathrm{I.A}}$ and $n_{\mathrm{I.T}}$ are the respective frequencies for each value of I.A or I.T ($\sum n_{\mathrm{I.A}} = \sum n_{\mathrm{I.T}} = 1$). – The T.E.T. is drawn through the mean point (I.Ā, I.T̄) with a slope $a = S_T/S_A$, which is the tangent of the angle between the T.E.T. axis and the I.A axis.

Standard deviation of A index $= S_A = \sqrt{(A-\bar{A})^2/N}$.

Standard deviation of T index $= S_T = \sqrt{(T-\bar{T})^2/N}$.

N = number of determined crystals

logic distribution diagrams permit the comparison of the various population mean points (I.Ā, I.T̄).

Provided that the main agents controlling the variations in typological populations are known (see next chapter), one can apply the method to the field of comparative petrology and discuss differences of typologic distribution and positions of the studied populations. One can also, using the same data, bring out variations in the physico-chemical conditions of the crystallization medium that have resulted in a single sample zircon population. Often, in granitic rocks, the zircon crystallization cycle is of long duration and may even cover the entire magmatic stages (e.g., Pupin 1976, pp. 214–219), so that the data obtained may not only relate to definite stages of magmatic crystallization but may also cover, as a matter of fact, the whole zircon crystallization period, the successive stages of zircon "typological evolution" being trapped inside other minerals as their growths proceed. The chronology or sequence of appearance of crystal forms then leads to the establishment of individual "typological evolutionary trend" (T.E.T.) (Pupin 1976, pp. 59 and foll.). In composite granitic bodies showing cogenetic rock units, it is possible to study the typological evolution from the first to the last units and to determine a differenciation T.E.T. (Pupin 1976, pp. 141 and foll.).

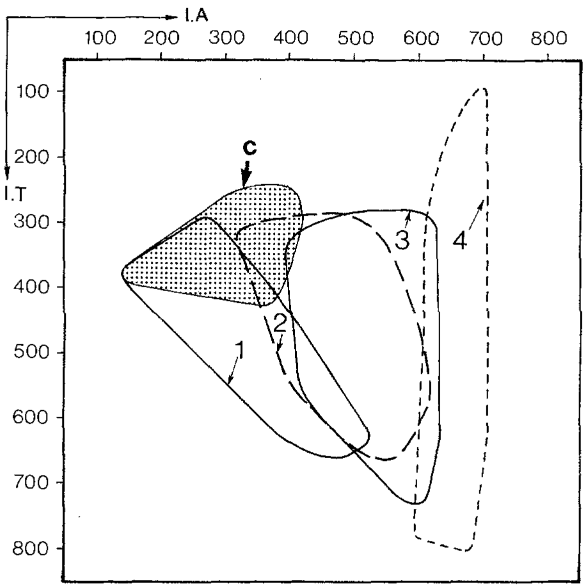

Fig. 3. Distribution of plutonic rocks in the typologic diagram: (*1*) diorites, quartz gabbros and diorites, tonalites; (*2*) granodiorites; (*3*) monzogranites and monzonites; (*4*) alkaline and hyperalkaline syenites and granites; (*c*) cordierite bearing rocks

Known Essential Factors Controlling Variations in Zircon Typological Populations

Results of the investigations of factors known to influence the growth of zircon typology have been reported in various publications (Pupin and Turco 1972c–1975; Pupin 1976; Pupin et al. 1978).

The chemical characteristics of the crystallization medium play a leading role in the origin and relative growth of zircon pyramids (Pupin and Turco 1975; Pupin 1976). Zircons originating in an hyperaluminous or hypoalkaline medium show well developed {211} pyramid whereas those grown in an hyperalkaline or hypoaluminous medium have well developed {101} pyramid; the Al/alkaline ratio is therefore believed to control the zircon population index Ā, an observation which is confirmed when considering the plutonic rocks distribution in the (I.A, I.T) diagram (Pupin 1976, pp. 179–180) (Fig. 3). The {301} pyramid shows a distinct spreading propensity in an alkaline medium where it occurs in the *T* [{100}, {110}, {101}, {301}] and K [{100}, {101}, {301}] types in potassium-rich alkaline medium. On the other hand, the {112} pyramid preferentially appears in hyperaluminous media where it can sometimes develop prominently (Pupin 1976, p. 296; Giraud et al. 1979).

As the leading factor governing the relative development of the zircon prisms really is the temperature of the crystallization medium, we have therefore proposed that mineral as a geothermometer (Pupin and Turco 1972) (Fig. 1).

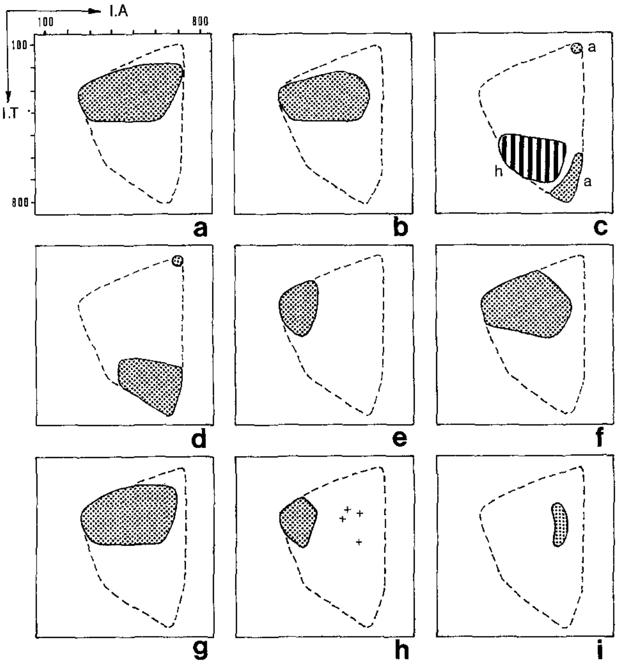

Fig. 4a–i. Distribution of mineral associations in granitic rocks: muscovite (**a**), anatase and brookite (**b**), amphiboles (**c**) (*a* = alkaline amphiboles; *h* = hornblende), pyroxenes and olivins (**d**), cordierite (**e**), garnet (**f**), tourmaline (**g**), monazite (**h**), xenotime (**i**)

More recently, the role of water in the development of crystal faces in zircon, especially in granitic magmas, has been investigated (Pupin et al. 1978). In water-poor magmas, zircon crystallises during an early magmatic period; in magmas rich in water, zircon crystallization begins early in the magmatic period and continues up to the end with the development of trace elements (U, Th, Y ...) rich-hydrozircon, as it has been confirmed by electron-probe investigations (Silver and Deutsch 1963; Köhler 1968, 1970; Veniale et al. 1968; Effimoff 1972). Metamictization of this hydrozircon commences with time and results in overgrowths with a distinctive zoned structure (e.g., Fig. 6a). The granites formed from such water-rich magmas display more or less significant deuteric phenomena associated with the growth of secondary minerals (muscovitization, sericitization, transformation of ferro-magnesian minerals, tourmalinization ...). In those granites, where we have been able to show the simultaneous crystallization of late zircon with interstitial quartz (Pupin 1976, pp. 214–219), the zircons populations index $\bar{T}$ is appreciably lowered by the late zircon crystallization.

When all the factors above mentioned which play prominent roles in the zircon typological distribution are considered, it is seen that associations in the rocks from which zircons populations have been studied are not random but show noteworthy characteristics (Fig. 4).

Muscovite (Fig. 4a) is present only in granitic rocks the zircon population index of which shows $\bar{T}<450$, which then led the authors to propose, in accordance with Lameyre (1966), the presence of a thermal threshold for the appearance of that mineral in granites (Pupin and Turco 1974a). A nearly similar distribution is noted for the anatase + brookite, garnet and tourmaline (Fig. 4b, f, g). On the other hand, zircon population indices of plutonic rocks with amphiboles, pyroxenes and peridots have high $\bar{T}$ values (>500), marking high crystallization temperatures (Fig. 4c, d). An exception to that rule that one sees on Fig. 4 is an hyperalkaline granite facies from Evisa, Corsica with riebeckite-aegyrine in which the very late octaedric type A zircon (I.T. = 200) is the only type present and is intergrown with interstitial fluorite (Pupin and Turco 1975). Zircon populations from euhedral or nodular cordierite rocks have low $\bar{A}$ and $\bar{T}$ indices (Fig. 4e). This is also true for most of the rocks containing monazite (Fig. 4h), which is preferentially found in typical sialic rocks (crystalline schists, migmatites, anatectic granites). Xenotime is more likely to be found (overgrowths on zircons) in rocks with an alkaline trend, the zircon population of which shows low $\bar{T}$ and high $\bar{A}$ indices (Fig. 4i).

Proposed Petrogenetic Classification

On the basis of the comparison of field observations, petrographical and geochemical data of the granites examined with the distribution of their zircon typological populations and their T.E.T., the following petrogenetical classification, the major part of the subdivisions of which are in agreement with most of the recent bibliographic data, is proposed:

A. Granites of crustal or mainly crustal origin (orogenic granites[1])

1. Autochthonous and intrusive aluminous leucogranites;
2. (Sub)autochthonous monzogranites and granodiorites;
3. Intrusive aluminous monzogranites and granodiorites.

B. Granites of crustal + mantle origin, hybrid granites (orogenic granites)

1. Calc-alkaline series granites;
2. Sub-alkaline series granites.

C. Granites of mantle or mainly mantle origin (anorogenic granites[1])

1. Alkaline series granites
2. Tholeiitic series granites.

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[1] "Orogenic" and "anorogenic granites" are employed in agreement with Bonin and Lameyre 1978

A. Granites of Crustal or Mainly Crustal Origin

1) Autochthonous and Intrusive Aluminous Leucogranites. These rocks, studied and described by Lameyre (1966) in the french Central Massif (eg.: Echassières, Saint Sylvestre – Saint Goussaud, Chateauponsac, Millevaches, Villeret, Grazières-Mages, ...) are hololeucocratic granites rich in quartz, two feldspars (a potassic one-albite – acid oligoclase)[2], biotite and some primary muscovite. If the granites studied by Lameyre (1966) do correspond, as a whole, to an entity, and can be found elsewhere in the world (e.g., Brittany, Maures, France; Galicy, Spain; Ivory Coast; Himalaya[3]) (Pupin et al. 1975; Pupin 1976; Pupin et al. 1979), the definition must be distinctive (Pupin 1976, p. 92) in order to avoid any confusion with others hololeucocratic, two micas granites with entirely different petrogenetic significance. The leucogranites here studied are hyperaluminous, which often finds expression with aluminous silicates (andalusite, sillimanite) or cordierite presence; one can also find zircon, apatite, monazite (Fig. 9h) + anatase ± garnet ± tourmaline. Those granites have obviously been subjected to considerable hydrothermal processes (Lameyre 1973), promoting economic concentrations of ore minerals (U, Sn) (Lameyre 1975, p. 318) and are thought to be of typically crustal extraction, having formed by the anatexis of hydrous crystalline schists under low $P-T$ conditions.

The zircon populations of these aluminous leucogranites show very low $\bar{A}$ and $\bar{T}$ indices, between 260 and 390, with subtypes L_{1-2} and $S_{1-2-3-6-7}$ well represented (Figs. 5a, b; 6a, b) and a mean T.E.T. that can be seen on Fig. 7, stock (1).

2) (Sub)autochthonous Monzogranites and Granodiorites. On the field, these granites can be traced to the migmatites without any break, and their anatectic origin is undisputable (Velay, French Central Massif; Valmasque, Argentera; Sainte-Anne d'Auray, Brittany, France). In most cases, they are usually biotite granites, often with cordierite nodules indicating hyperaluminous trend. In accordance with the interrelationship of origin, the accessory minerals suite is practically like that of the aluminous leucogranites (zircon, apatite, anatase – brookite, monazite ± garnet ± tourmaline). The zircon populations still give low $\bar{A}$ (~ 300) and $\bar{T}$ (~ 350) indices, with a good number of subtypes $S_{1-2-3-6-7}$ (Figs. 5c, 6c, d). These granites' mean T.E.T. is clearly shown on Fig. 7, stock 2. Zircon population of anatectic granites are very similar to those observed in migmatites (Alinat 1975; Pupin 1976, p. 293 and foll.).

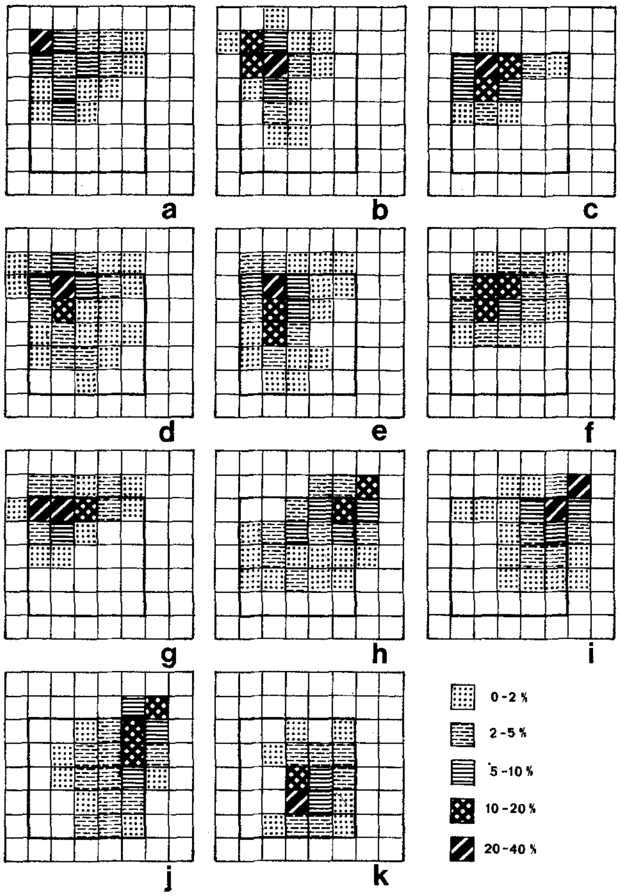

Fig. 5a–k. Typologic distribution of zircon populations from granites: aluminous leucogranites, stock 1 [Saint-Sylvestre (**a**), Muros, Galicia (**b**)]; (sub)autochthonous monzogranites, stock 2 [Velay (**c**), Guéret (**d**)]; intrusive aluminous monzogranites, stock 3 [Margeride (**e**), Plan de la Tour (**f**), La Souterraine (**g**)]; calc-alkaline series: stock 4a [Sidobre granodiorite (**h**), Elbe monzogranite (**i**)] and 4b [Argentera monzogranite (**j**), Ballon d'Alsace monzogranite (**k**)]

In this second group could be included the "Guéret type" granites (French Central Massif), the peculiarity of which has been emphasized by Didier and Lameyre (1971). These granites, which are thought to be formed by crustal reactivation (Kurtbas et al. 1969; Ranchin 1970), show indeed a peculiar feature by having zircons with complex and oscillatory zonation of {101} and {211} pyramids (Pupin 1976, p. 71) (Figs. 5d, 6e). This fact may point out a succession of crystallization phases in a medium with recurrent chemical properties, suggesting probable polyphased anatexis during a long basement evolution.

3) Intrusive Aluminous Monzogranites and Granodiorites. They are porphyroid granites with characteristic idiomorphic cordierite and cognate granodiorites (La

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[2] They are often leucomonzogranites

[3] Study in progress, joint authorship with Debon and Le Fort

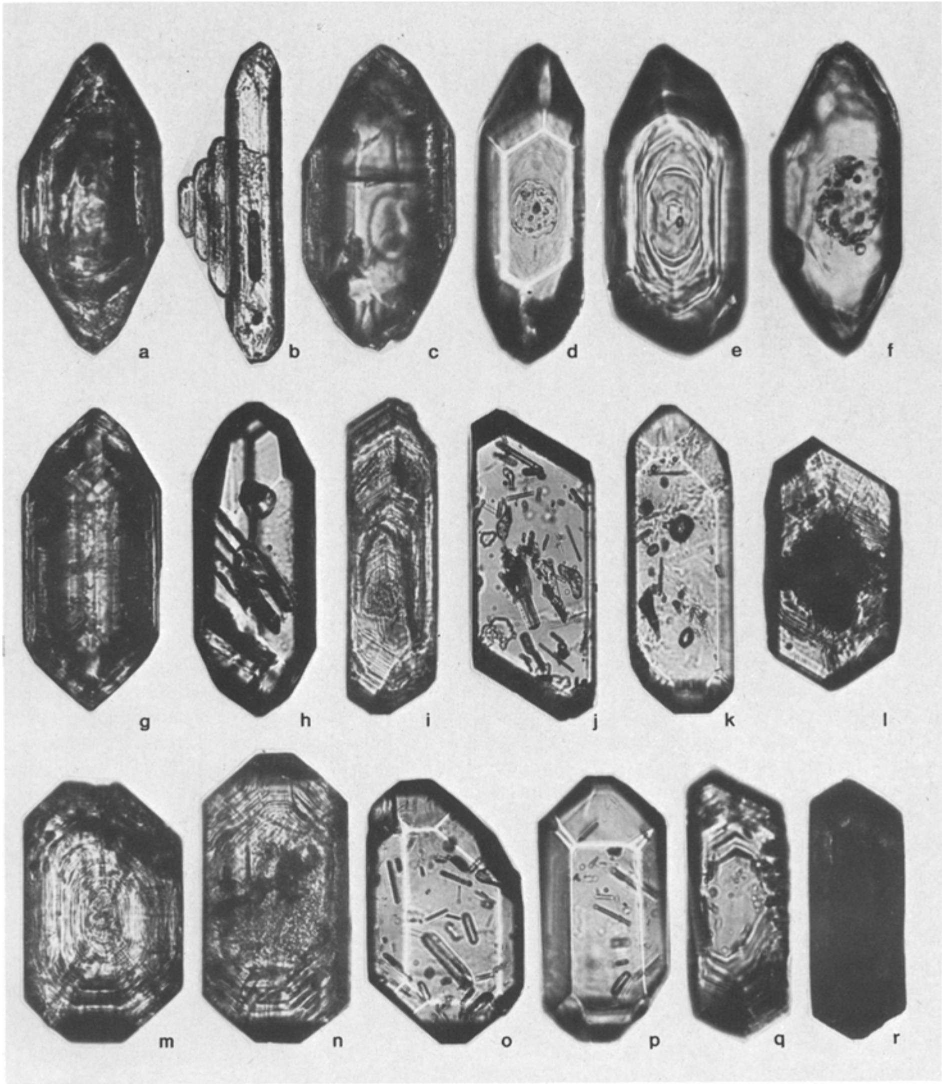

Fig. 6a–r. Zircon crystals from granitic rocks with their subtypes and stock classifications. Zircons from aluminous leucogranites, stock 1 [Echassières (**a**; S_1; 0.150 mm); Ferké, Ivory Coast (**b**; S_{1-2}; 0.250 mm)]; (sub)autochthonous monzogranites, stock 2 [Sainte-Anne d'Auray (**c**; S_2; 0.140 mm); Velay (**d**; SZ_2; 0.160 mm); Guéret (**e**; S_3; 0.110 mm)]; intrusive aluminous monzogranites, stock 3 [Margeride (**f**; S_6; 0.145 mm); Plan de la Tour (**g**; S_4; 0.235 mm)]; calc-alkaline series granites, stock 4a [Sidobre granodiorite (**h**; S_{13}; 0.180 mm) and monzogranite (**i**; L_5; 0.170 mm); Monte Capanne, Elba monzogranite (**j**; G_1; 0.220 mm)]; stock 4b [Argentera monzogranite (**k**; U_{24}; 0.210 mm – **l**; G_1; 0.120 mm); Ballon d'alsace monzogranite (**m**; S_{19}; 0.130 mm)]; stock 4c [Saint-Guiral monzogranite (**n**; S_{20}; 0.180 mm); Panticosa granodiorite (**o**; S_{19}; 0.155 mm), leucogranodiorite (**p**; S_{20}; 0.120 mm) and monzogranite (**q**; G_1; 0.110 mm); Aar monzogranite (**r**; P_2; 0.170 mm)]

Souterraine, Margeride, Laubies, Saint-Cierge-la Serre, Tournon, French Central Massif; Rouet, Tanneron and Plan de la Tour, Maures, France; Himalaya). They are classified with essentially crustal granites because, from a petrographic point of view, apart from a little higher basicity, they display conspicuous analogies with the above mentioned aluminous leucogranites. They are granites with quartz, potash feldspar, oligoclase-andesine, biotite, secondary muscovite + cordierite + monazite (Fig. 9g) + zircon + apatite + anatase (very rarely titanite) ± garnet ± tourmaline. Water still shows a strong influence (secondary) muscovitization and sericitization, biotite chloritization, cordierite pinitization ...). The zircon percentage remains low (Pupin 1976, p. 222), and the zircon-monazite association can often be seen (Fig. 9g). As for the leucogranites, these aluminous monzogranites-granodiorites can be found along preferential structures in the orogenic areas (i.e., Rouet-Plan de la Tour area, south-eastern France; Margeride-Tournon area, French Central Massif), and are often "connected" with aluminous leucogranites (Margeride) or with Guéret type granites (La Souterraine, French Central Massif). Yet, a fundamental point distinguishes these granites from those of the first two groups, i.e. the fact that there are basic microgranular xenoliths (Didier 1964, 1973), indicating little mantle contribution (hybridization), if one agrees that those xenoliths in the greater part of intrusive granites were remnents of basic magma (Leterrier and Debon 1978; Orsini 1979).

The zircon populations still show low $\bar{A}$ and $\bar{T}$ indices (250 to 440) (Figs. 5e–g; 6f, g; 9i) and a mean T.E.T. which is shown on Fig. 7, stock 3.

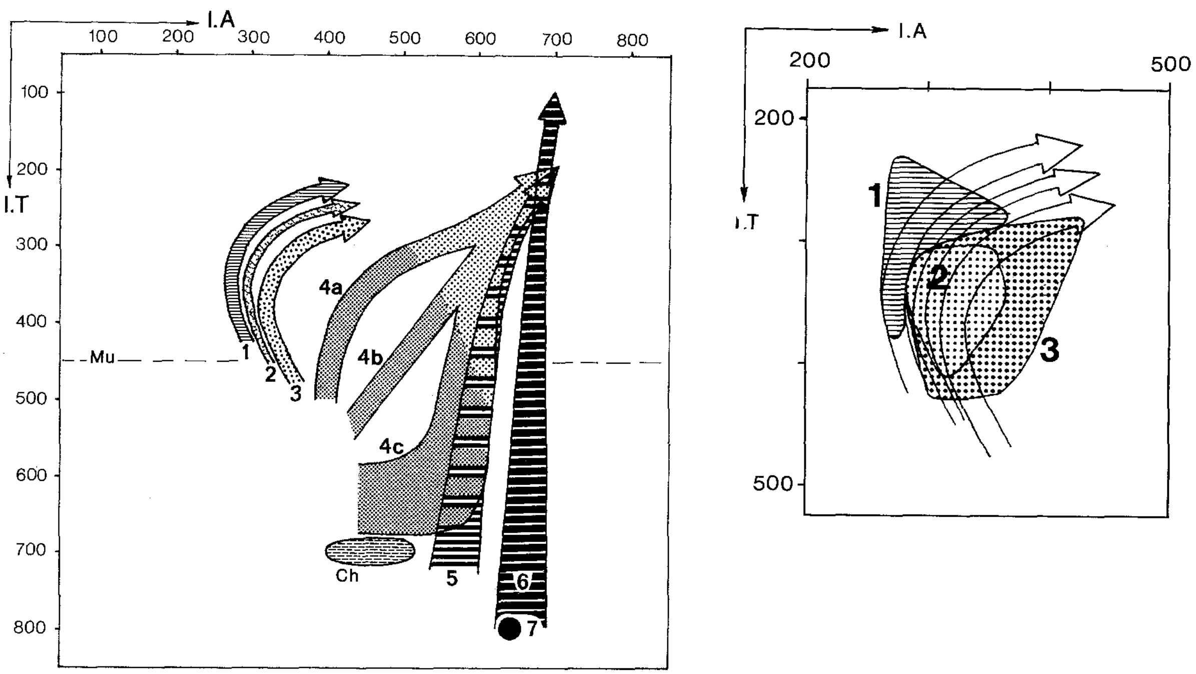

Fig. 7. **a** Distribution of mean points and mean T.E.T. of zircon populations from: Granites of crustal or mainly crustal origin: (*1*) aluminous leucogranites; (*2*) (sub)autochthonous monzogranites and granodiorites; (*3*) intrusive aluminous monzogranites and granodiorites. – Granites of crustal+mantle origin, hybrid granites: (*4a, b, c*) calc-alkaline series granites (*dark doted area*=granodiorites+monzogranites; *clear doted area*=monzogranites+alkaline granites); (*5*) sub-alkaline series granites. – Granites of mantle or mainly mantle origin: (*6*) alkaline series granites; (*7*) tholeiitic series granites. – *Mu*, limit of the muscovite granites (I.T < 450); *Ch*, magmatic charnockites area. If stock 4 exactly represent the repartition known up to now of the granites of the calc-alkaline series, stocks 1, 2, 3, 5, 6 are the areas of the mean points greater frequencies of the corresponding zircon populations, graphically drawn. For stocks 1 to 3, which overlap broadly each other, the *three curved bands 1–3* mark the relative positions of the areas of repartition of the mean points and of the global typological evolutionary trend of populations; the great majority of the mean points of the zircon populations of a stock lie on the corresponding curved line and inside its concavity. To illustrate this fact, an example is taken with 45 granite samples from stocks 1, 2, 3 in the French Central Massif (Fig. 7b): 91% of the mean points are situed on the curve or inside its concavity for each stock. Moreover, a fundamental field argument to distinguish the stock 3 from the stocks 1–2 is the existence only in the stock 3 of basic microgranular xenoliths. **b** Repartition of mean points of zircon populations from granitic rocks of stocks 1, 2, 3 in the French Central Massif (45 samples; respectively 10, 10 and 25 for stocks 1, 2, 3)

B. Granites of Crustal+Mantle Origin (Hybrid Granites)

1) Calc-Alkaline Series Granites. Generally these intrusive granites form a very large rock group the units of which are very diversified. If the granites of the stocks 1,2,3 are broadly present in the French Central Massif, the calc-alkaline members are found in large quantity in the old "pyrénéo-corso-sarde" area. In the outcrop, the bodies can be formed of only a single petrographic entity (i.e., Monte Capanne monzogranite, Elba; Pont-de-Montvert monzogranite French Central Massif). More often however, they are commonly complex, sometimes concentric in pattern, with two or more cogenetic units (i.e., Sidobre granodiorite-monzogranite, French Central Massif; Panticosa quartz gabbro – granodiorite – leucogranodiorite – monzogranite, Pyrénées, France) (Didier 1964; Debon 1975). All these granites show basic microgranular xenoliths in varying quantities and are sometimes associated with basic rocks (gabbro, quartz gabbro, diorite, quartz diorite).

If the major elements chemistry alone were considered, it is often difficult to separate these granites from the aluminous ones considered earlier above (Pupin 1976, p. 78); zircons study however offers an easy discrimination (Pupin and Turco 1975).

The large area associated with this granite series in the (I.A, I.T.) diagram (Fig. 7, stock 4) has been divided into three main stocks (4a–c) depending upon the mean aspect of the individual and differenciation tendencies T.E.T.:

– *Stock 4a:* biotite granodiorite – biotite ± secondary muscovite monzogranite – biotite ± secondary muscovite alkaline granite (eg., Monte Capanne, Elba; Sidobre, French Central Massif) (Figs. 5h, i; 6 h–j).

– *Stock 4b:* biotite ± amphibole granodiorite – biotite + amphibole monzogranite – biotite ± secondary muscovite monzogranite – biotite ± secondary

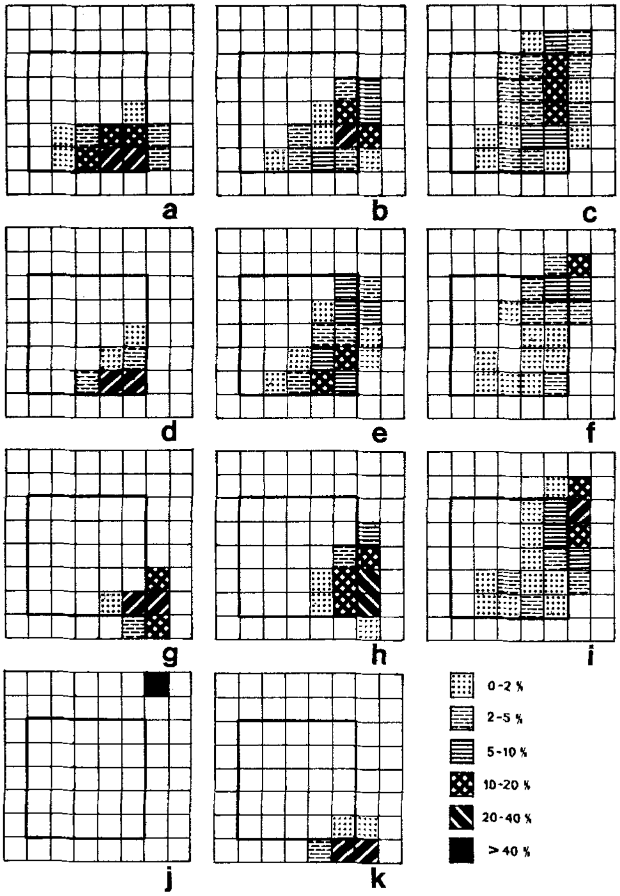

Fig. 8a–k. Zircon crystals from granitic rocks with their subtypes and stock classifications. Typologic distribution of zircon populations from granites: calc-alkaline series: stock 4c [Panticosa granodiorite (**a**), leucogranodiorite (**b**) and monzogranite (**c**)]; sub-alkaline series, stock 5 [Traouiéros (**d**), La Clarté (**e**) and Kerleo-Canton (**f**) monzogranites]; alkaline series, stock 6 [Tolla hypersolvus (**g**), transsolvus (**h**) and subsolvus (**i**) granites; Evisa hyperalkaline albitized granite (**j**)]; tholeiitic series, stock 7 [Inzecca trondhjemite (**k**)]

muscovite alkaline granite (eg., Ballon d'Alsace, Vosges, France; Villefranche de Rouergue, Charbonnières les Varennes, French Central Massif; Argentera, South Alps, France – Pupin and Turco 1974b –) (Figs. 5j, K; 6k–m).

– *Stock 4c:* biotite ± amphibole ± pyroxene granodiorite – biotite ± amphibole ± pyroxene monzogranite – biotite ± secondary muscovite alkaline granite (eg., Panticosa, eastern Cauterets, Pyrénées, France – Debon 1975 –; Bordères, Pyrénées, France – Forghani 1965 –; Bono, Budduso, Sardinia, Italy – Hermitte 1975–; Aar, Switzerland; Aigoual, Saint-Guiral-Liron, Pont de Montvert, Borne, French Central Massif) (Figs. 6n–r; 8a–c).

The association with basic rocks is especially frequent in the stock 4c, where the number of microgranular basic xenoliths seems to be greater. Zircon itself is more abundant in this type of stock (Pupin 1976, p. 223), although in the three a, b, c, stocks, the zircon percentages decrease from granodioritic rocks to the more differentiated ones. At the end of the differentiation (or at the end of crystallization of the more differentiated rocks), all these stocks converge on the G type [{110} {101}] (Fig. 1), thus allowing a fairly easy distinction between the final hololeucocratic monzogranites and alkaline granites of these series with quartz, potash feldspar, albite – acidic oligoclase, biotite ± secondary muscovite + anatase + zircon + apatite ± garnet ± tourmaline ± monazite (rare) ± xenotime, but without cordierite, and the aluminous leucogranites of the stock 1 (Fig. 7). In the granodioritic rocks, sphene is often abundant, together with zircon and apatite.

2) Subalkaline Series Granites. An example of this series had been studied by Barrière (1977) in the Ploumanac'h complex of northern Brittany; Barrière did stress the primarily mantle origin of the rocks and the distinction of this and the calc-alkaline series. The rock association in the Ploumanac'h is as follows: monzogranite and syenogranite with quartz – microline – oligoclase – biotite – hornblende (Traouiéros – La Clarté), biotite monzogranite (Canton), biotite + secondary muscovite leucomonzogranite (Woas Wen). The series first rocks are associated with basic rocks (gabbros, diorites, quartz diorites).

The observed characteristic features of the zircon typology (Pupin et al. 1979) (Figs. 8d–f; 9a, b) give a stock 5 (Fig. 7) that not only fall between the calc-alkaline and alkaline series, but also overlap the calc-alkaline series (stock 4c in part). Zircon populations of the subalkaline series with higher and lower $\bar{T}$ indices are respectively located at the alkaline series hypersolvus and subsolvus granites levels in the (I.A, I.T.) diagram. At the end of differentiation (or at the end of crystallization of the more differentiated rocks), the stock converges on the G type (Fig. 1).

Other monzogranites of the same consanguinity are now known (i.e., Caldas de Reyes, Galicia, Spain – Pupin 1976; Kaltungo, Nigeria – Enu 1978).

C. Granites of Mantle or Mainly Mantle Origin

1) Alkaline Series Granites. These are alkaline and hyperalkaline granites found in subvolcanic, anorogenic complexes (often so-called "ring granites"). The hot and dry magmas productive of these mantle-origin granites (Bonin and Lameyre 1978), give rise to hypersolvus granites (Tuttle and Bowen 1958), with characteristic string perthites. Coloured minerals are iron rich (fayalite, ferro-augite, hedenbergite, aegi-

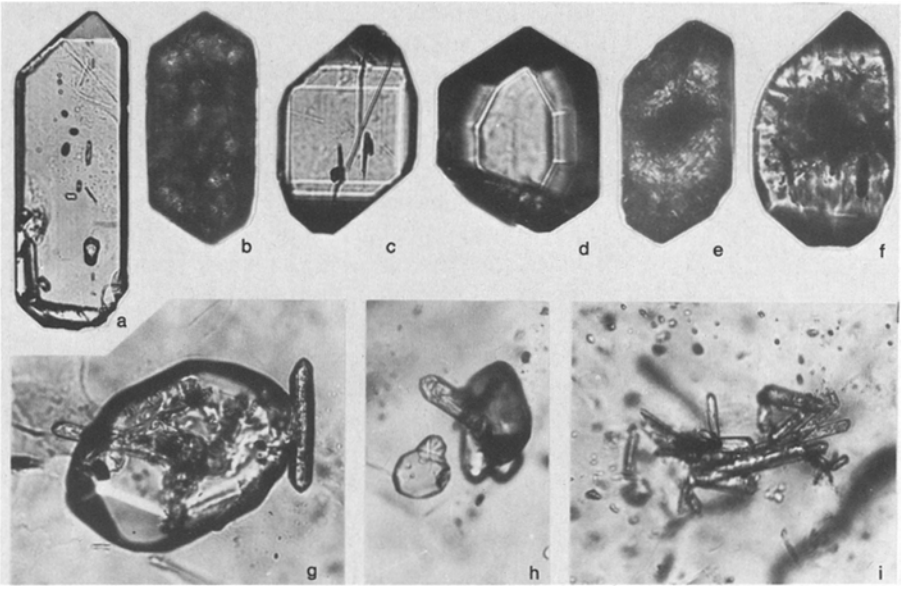

Fig. 9a–i. Zircons from sub-alkaline series granites, stock 5 [Caldas de Reyes, Galicia (**a**; S_{25}; 0.255 mm) and La Clarté (**b**; P_1; 0.160 mm) monzogranites]; alkaline series granites, stock 6 [Tolla hypersolvus granite (**c**; T_{13}; 0.105 mm–**d**; T_5; 0.095 mm); La Chiappa subsolvus granite (**e**; P_1; 0.150 mm)]; tholeiitic series plagiogranites [Inzecca trondhjemite (**f**; N_5; 0.200 mm)]. Monazite-zircon association in quartz from intrusive aluminous monzogranite (**g**; La Souterraine; monazite M = 0.095 mm), aluminous leucogranite (**h**; Saint-Sylvestre; monazite M = 0.030 mm). Late zircon aggregate in quartz from an intrusive aluminous monzogranite (**i**; La Souterraine; aggregate = 0.110 mm)

rine, hastingsite, riebeckite, arfvedsonite and biotite near the annite composition) (Bonin and Lameyre 1978). The crystallization becomes agpaïtic into the hyperalkaline rocks. Transsolvus and subsolvus (Bonin 1972) granites types can be associated with hypersolvus ones (Martin and Bonin 1976).

Zircon populations of these granites are very peculiar:

- large quantity of zircons (hundreds, indeed thousands of ppm in weight) are often observed;
- all of them, except the subsolvus rocks which show a convergence of calc-alkaline and subalkaline series towards the end of differentiation products, possess the highest known $\bar{A}$ indices for all granitic rocks which is in agreement with the preferential development of the {101} pyramid in the alkaline media (Figs. 8g–j; 9c–e);
- hypersolvus rocks show little spread of populations, with very high $\bar{T}$ indices (670 to 800) (Fig. 8g);
- new types of zircon (among these *K* [{100} {101} {301}], *T* [{100} {110} {101} {301}]) (Fig. 9c, d) can be found in relatively high percentages;
- as expected in water deficient magmas, the hypersolvus rocks have zircons that are devoid of hydrozircon overgrowths;
- in the hyperalkaline albitized granites, late zircon crystallization can produce octaedric A type crystal populations, which are, as far we know, not seen in granites outside the alkaline series (Pupin and Turco 1975) (Fig. 8j).

The stock thus established (6) is, in actual fact, vertical and straight in the (I.A, I.T) diagram (Fig. 7) and, apart from the more differentiated subsolvus rocks, shows a distinct distribution pattern from the previous stocks. Also the stock 6 trends towards the G type (then the A type), which appears to be the extreme type that could crystallize in alkaline and relatively cool medium (~600° C – Pupin and Turco 1972c), the medium itself forming at the end of crystallization of numerous magmas with monzogranitic or alkaline chemical composition.

2) Tholeiitic Series Granites. Up to now, no detailed investigations have been made on the zircons of these sparingly distributed granites. Nevertheless, the recent study of a trondhjemitic composition "plagiogranite" encountered in the Inzecca ophiolites in Corsica (Jauzein et al. 1979) and considered to have crystallized out of a liquid of the extreme differentiation of a tholeiitic magma (Ohnenstetter and Ohnenstetter 1976), has been considered to be of very great interest. As a matter of fact, the zircon population of that trondhjemite exhibit great analogies with populations from alkaline hypersolvus granites and associated rhyolites in the alkaline complexes overlying calderas:

- large quantity of zircons;
- very localized typologic distribution (Fig. 8k) and $\bar{T}$ index = 797, one of the highest found up to date in plutonic rocks (Pupin et al. 1979);
- a high frequency of N_5 and K_1 subtypes, which are generally not found in orogenic plutonic rocks (Fig. 9f).

That plagiogranite, which appears to have unquestionably formed from a pyrolitic magma that is free of crustal contamination occupies an interesting position in the (I.A, I.T) diagram. It is located near

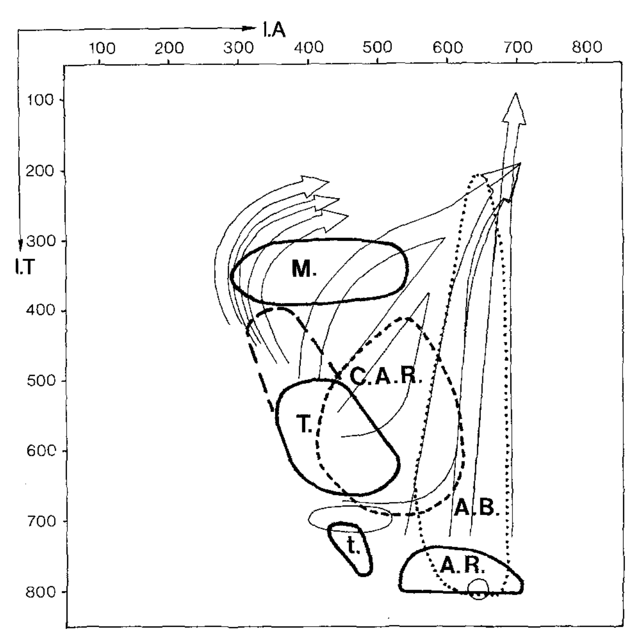

Fig. 10. Distribution of some non granitic groups of endogenous rocks: (*A.B.*) alkaline basalts with gem-quality zircons; (*A.R.*) alkaline series rhyolites from anorogenic complexes; (*C.A.R.*) calc-alkaline series rhyolites (orogenic); (*M*) migmatites; (*t*) trachyandesites; (*T*) tonalites

stocks 5 and 6 in the area of the alkaline rhyolites that are related to the anorogenic complexes (Fig. 10), and which are considered to be either entirely or substantially of mantle origin.

General Views and Discussion

Before summarising the fundamental points of the preceeding presentation, some comments will be made on Fig. 10 which contains some non granitic groups of rocks:

– *migmatites* (M) (Pupin 1976, p. 297; 21 samples) show rather low $\bar{T}$ indices (300–400) (crystallization temperature ~650–700° C) and occupy mainly the areas of essentially crustal granites (1 to 4a);

– *tonalites and quartz gabbro-diorites* (T) (Pupin 1976, p. 179; 25 samples) locate at the root of the calc-alkaline stocks (less differentiated rocks) and under anatectic granites (they, themselves, can be formed from the anatexis of amphibolitic gneiss and amphibolites). The convergence of the zircon populations position of quartz diorites derived from these two processes can also be explained by the geochemical convergence of the magmas thus obtained: the sialic crust-mantle hybridization of the calc-alkaline stock can, in a way, be found again in the anatexis of gneiss and amphibolitic series through the mainly mantle origin of most of the amphibolites (ancient alkaline or tholeiitic basalts or basic tuffs);

– *magmatic charnockites* (Ch) (Pupin 1976, p. 351; 6 samples from Ivory Coast and Rogaland, Norway) locate right under the quartzitic tonalites – gabbros – diorites group and the calc-alkaline stock 4c (Fig. 7), which shows the greatest number of basic rocks associations of granites. A convergence of these rocks with the basic calc-alkaline series rocks of very deep origin is therefore indicated which could be used as an argument for regarding them as being formed in typical magmatic calc-alkaline area;

– *calc-alkaline rhyolites* (C.A.R.) (Tessier et al. 1978; 15 samples from Corsica and French Central Massif) cover all the lower part of stock 4; the observed difference when compared with the crystalline equivalents can be explained as resulting from the break in zircon crystallization consequent on rapid cooling in rhyolites (vitreous mesostase rhyolites), whereas crystallization is not similarly interrupted in granites (Pupin 1976, p. 269);

– the same observation can be made for the *alkaline rhyolites* (A.R.) related to the anorogenic subvolcanic complexes (Pupin 1978; Tessier et al. 1978; 26 samples from Corsica and Estérel, France); attention is especially drawn to their localization, right at the roots of stocks 5 and 6, and also to the already mentioned position of the tholeiitic plagiogranite. The place of the ring shaped anorogenic complexes within the areas of plate spreading and especially in the intracontinental rifts zone could be found again with the subalkaline series granites (eg., the red hercynian granites alignment Aber Ildut – Morlaix bay – Ploumanac'h – Flamanville – Barfleur in northern Brittany and Contentin, France; Barrière 1977);

– the genesis of the gem-quality zircons from *alkaline basalts* is not well explained yet (Pupin 1976, p. 271), but it is worth noting that their population fields (5 have been studied from Madagascar, Cambodia, Tasmania and Velay, France) accord very well with stocks 5 and 6 (A.B. Fig. 10).

In the Fig. 7, the distribution of the different genetic types of granites comes out with an extreme logic: the sialic origin granites with low $\bar{A}$ and $\bar{T}$ indices and the mantle origin granites with high $\bar{A}$ and $\bar{T}$ indices. In between, the hybrid granites are essentially represented by the calc-alkaline rocks. This type of distribution pattern is diagramatically represented in Fig. 11.

The association with basic bodies (gabbros, diorites ...) is likely to be found in the granites of stocks 4c to 7, where variation of the lithologic types involves the existence of often more complicated bodies, in the same way that the basic microcrystalline xenoliths which are not found in stocks 1 and 2 be-

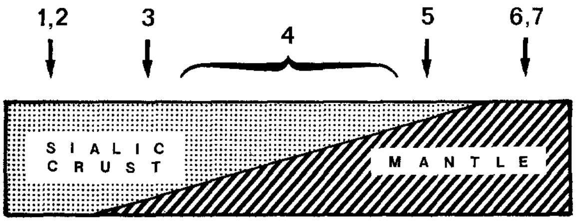

Fig. 11. Schematic diagram summarizing origin of material for different stocks of granites (*1 to 7*)

come visible in stock 3 and are numerous indeed in the 4c stock. The abundance of micrograrites dykes and bodies also increases from stock 1 to 6.

The zircon percentage in granites increases from stock 1 (where it is especially low) to stocks 6–7 (uncommonly rich). The anatectic phenomena seems to be productive of a zirconium segregation inside the sialic crust, by extracting from it some melts impoverished in that element (Pupin 1976, p. 222). The partial melting of the mantle which was invoked by Bonin and Lameyre (1978) to account for the alkaline magma for the formation of hypersolvus granite is also capable of concentrating appreciable quantity of zirconium in as much as this element is normally present in noticeable quantity in basic magmas (Chao and Fleisher 1960).

The zircon inclusions (Pupin 1976) are also different according to the stock chosen. Generally zircons of the 1-2-3 stocks are inclusions poor and are similar to those found in migmatites. Inclusions become more numerous and diversified in the other stocks (4 to 7): examples of inclusions in subvolcanic rocks are stocky microlites, negative crystals and vitreous materials.

It granites do appear as complex rocks on the whole, the genetic scheme compiled out of zircons study gives a fairly clear picture which should enable us to deal more easily with the problems related to that type of rock. One can readily see that term "monzogranites" in the 1, 2, 3, 4a, b, c, 5 stocks do not have the same meaning, even if most of them, at first sight, appear to be common biotite granites. This is also true for granodiorites, or for two-mica granites with an alkaline tendency, the petrogenesis of which can be very different: stock 1 or stocks 4a, b, c, 5, 6 ends.

The most critical point is the discrimination between the ends of stocks converging on the G type. In that case, the individual populations T.E.T. can be very useful, since their respective slopes change with their belonging to such or such stock (Pupin 1976); eg., 4a stock: Sidobre monzogranite ($\alpha = 35°$); 4b stock: Argentera monzogranite ($\alpha = 47°$); 4c stock: Aar monzogranite ($\alpha = 60°$); 6 stock: La Chiappa subsolvus alkaline granite, Corsica ($\alpha = 65°$). It is also possible to have a look at the populations early zircons [with a prevailing {100} prism]; on the average those crystals show larger {211} pyramids in the calc-alkaline series granites than in the alkaline one.

Zircon Typology and the Initial Ratios of Sr^{87}/Sr^{86} in Granitic Rocks

As a whole, there is some correlation between the genetic schema derived from the typologic study of zircon populations and the Sr^{87}/Sr^{86} ratios, but in detail, the coherence of the results is not always very good.

Granites from the very roots of alkaline and subalkaline stocks 6 and 5 have the lowest Sr^{87}/Sr^{86} ratios [0.703–0.707 for the hypersolvus alkaline-peralkaline granites from Evisa and Tolla, Corsica (Bonin 1972); 0.705 for the monzogranite from Ploumanac'h, Brittany (Barrière 1977)]. Same values are found for the plagiogranites from the ophiolitic complexes of Troodos, Cyprus: 0.704–0.706 (Coleman and Peterman 1975). The granites of the calc-alkaline series (4) have higher strontium isotope ratios: 0.706–0.708 for monzogranites-granodiorites from Thiers, Pont-de-Montvert, Borne, Aigoual, Piégut-Pluviers, Confolens, French Central Massif (Duthou 1977; Miahle 1980); 0.710–0.712 for the more recent granites from Aegean Sea (Altherr and Wendt 1978).

The aluminous granites from stocks 1 to 3 show generally higher Sr^{87}/Sr^{86} ratios:

– *Stock 3:* 0.708 to 0.714 (Margeride monzogranite; Couturié et al. 1971; Vachette et al. 1979); 0.709 (Plan de la Tour and Rouet granites; Roubault et al. 1970); 0.719 (cordierite bearing monzogranites from Lower Himalaya; Le Fort et al. 1980):

– *Stock 2:* 0.709 to 0.718 for the migmatitic granite from Treban, French Central Massif (Duthou 1977), but 0.706 for the migmatitic granite from Velay (Vachette et al. 1971):

– *Stock 1:* 0.709 to 0.717 for most of the aluminous leucogranites from the French Central Massif (Saint-Mathieu, Blond, Cognac, small stocks in the Margeride), but respectively 0.705 and 0.707 for Chateauponsac and Saint-Sylvestre leucogranites in the same area (Couturié et al. 1971; Duthou 1977).

For the stocks 5 to 7, the Sr^{87}/Sr^{86} ratios are akin to the mantle values (0.702–0.704), and more typically sialic (>0.710) for aluminous granites of the stocks 1 to 3; intermediate values can be found for stock 4 where the contamination between sialic crust and mantle is fairly well developed. Nevertheless, the low Sr^{87}/Sr^{86} ratios (0.705, 0.707) obtained from some aluminous leucogranites and the autochthonous granite from Velay show that in granitic rocks, these ratios must be carefully interpreted.

Recent geochronological data on hypovolcanic alkaline rocks from Nigeria and Niger (Van Breemen et al. 1975; Bowden et al. 1976; in: Ducrot et al. 1979) have shown high Sr isotope ratios (0.706 to 0.752) for magmas of very deep origin, probably due to a contamination from the crust. Bonin and Lameyre (1978) have also proposed three different possibilities to explain these high values: (i) an overheated basic intrusion induce the melt of the continental crust; (ii) contamination with Sr from the surrounding rocks or from circulating waters in those; (iii) duration of magma transit from its source to its actual position.

The similarity of typologic data from a same batholith over great distances (one hundred kilometers in the Margeride, French Central Massif) is a fundamental argument to consider that zircon populations reflect very accurately the origin of the magma. Postmagmatic geochemical variations induced locally by deuteric processes are without any effect on the zircon populations.

Aluminous leucogranites and hypersolvus alkaline granites are respectively two very specific entities among granitic rocks and are very well defined what with the petrography (main and accessory minerals) and what with the field (lithologic associations, enclaves, geodynamic setting). These specificities are also found in the very well defined repartition of their zircon populations (I.$\bar{A}$, I.$\bar{T}$ $\sim$300, 300 for aluminous leucogranites; 650, 700 for hypersolvus alkaline granites). On the contrary, the great variations in the initial ratios of Sr^{87}/Sr^{86} do not seem to reflect the same very remarkable specificities.

Conclusion

Zircon is an exceptionally significant common mineral of rocks. The study of a granite's zircon population[4] can provide extremely valuable data about its petrogenesis. The zircon's crystallization period, thereby the magma's water content, chemical and temperature variations of the crystallization medium can be estimated. The determination of the stock relationship of a rock gives data about the parent magma. The zircon population distribution in the (I.A, I.T) diagram also allows the foreseeing of the mineral associations, mainly subordinate, likely to be associated with the zircon. Apart from shedding light on the question of granite petrology, zircon also gives a criterion for dealing with the problems of comparative petrology and for resolving the question of the possible petrogenetic relationship of juxtaposed granite outcrops.

Acknowledgements. The author is very grateful to Professor G.H. Turco, Nice, for many fruitful discussions during all the period of his research. Thanks are also due to Professors A.A. Kayode, Ife, Nigeria, and J.E. Dietrich, Nice, for the english translation of the earlier french version of the manuscript. Carefull review by D. Gebauer and M. Grunenfelder are gratefully acknowledged.

References

Alinat M (1975) Le zircon dans les roches de la série métamorphique de l'anticlinal de Tulle (Corrèze, Massif Central français). Applications pétrogénétiques. Thèse Doct 3e cycle, Univ Nice (France), 196 pp

Alper A, Poldervaart A (1957) Zircons from the Animas stock and associated rocks, New Mexico. Econ Geol 52:8, 952–971

Altherr R, Wendt I (1978) Miozäne barrow-Metamorphose und granitischer Plutonismus in der Zentralägäis. Bund Geowiss Rohst, DFG We 345/23 (1):90 pp

Barrière M (1977) Le complexe de Ploumanac'h, Massif armoricain. Thèse Doct Etat, Univ Brest (France), 291 pp

Bonin B (1972) Le complexe granitique de la région de Tolla-Cauro (Corse). Thèse Doct 3e cycle, Univ Paris (France), 127 pp

Bonin B (1975) Il y a granites et granites ... La Recherche 6 (57):570–573

Bonin B, Lameyre J (1978) Réflexions sur la position et l'origine des complexes magmatiques anorogéniques. Bull Soc Géol Fr 7, XX (1):45–59

Bowden P, Van Breemen D, Hutchinson J, Turner DC (1976) Palaeozoic and mesozoic age trends for alkaline ring complexes in Niger and Nigeria. Nature 259 (5541):297–299

Chao ECT, Fleischer M (1960) Abundance of zirconium in igneous rocks. 21th Int Geol Congr Report 1:106–131

Coleman RG, Peterman ZE (1975) Oceanic plagiogranites. J Geophys Res 80:1099–1108

Couturié JP, Roques M, Vachette M (1971) Age calédonien tardif du granite de la Margeride (Massif Central français) et âge hercynien des leucogranites qui le traversent. C R Acad Sc Paris 272 [D]:3235–3238

Debon F (1975) Les massifs granitoïdes à structure concentrique de Cauterets-Panticosa (Pyrénées occidentales) et leurs enclaves. Thèse Doct Etat, Univ Nancy (France), Mem Sc Terre 33:420 pp

Didier J (1964) Etude pétrographique des enclaves de quelques granites du Massif Central français. Thèse Doct Etat, Univ Clermont-Ferrand (France), Ann Fac Sc 23:254 pp

Didier J (1971) Granites and their enclaves. Elsevier Publ Cie 3, 393 pp

Didier J, Lameyre J (1971) Les roches granitiques du Massif Central. Symposium J Jung, Clermont-Ferrand, 133–156

Ducrot J, Lancelot JR, Reille JL (1979) Datation en Montagne Noire d'un témoin d'une phase majeure d'amincissement crustal caractéristique de l'Europe prévarisque. Bull Soc Géol Fr XXI (4):501–505

Duthou JL (1977) Chronologie Rb–Sr et géochimie des granitoïdes d'un segment de la chaîne varisque. Relations avec le métamorphisme: Le Nord Limousin (Massif Central français). Thèse Doct Etat, Ann Sc Univ Clermont, 63 (30): 294 pp

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[4] The method's apprenticeship can be made in the Laboratoire de Pétrologie-Minéralogie of Nice (France) in a few days. There are no great difficulties and, with some habit, one or two days are enough, beginning with the rough rock, to achieve the typological distribution of zircon populations

Effimoff I (1972) Chemical and morphological variations of zircons from the Boulder batholith, Montana. Diss Univ St Lawrence Cincinnati, 166 pp

Enu EI (1978) Contribution à l'étude sédimentologique des formations crétacées dans la haute vallée de la Bénoué (région de Cham, Nigéria nord-oriental). Thèse Doct 3è cycle, Univ Nice (France), 178 pp

Forghani AH (1965) Sur la structure annulaire du massif éruptif de Bordères, Hautes-Pyrénées. CR Acad Sc Paris 260:6943–6945

Giraud JD, Pupin JP, Turco G (1979) La microdiorite quartzique d'Alghero (Sardaigne). Relations avec le volcanisme calco-alcalin cenozoïque sarde. Réun Ann Sc Terre, Lyon (France), p 221

Hermitte D (1975) La morphologie des zircons dans les intrusions calco-alcalines du centre-nord de la Sardaigne. Thèse Doct 3è cycle, Univ Marseille (France), 159 pp

Jauzein P, Pupin JP, Bonin B (1979) Les zircons des trondhjemites corses: typologie – implications. Réun Ann Sc Terre, Lyon (France), p 262

Köhler H (1968) Über Zirkone moldanubischer Granite. Diss Univ München

Köhler H (1970) Die Änderung der Zirkonmorphologie mit dem Differentiationsgrad eines Granits. Neues Jahrb Mineral, Monatsh 9:405–420

Kurtbas K, Marquaire C, Ranchin G (1969) Différenciations pétrographiques et géochimiques dans le massif granitique de Guéret et les massifs annexes de la Marche occidentale. C R Acad Sc Paris 268 [D]:2396–2398

Lameyre J (1966) Leucogranites et muscovitisation dans le Massif Central français. Thèse Doct Etat, Univ Clermont-Ferrand (France), Ann Fac Sc 29: 264 pp

Lameyre J (1973) Les marques de l'eau dans les leucogranites du Massif Central français. Bull Soc Géol Fr 15:288–295

Lameyre J (1975) Roches et minéraux. 2. – Les formations, Doin (éd). Paris, pp 135–352

Larsen LH, Poldervaart A (1957) Measurement and distribution of zircons in some granitic rocks of magmatic origin. Mineral Mag 31:544–564

Le Fort P, Debon F, Sonet J (1980) La ceinture des granites à cordiérite du »Bas-Himalaya«. Typologie et âge Rb–Sr du massif de Manserah (Pakistan). Réun Ann Sc Terre, Marseille (France), p 218

Leterrier J, Debon F (1978) Caractères chimiques comparés des roches granitoïdes et de leurs enclaves microgrenues. Implications génétiques. Bull Soc Géol Fr 7, XX (1):3–10

Martin RF, Bonin B (1976) Water and magma genesis: the association hypersolvus granite-subsolvus granite. Can Mineral 14:228–237

Miahle J (1980) Le massif granitique de la Borne (Cévennes). Thèse Doct 3è cycle, Univ Clermont-Ferrand (France), 130 pp

Ohnenstetter D, Ohnenstetter M (1976) Modèle de fonctionnement d'une ride médio-océanique à partir de l'étude pétrologique des ophiolites corses. Bull Soc Géol Fr 18 (4):889–894

Orsini J (1979) Contribution à la connaissance des granitoïdes tardi-orogéniques du batholite corso-sarde. Les enclaves sombres de l'association plutonique calco-alcaline. Travaux Lab Sc Terre Marseille (France) C3, 104 pp

Poldervaart A (1950) Statistical studies of zircon as a criterion in granitization. Nature 165:574–575

Poldervaart A (1956) Zircon in rocks. 2. – Igneous rocks. Am J Sci 254:521–554

Pupin JP (1976) Signification des caractères morphologiques du zircon commun des roches en pétrologie. Base de la méthode typologique. Applications. Thèse Doct Etat, Univ Nice (France), 394 pp

Pupin JP, Bonin B, Tessier M, Turco G (1978) Rôle de l'eau sur les caractères morphologiques et la cristallisation du zircon dans les granites. Bull Soc Géol Fr 20 (5):721–725

Pupin JP, Casanova R, Turco G (1975) Les zircons de quelques granitoïdes précambriens de Côte d'Ivoire. Bull Suisse Mineral Petr 55/1:35–50

Pupin JP, Dupuis C, Turco G (1979) Le zircon et l'origine mantellique de certains granites: le point après l'étude du complexe de Ploumanac'h-Ile Grande (Bretagne septentrionale). Réun Ann Sc Terre, Lyon (France), p 387

Pupin JP, Turco G (1972a) Une typologie originale du zircon accessoire. Bull Soc Fr Mineral Cristallogr 95:348–359

Pupin JP, Turco G (1972b) Application des données morphologiques du zircon accessoire en pétrologie endogène. C R Acad Sci Paris 275 [D]:799–802

Pupin JP, Turco G (1972c) Le zircon accessoire en géothermométrie. C R Acad Sci Paris 274 [D]:2121–2124

Pupin JP, Turco G (1974a) Contrôle thermique du développement de la muscovite dans les granitoïdes et morphologie du zircon. C R Acad Sci Paris 278 [D]:2719–2722

Pupin JP, Turco G (1974b) Application à quelques roches endogènes du Massif franco-italien de l'Argentera-Mercantour d'une typologie originale du zircon assessoire. Etude comparative avec la méthode des RMA. Bull Soc Fr Mineral Cristallogr 97:59–69

Pupin JP, Turco G (1975) Typologie de zircon accessoire dans les roches plutoniques dioritiques, granitiques et syénitiques. Facteurs essentiels déterminant les variations typologiques. Pétrologie I (2):139–156

Ranchin G (1970) La géochimie de l'uranium et la différenciation granitique dans la province uranifère du Nord-Limousin. Thèse Doct Etat, Univ Nancy (France), 483 pp

Read HH (1957) The granite controversy. Murley (éd)

Roubault M, Bordet P, Leutwein F, Sonet J, Zimmermann JL (1970) Ages absolus des formations cristallophylliennes des massifs des Maures et du Tanneron. C R Acad Sci Paris 271 [D]:1067–1070

Silver LT, Deutsch S (1963) Uranium-lead isotopic variations in zircons: a case study. J Geol 71:721–758

Tessier M, Pupin JP, Turco G, Vellutini P (1978) Le zircon, un argument pour distinguer les rhyolites orogéniques des rhyolites des complexes annulaires: l'exemple corso-provençal. C R Acad Sci Paris 287 [D]:407–410

Tuttle OF, Bowen NL (1958) Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8-KAlSi_3O_8-SiO_2-H_2O$. Geol Soc Am Mem 74:1–153

Vachette M, Roques M, Couturié JP (1971) Age hercynien précoce du massif de granite du Velay (Massif Central français) et âge calédonien des migmatites en panneaux dans ce massif. C R Acad Sci Paris 272 [D]:3116–3119

Vachette M, Vialette Y, Couturié JP (1979) Age namurien du granite de la Margeride. Conséquenses. Réun Ann Sc Terre, Lyon (France), p 452

Van Breemen O, Hutchinson J, Bowden P (1975) Age and origin of the nigerian mesozoic granites. A Rb–Sr isotopic study. Contrib Mineral Petrol 50:157–172

Veniale F, Pigorini B, Soggetti F (1968) Petrological significance of the accessory zircon in the granites from Baveno M, Orfano and Alzo (North Italy). Int Geol Congr Report, 23° sess Czechosl 13:243–268

Received October 30, 1979; Accepted May 28, 1980