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Magmatic Zoning of Hercynian Granitoids in France based on Zircon Typology

by *J. P. Pupin*

Abstract

Typological methods of studying zircon in granites permits information on their host rocks to be obtained rapidly and easily. Statistical studies show that reproducibility is good even in the interior of the same homogeneous massif and the study of a zircon population of 100 grains gives results adequate to define such a massif. The genetic value of the diagram employed is underlined by the relationship which exists between zircon typology (morphology) and the geochemical criteria routinely used to determine the genesis of the rocks (trace elements, R. E. E. isotope geochemistry).

The diagram of genetic classification of granites (Pupin, 1980) was used to determine the origin and interrelationships of Hercynian rocks in Brittany, the "Massif Central", and Corsica. The analysis shows that magmatic zones of varying complexity exist in the Variscan basement. Some overlap exists between individual groups, but the zonation is characterized by the following succession:

1. calc-alkaline granites derived from water-rich magmas;
2. parautochthonous or rarely intrusive aluminous anatectic granites;
3. intrusive aluminous anatectic granites, often with porphyritic texture, and with basic microgranular enclaves;
4. calc-alkaline and K-calc-alkaline granites derived from "hot and dry" magmas;
5. K-subalkaline granites.

Magmatic zonations (1-2-3-4), (2-3-4-5), and (1-4) correspond respectively to the French "Massif Central", Brittany, and Corsica.

These patterns of zoning are believed to have been related to major plate tectonic structures, the granites 1 to 5 having been produced from progressively hotter and drier magmas. Magmatism can help provide important criteria for reconstructing the polarity in paleogeodynamic setting, in particular zones of subduction-collision.

Keywords: Hercynian orogeny, magmatic zoning, calc-alkaline granites, zircon typology. Brittany, Corsica, French Massif Central.

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1. Introduction

Mobile belts are crustal segments that have experienced a high thermal flux and strong plastic/rigid deformation. Besides the occurrence of regionally metamorphosed rocks, the most outstanding feature of mobile belts is the occurrence of numerous granites with differing compositional, textural, and geological characteristics.

In many cases, cross-sections through mobile belts and adjacent stable areas (cratons) show a more or less obvious magmatic zoning which differs from belt to belt. The mapping and interpretation of the magmatic zoning in ancient and modern belts provides a fundamental tool for understanding geodynamic processes along active continental margins of different types and ages.

In the present paper, the author outlines the magmatic zoning of Hercynian granitoids from Corsica, the French "Massif Central", and Brittany, and proposes a preliminary model to explain their similarities. The magmatic zoning of the three areas is based on the study of 250 samples by the zircon method (Pupin, 1976, 1980).

2. The Zircon method. Reproducibility and statistical significance

The typological method (fig. 1) which defines zircon crystals on the basis of the relative development of prism faces (index T) and pyramid faces (index A), has been described in several earlier works (Pupin and Turco, 1972a, c, 1975a; Pupin, 1976, 1980).

Zircon populations are obtained by using a routine procedure of concentration. A rapid method of concentrating zircons allows a population from a massive rock to be obtained in about two hours: 500 g of fresh solid rock are broken up with a hammer and then crushed in a vibrating pulverizer with oscillating discs (about 15 seconds); the crushed product is sifted by hand using two small sieves (0.050 and 0.160 mm); ∅ 10 cm); gravity separation using bromoform concentrates the heavy residue which is washed in solvent, dried, and then electromagnetically separated; the fraction that is not attracted by the maximum magnetic intensity is then mounted in Canada balsam on microscope glass slides beneath a cover glass and is, in most cases, sufficiently rich in zircon to allow typological study.

In a typical sample of the total population of a rock mounted in balsam and observed under the microscope with a magnification × 250, one randomly picks 100 crystals of zircon. The typological measurement of these crystals allows one to construct a diagram of the typological distribution which shows the absolute frequency of the different types and subtypes which constitute the total population.

The number of subtypes of natural zircon populations show a wide range of variations. There are populations with only one subtype (for example, A type in the albitized peralkaline granite from Evisa, Corsica), or with very few subtypes

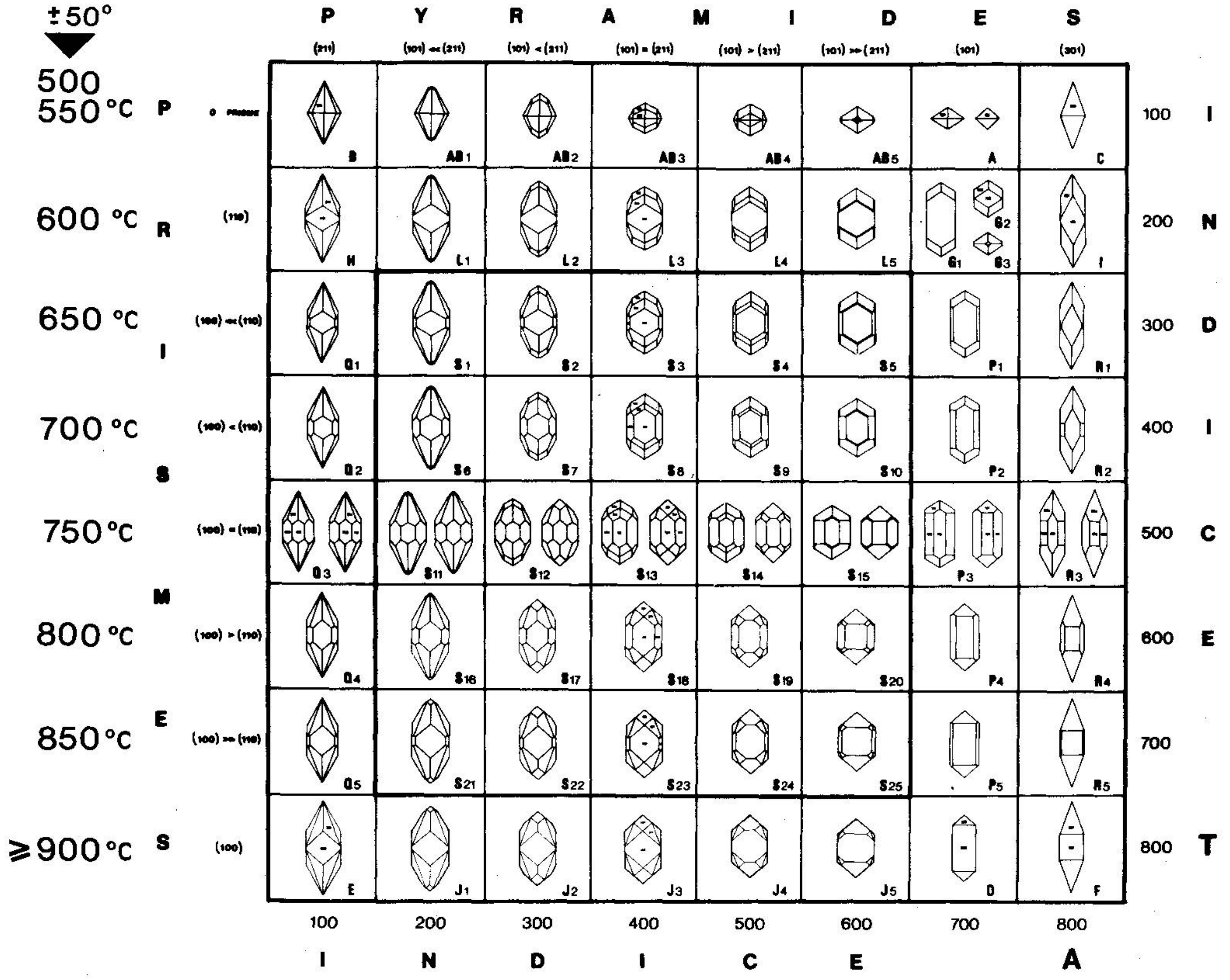

Fig. 1 Main types and subtypes of the typologic classification and corresponding geothermometric scale. The two variables (A, T) depend upon the relative development of the crystalline faces (respectively pyramids and prisms of the zircon).

(for example, D type and J_5, N_5, P_5 subtypes in phonolites from Roche Tuilière, Auvergne, and Roc des Pradoux, Velay, French Massif Central). Others contain a large number of subtypes (38 different subtypes for 28 squares of the typological diagram in the hololeucocratic microgranite from Argentera, France; 30 different subtypes for 29 squares in the biotite quartz-trachyte from Puy de Dôme, French Massif Central). The majority of the populations lie between these extreme cases and possess from 10 to 22 different subtypes of variable frequencies. The five most frequent subtypes generally constitute more than 50% of the population. With the exception of xenocrystals, a large variety of subtypes suggest highly changeable conditions in the mode of magma crystallization.

Each type and subtype has its own coordinates A and T in the typological diagram (fig. 1); it is therefore possible to calculate the mean ($I.\bar{A}$, $I.\bar{T}$) of the zircon population (Pupin and Turco, 1972c, Pupin, 1976, 1980).

For fairly uniform populations with few different subtypes, a good value for the Ā and T̄ indices is obtained from a small number of crystals. For more variable populations with numerous different subtypes, tests done on populations distributed over some 20 squares of the typological diagram indicate that Δ I.Ā and Δ I.T̄ ≦ 40 for a population of more than 10 crystals, ≦ 15 for a population more than 50 crystals. A reliable picture of the true population will therefore be obtained by analysing more than 50 crystals; taking into account indeterminate crystals (generally less than 30 per cent for endogenous rocks), significant results can be obtained from a study of 100 crystals.

What about the influence of crystal size on the typological distribution? We note that in the typologically widespread magmatic rock populations, where the zircons are not of synchronous crystallization, the earliest crystals are generally larger than the later ones (with numerous minute late zircons of synchronous crystallization with quartz in water-rich granitic magmas [Pupin et al., 1978]). Therefore, in order to make meaningful comparisons, it is necessary to work on the same grain size, namely the class from 0.050 to 0.160 mm, which is the easiest to obtain and study, and where the majority of the zircons is generally concentrated. Several examples have shown that the different grain sizes of a population of the same rock: 0.063–0.080, 0.080–0.100, 0.100–0.125, 0.050–0.160, 0.160–0.315 mm nevertheless yield only Δ I.Ā ≦ 20 and Δ I.T̄ ≦ 50.

Finally, within the same fairly homogeneous geological formation (a non complex granitic batholith, volcanic flow, etc....), even the study of one sample gives a reasonably precise indication of the nature and origin of the material. Generally, the widest range between different samples of the same massif are reflected by I.T, which must be related to differences in the physico-chemical conditions prevailing during crystallization of the magma which are underlined by the differences in texture, mineralogy, deuteric alteration, etc.... For the identical formation, I.T̄ ≦ 120, I.Ā ≦ 50 signifies that the distribution of mean points (I.Ā, I.T̄) of the populations from samples of the same «homogeneous» massif barely exceeds on the surface more than half the area corresponding to a main subtype in the diagram (I.A, I.T) (half a square of the typological diagram).

3. The Zircon method and granite classification

The use of the zircon method as a tool for the classification and interpretation of plutonic and volcanic granitoids has been improved greatly during the last ten years by the systematic study of zircon crystal typology (for references see Pupin, 1980). By observing the relative development of the different prismatic and pyramidal faces as well as measuring the variability of zircon popu-

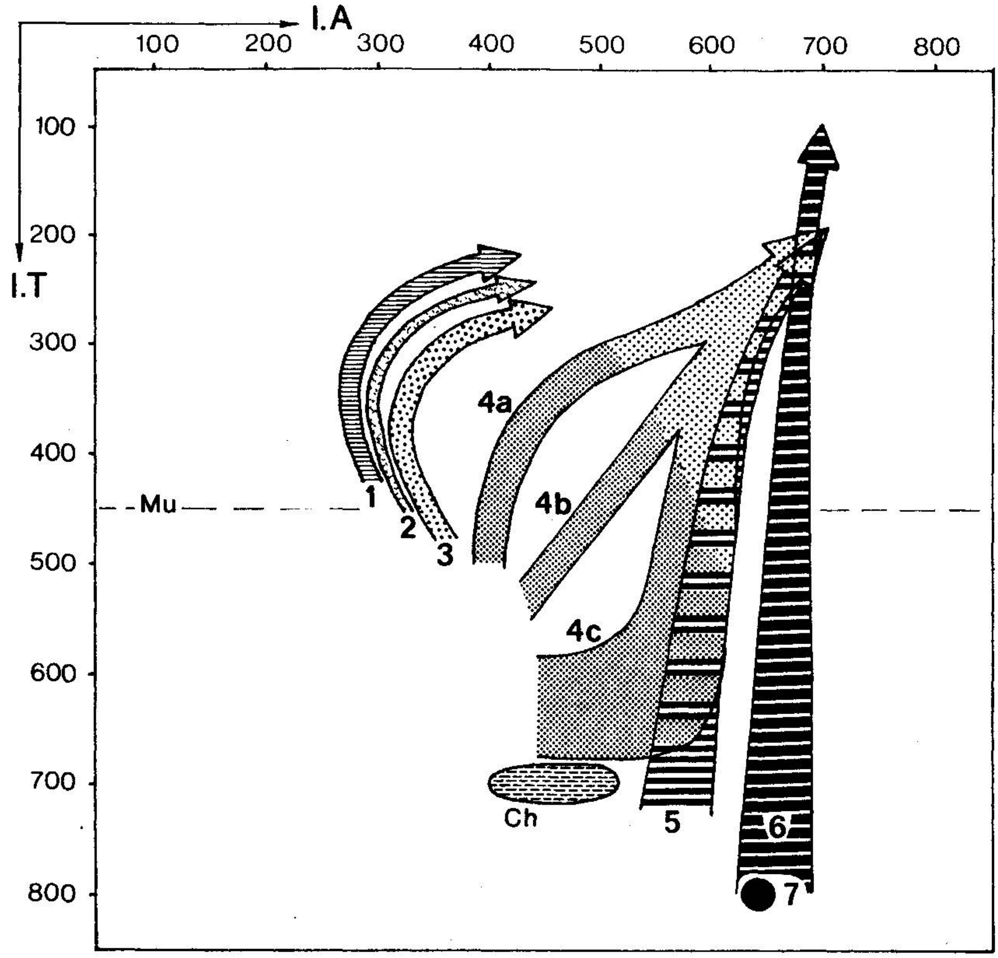

Fig. 2 Distribution of mean points and mean Typological Evolutionary Trends of zircon populations (Pupin, 1980) from: Aluminous anatectic granites: (1) aluminous leucogranites; (2) (par)autochthonous monzogranites and granodiorites; (3) intrusive aluminous monzogranites and granodiorites. - Hybrid granites of crustal + mantle origin: (4 a, 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.

lation in a given sample, it is possible to determine different types of granite and some of their special characteristics. For example, one can distinguish: (1) granites with a short vs. long crystallization period for zircon, (2) granites evolved from "dry" as opposed to "hydrous" magmas, (3) granite of low, medium, or high crystallization temperature, and even (4) the potential for mineralization in granites (e.g. tin-bearing granites) (Pupin, 1976; Pupin and Turco, 1972b, 1974, 1975, Pupin et al., 1978). The temperature of crystallization of magma, in terms of the zircons, is given by the index T. A high T index indicates a higher crystallization temperature than does a low T index (Pupin and Turco, 1972b) (fig. 1).

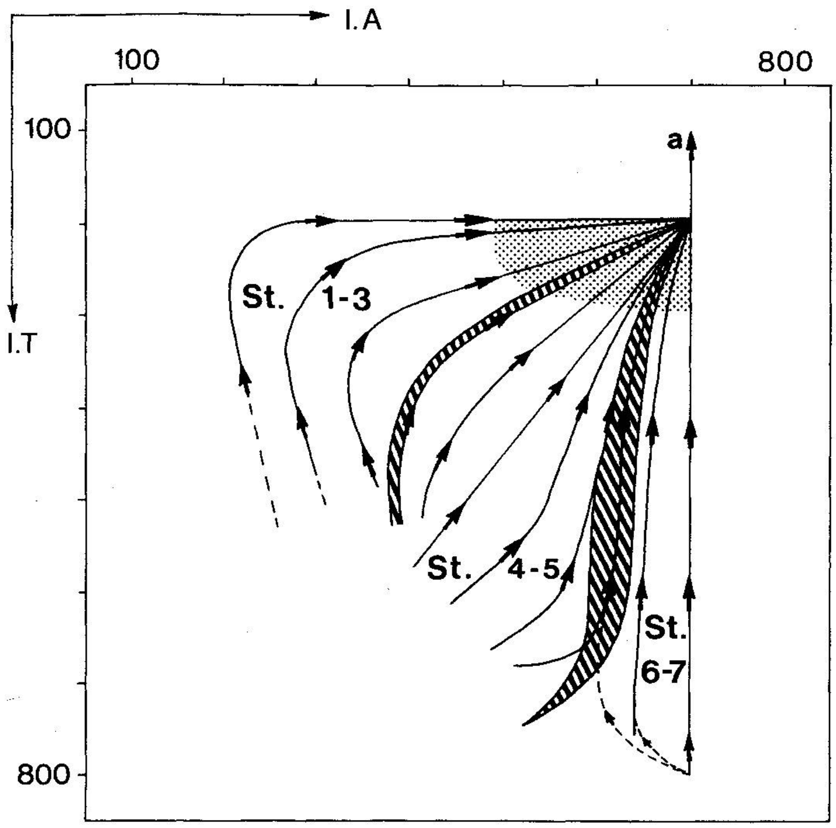

Fig. 3 Main domains of the typologic diagram for the granitic rocks (*St* = granitic stocks or subgroups; PUPIN, 1980). *Hatched areas* = boundary zones between two contiguous main domains (st. 1–3 = aluminous anatectic granites; st. 4–5 = hybrid granites: calc-alkaline and subalkaline series granites; st. 6–7 = granites of mantle or mainly mantle origin: alkaline and tholeiitic series granites). *Dotted area* = main domain of mineralized granites with cassiterite, topaz... (highly differentiated magmas from different stocks). *a* = albitized granites in alkaline series. Arrows indicate mean Typological Evolutionary Trends (T.E.T.) of zircon populations in the different domains.

Together with chemical, petrographic, geological, and isotopic data, such features result in the development of the following classification of granite (fig. 2 and 3, table 1):

A) Granites derived by crustal melting due to regional anatexis and/or induced melting by rising granitic bodies. This group comprises three subgroups (1, 2, 3) with a parallel disposition of their evolutionary trends on the zircon typologic grid.

B) Hybrid granites, which embrace a twofold subdivision: (4) calc-alkaline granites (normal K types and high K types) and (5) K-sub-alkaline granites.

C) Mainly mantle-derived granites, which also comprise two subgroups: (6) alkaline granites and (7) tholeiitic granites.

The main characteristics of the three groups and their subgroups are summarized in table 1, which also shows a tentative correlation between granite classification based on zircon typology and other criteria. In some cases, such correlation may not be rigorously correct because many current classifications are based on only one or too few of the many attributes of granite geology, petrography, or chemistry.

Figure 4 is a synoptic zircon typologic diagram of about 487 samples of granites from various bodies in Brittany, the French Massif Central, the Vosges and Black Forest Massifs, the Western Alps, Provence, Corsica, the Pyrenees, Sardinia, the Alpine Mediterranean regions (Aegean granites and granites from Tuscany-Elba in northern Italy), Morocco, Spain, Senegal, Nigeria, the Ivory Coast, and Mexico. Two distinct domains of high concentration can be easily recognized: one is concentrated on ($\bar{A}$, $\bar{T}$) ~ (325, 325) corresponding to the relatively low temperature granites derived from crustal anatexis; the other with ($\bar{A}$, $\bar{T}$) ~ (475, 625) corresponds to the root of the calc-alkaline field and overlaps the andesite field of Giraud et al. (1980). This clear separation between two

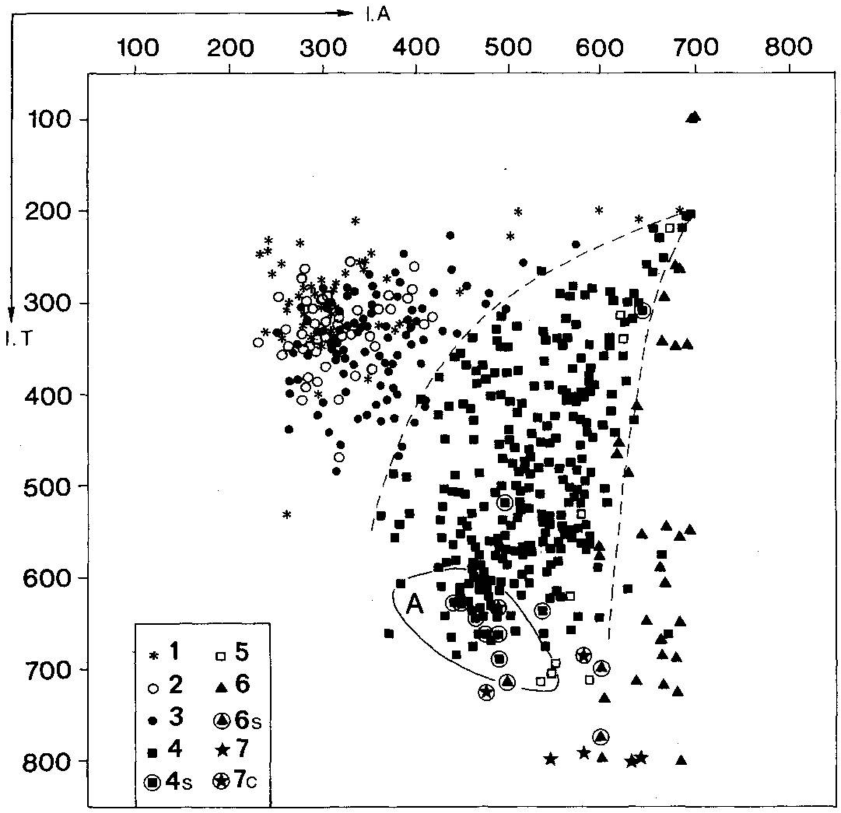

Fig. 4 Mean points distribution of zircon populations from various granitic (487 samples) and syenitic rocks (11 samples); 1 to 7: corresponding granitic subgroups; 4s: syenitic rocks from K calc-alkaline series; 6s: alkaline-peralkaline syenites; 7c: sodic granites with tholeiitic affinities; A: andesites (main field). Some data are reported from Alinat et al. (1979), Hermitte (1975), Tessier (1979).
The Ā and T̄ indices are determined with the following formulas:

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

where $n_{\mathrm{I.A}}$ and $n_{\mathrm{I.T}}$ are the respective frequencies for each value of I.A or I.T ($\Sigma n_{\mathrm{I.A}} = \Sigma n_{\mathrm{I.T}} = 1$).

Table 1 Main characteristics of the different subgroups of granitic rocks.

		Subgroups or stocks (Pupin, 1980)				Main petrographic types	Texture	Evolution trends done by zircon typology (fig. 2.3)	Nature of intrusion	Level of intrusion
A	Aluminous anatectic granites	1				Alkaline-rich leucogranites or leucomonzogranites (Lameyre, 1966)	evengrained	convex	allochthonous to autochthonous	high medium
		2				Monzogranites to granodiorites	evengrained	convex	autochthonous to (par)autochthonous	medium
		3				Monzogranites to granodiorites	porphyritic (evengrained)	convex	allochthonous	high
B	Hybrid granites	4	calc-alkaline granites	Normal K calc alk. High-K calc alk. (Pupin, 1981)	low temperature hydrated calk-alk. granites associated with tonalites	Tonalites, granodiorites, adamellites, monzogranites (alkaline granites)	evengrained porphyritic (in some cases associated = same zircon population)	straight (oblique) convex concav	allochthonous	high (medium)
					high temperature, dry calc-alk. granites					
				charnockites						Deep
		5	Sub-alkaline granites			K-monzogranites (K-monzonites)	evengrained porphyritic	straight (sub vertical)	allochthonous	high
C	Mainly mantle derived granites	6	Alkaline granites			Alkaline granites (hypersolvus, transsolvus, subsolvus; Martin, Bonin (1976)	evengrained	straight (vertical)	allochthonous	high
		7	Tholeiitic granites			Plagiogranites = trondjhemites	eventrained		allochthonous	high

		Relations with basic bodies	Acidic/basic magmatism	Magnetic Enclaves (DIDIER, 1973)	Volcanic Associated rocks	Tectonic	Sr^{86}/Sr^{87} initial ratios	Current other classifications		
								PITCHER (1982)	CHAPPELL and WHITE (1974)	BOWDEN et al. (1982)
A	1	absent	–	generally absent to rare	absent	compressional to tensional	low to high	S	S	Crustal Anatectic granites
	2	absent	–	generally absent to rare	absent	compressional	(low to) high	S	S	
	3	Lamprophyres	Acidic prior to basic	rare	rare	tensional (?)	frequently medium	I?	S?	
B	4	± frequent	Basic prior to acidic (synchronous)	frequent	frequent	tensional to compressional	low to high	I/S	I/S	C.A. normal K C.A. high K C.A. low K
		frequent		frequent	absent		low	I	I	
	5	frequent	synchronous	frequent	frequent	tensional	low to medium	–	I	C.A. high K
C	6	frequent	synchronous	rare	frequent	tensional	generally low	A	A	Na-Alk.
	7	very frequent	–	rare	frequent	tensional	low	M	–	Thol. Granites

domains indicates quite distinct processes acting during the genesis of their corresponding granites. From this point of view, it is of interest to notice that the "Hybrid Granites" maximum lies closer to the "Mainly Mantle-Derived Granites" than to the "Mainly Crustal-Derived Granites". Also, the general evolutionary trends in the "Hybrid Granites" depicted by zircon typology is closer to the "Mainly Mantle-Derived Granites", especially if the K-subalkaline subgroup is considered.

4. Relationship between Zircon typology and geochemistry of the Host Rocks

The relationships between the proportion of major elements of granites and the typology of their zircon populations has been studied for the past decade. In a general way, it has been concluded (PUPIN, 1976, 1980) that the chemistry of the major elements in the medium of crystallization plays a role in the development of pyramid faces of zircons: the hyperaluminum content promotes the development of {211} and helps in the development of {112} and {321}; hyperalkalinity favors the development of {101} and helps {301}. Finally, the amount of water in the magma plays a role in determining the period of zircon crystallization (early in dry magmas; early to late in strongly hydrated magmas), and hence indirectly in the relative development of zircon prism faces.

The relationship between the trace element content of granites and zircon typology is presently the subject of study (unpublished, in collaboration with R. Altherr; granitoids of the Aegean Sea). In a general sense, the V, Co, Ni and Zr content coincide with the $\bar{T}$ index of the zircon population. The positive correlation between Zr and I.T has already been suggested from estimated zircon abundances in the host rocks (PUPIN, 1976). High amounts of zircon are found preferentially in rocks which have populations with a high $\bar{T}$ index (tholeiitic granites, hypersolvus alkaline granites, alkaline syenites, relatively dry calc-alkaline granites, etc...). Lower values appear in rocks impoverished in heavy elements and with a low $\bar{T}$ index, either because they are produced by only partially fusing sialic crust (for example anatectic granites s.s.), or because they are strongly differentiated (calc-alkaline granites or alkaline subsolvus rich in fluid phase).

Results from the literature dealing with Rare Earths in granitic rocks (EMMERMANN et al., 1975; FOURCADE and ALLEGRE, 1981; MIAHLE, 1980; BUMA et al., 1971; COCHERIE, 1978; COCHERIE et al., 1981; FOURCADE et al., 1977; OHNENSTETTER and OHNENSTETTER, 1980) allow a positive correlation to be made between total R.E.E. value and the $\bar{T}$ index of the zircon populations (fig. 5a). The low values are found in rocks produced from partial melting of sialic crust (anatectic granitic s.s.) or crystallized after a process of magmatic crystallization (differenciated calc-alkaline or subalkaline, for example). A positive correlation is equally obvious for the content of Ce and La of all rocks

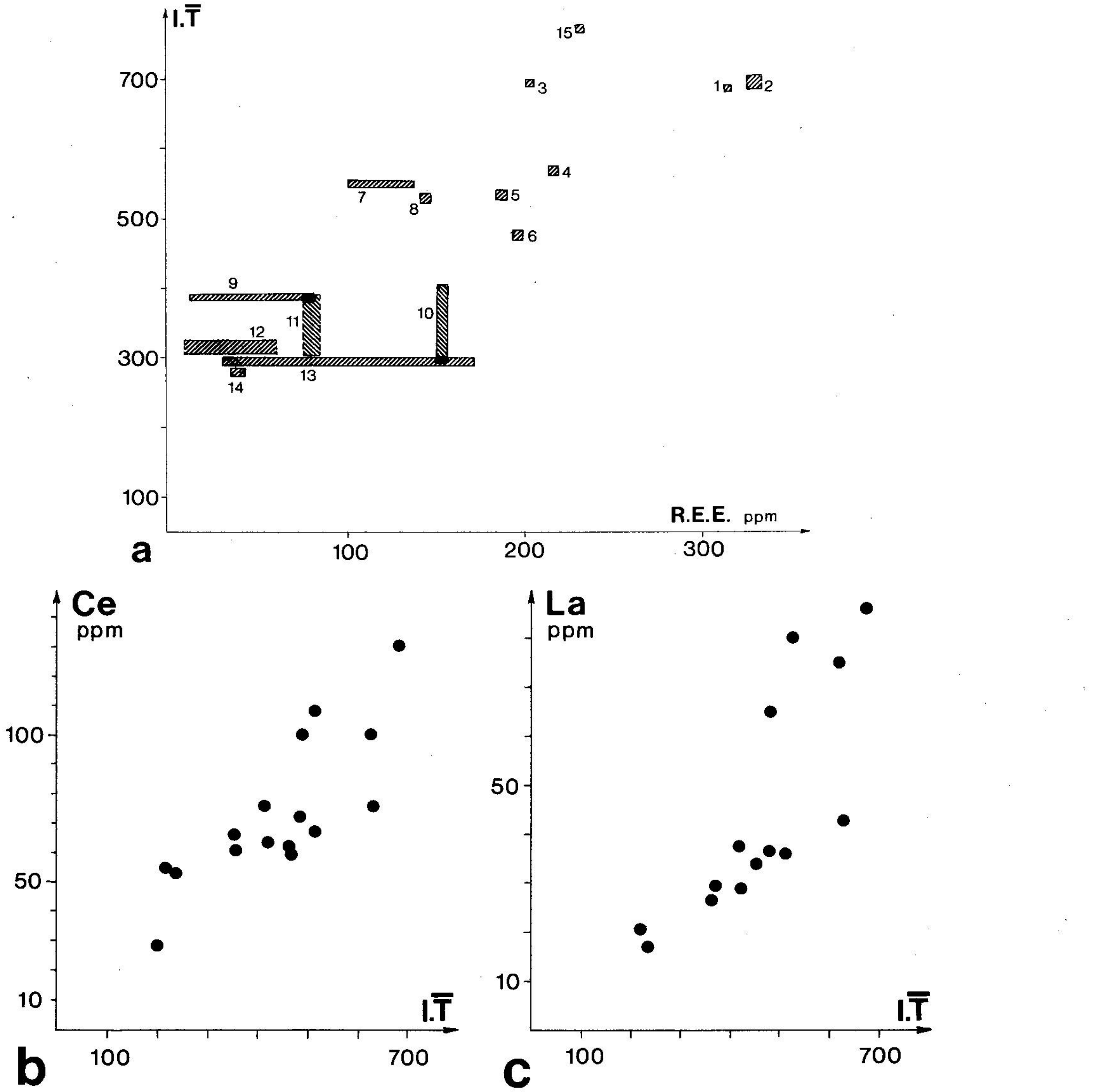

Fig. 5 Relationship between the T̄ index of zircon populations and total R. E. E. (a), Ce (b) and La (c) contents of the host rocks.

(a) (1) alkaline series, fayalite-hastingsite granite (Tolla-Cauro, Corsica); (2) Cape Ann alkaline granite, New England; (3) subalkaline series, syenogranite (Ploumanac'h, Brittany); (4) calc-alkaline granite (Ajaccio, Corsica); (5) muscovite granites with tourmaline nodules (Querigut complex, Pyrénées); (6) aluminous leucogranite (Eyrein, Limousin); (7) Manaslu aluminous leucogranite, Himalaya; (8) calc-alkaline granite (St-Laurent, Pyrénées); (9) monzogranite, Guéret, French Massif Central; (10) calc-alkaline 2-mica granite (Ax-les-Thermes, Oriental Pyrénées); (11) St-Blasien granite, Schwarzwald, West Germany; (12) Marlsburg granite, Schwarzwald; (13) Albtal granite, Schwarzwald; (14) calc-alkaline granite, Pont-de-Montvert, French Central Massif; (15) tholeiitic series, albite granite, Corsica.

Data from: (1, 3, 5, 6, 10) Fourcade and Allègre, 1981; (2) Buma et al., 1971; (4, 8) Cocherie et al., 1981; (7) Fourcade et al., 1977; (9) Derré et al., 1981; (11, 12, 13) Emmermann et al., 1975; (14) Mialhe, 1981; (15) Cocherie, 1978.

(b and c) calc-alkaline granitoids, Aegean sea (Altherr and Wendt, 1978).

(fig. 5b, c). The typological diagram of zircons therefore clearly explains the lack of correlation between major elements and ΣR.E.E. (EMMERMANN et al., 1975), because certain major elements (Al, Na, K) are essentially correlated to zircon pyramid faces (the lower part of the typological diagram) and the ΣR.E.E. to zircon prism faces (ordinate of the typological diagram). There is also disagreement between various authors concerning the relationship between R.E.E. and the amount of SiO_2 in host rocks : various authors state that the R.E.E. content in granitic rocks increases (HASKIN et al., 1968) or decreases (EMMERMANN et al., 1975) with increasing SiO_2 content. The typological diagram readily accounts for these two possibilities according to the samples analysed: there are granites rich in silica with high $\bar{T}$ indices and high amounts of R.E.E. (for example hypersolvus alkaline granites) and others with low $\bar{T}$ indices and small amounts of R.E.E. (for example, aluminous leucogranites or differentiated calc-alkalines). Granites situated between the two, notably calc-alkaline s.l., have R.E.E. contents intermediate between these two end members.

Figure 6 shows the distribution of R.E.E. (CORYELL et al., 1963) in the samples studied. In a general sense, the more siliceous and hololeucocratic show the strongest anomalies in Eu and a more or less important fractionation in heavy R.E.E., regardless of their mode of genesis. At this level, the overall abundance of R.E.E. seems more discriminating than the particular distribution of R.E.E. itself.

A negative relationship exists between the initial Sr 87 / Sr 86 ratio of granites and the $\bar{T}$ indices of their zircon populations (fig. 7). This relationship is not always true however (for example, low and high ratio are sometimes respectively obtained for anatectic granites and alkaline granites of mantle origin); therefore making it risky to make petrographic interpretations based only on this relationship (MCCARTHY et al., 1978).

Presently published data on Nd-Sm are still insufficient, notably on Variscan granites of Western Europe, to permit meaningful comparisons.

Finally, there is a generally negative relationship between the $\delta^{18}O$ (‰) of granites and the $\bar{T}$ index of their zircon populations: in oceanic islands, the differentiated products have $\delta^{18}O < 6.5$‰ and $\bar{T}$ indices > 700, the majority of granites contain $\delta^{18}O$ between +7 and +14 and I.$\bar{T}$ between 650 and 300 and aluminous leucogranites with two micas are rich in ^{18}O, with values of $\delta^{18}O$ between +10 and +14 and 350 > I.$\bar{T}$ > 200 (SHEPPARD, 1982; HALLIDAY, 1982; CUNEY et al., 1982; FOUILLAC et al., 1982).

In summary, the T index of the typology diagram (developed relative to prism {100} and {110} of zircon) is directly and positively correlated with the temperature of crystallization of zircon and indirectly and negatively correlated with the water content of the magma; it is still further related:

- positively with the amount of certain trace elements (V, Co, Ni, Zr);

- positively with the amount of R. E. E.;
- negatively with the initial strontium isotope ratio and $\delta^{18}O$ of the host granites.

These correlations with geochemical criteria usually used to discuss the petrogenesis of the rocks analysed underline the genetic value of the typologic di-

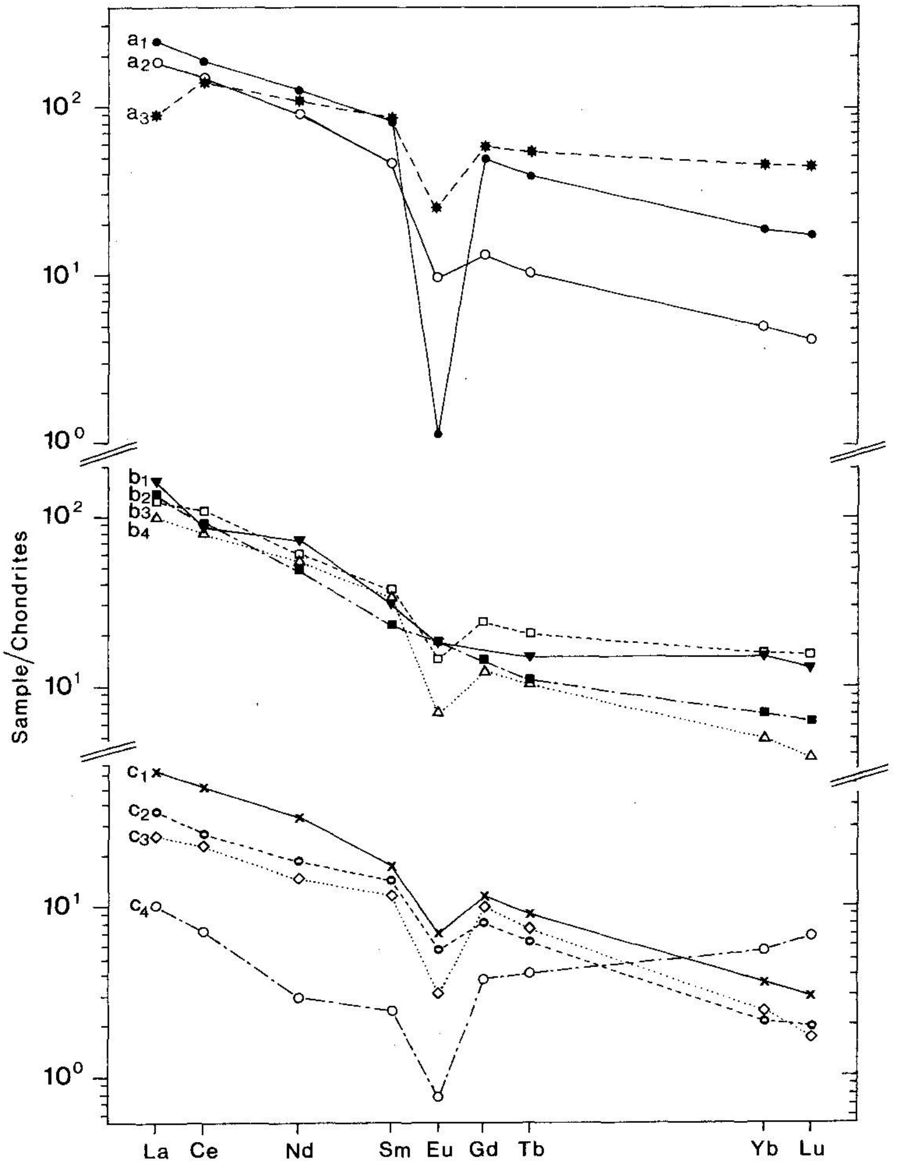

Fig. 6 Typical chondrite normalized R. E. E. distribution in various granitoid types: (a_1) alkaline series (subgroup 6) fayalite-hastingsite granite, Tolla-Cauro, Corsica; (a_2) subalkaline series (subgroup 5), syenogranite, Ploumanac'h, Brittany; (a_3) tholeiitic series (subgroup 7), albite granite, Corsica. Subgroup 4: (b_1) Albtal granite, Schwarzwald; (b_2) granodiorite-monzogranite, Querigut complex, Oriental Pyrénées; (b_3) monzogranite, St-Laurent, Oriental Pyrenees; (b_4) calc-alkaline 2-mica granite, Ax-les-Thermes, Oriental Pyrenees. Subgroup 1: (c_1) and (c_4) muscovite granitoids with tourmaline nodules, Querigut complex, Oriental Pyrenees; (c_2) Manaslu leucogranite, Himalaya; (c_3) Eyrein leucogranite, Limousin.
Data from: (a_1, a_2, b_2, b_4, c_1, c_3, c_4) FOURCADE and ALLÈGRE, 1981; (b_1) EMMERMANN et al., 1975; (b_3) COCHERIE et al., 1981; (c_2) FOURCADE et al., 1977; (a_3) COCHERIE, 1978 in OHNENSTETTER and OHNENSTETTER, 1980.

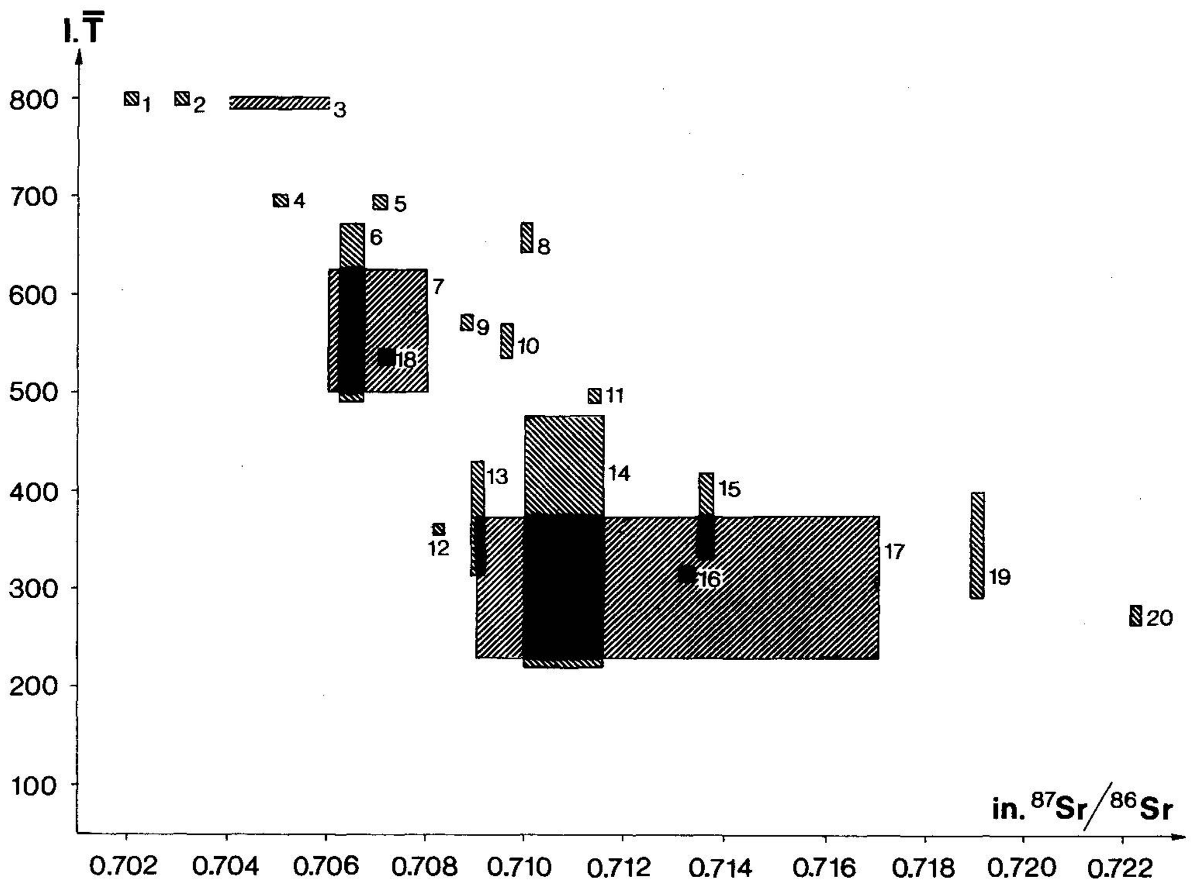

Fig. 7 Relationship between the T index of zircon populations and the Initial Ratios of ^{87}Sr/^{86}Sr in granitic rocks.

(1) tholeiitic granophyre, Islande (Jauzein et al., 1982); (2) Evisa peralkaline granite, Corsica (Bonin, 1972); (3) tholeiitic plagiogranites, Cyprus (Coleman et Peterman, 1975); (4) Ploumanac'h monzogranite, Brittany (Barrière, 1977); (5) Tolla alkaline granite, Corsica (Bonin, 1972); (6) calc-alkaline granites, Corsica (Cocherie et al., 1982); (7) Thiers-Confolens granites, French Massif Central (Duthou, 1977); (8) Mykonos granite, Aegean Sea (Altherr and Wendt, 1978); (9) Albtal granite, Schwarzwald (Schuler and Steiger, 1978); (10) Aigoual-St-Guiral granite, French Massif Central (Hamet and Mattauer, 1977; Vialette and Sabourdy, 1977); (11) Bouges granite, French Massif Central (Vialette et al., 1977, 1979); (12) Vienne-Tournon granite, French Massif Central (Batias and Duthou, 1979); (13) Plan de la Tour granite, Maures (Roubault et al., 1970); (14) Ikaria, Tinos and Delos granites, Aegean Sea (Altherr and Wendt, 1978); (15) Margeride granite, French Massif Central (Vachette et al., 1979); (16) Finiels granite, French Massif Central (Vialette et al., 1977, 1979); (17) various leucogranites, French Massif Central (Duthou, 1977); (18) Borne granite, French Massif Central (Mialhe, 1980); (19) cordierite granites. Himalaya (Le Fort et al., 1980); (20) Pianottoli-Caldarello alkaline subsolvus granite (Bonin, unpublished).

agram. For this reason, and because of its relative independence from secondary transformations which alter certain essential primary minerals or modify the original geochemical relations, the typological method has been choosen to document the spatial distribution of Variscan granites as a function of their origin.

This method has several other advantages: it is an easy, rapid, and cheap procedure. Furthermore, it is independent of the degree of weathering of samples, an important consideration in regions with either few outcrops or with outcrops of poor quality. All these factors make the zircon method very useful for the quick mapping of magmatic zoning on a regional scale. Last, but not least, the zircon method permits easy classification of even small, rather homogeneous bodies. Because of their homogeneity, such bodies are difficult to classify using other methods, particularly those based on trend, suite or family concepts, methods that require a more or less large chemical/petrographic variation in the bodies studied in order to be successful.

5. Magmatic zoning in Brittany, the French Massif Central, and Corsica

The magmatic zoning maps of Hercynian granitoids of the areas selected (fig. 8) are shown in figures 9 to 14. The areas were selected because they are considered as sites of former active continental margins situated more or less near to possible subduction and/or collision sutures developed between lithospheric plates or microplates (MATTE, 1976; COGNE, 1967; CHAURIS, 1977; LAMEYRE and AUTRAN, 1980).

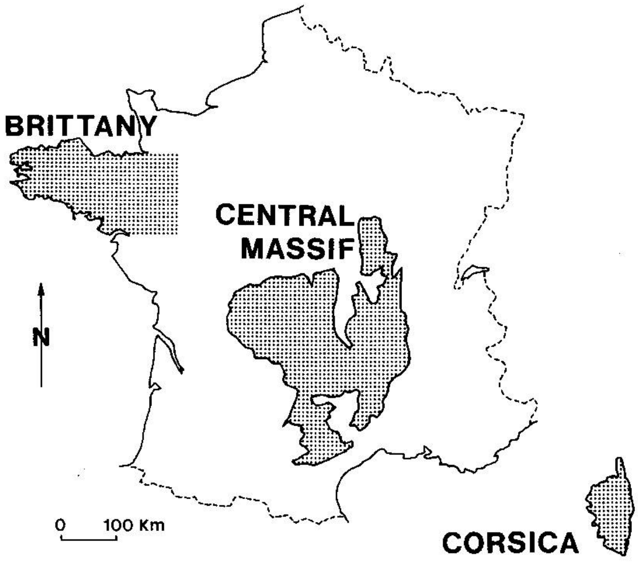

Fig. 8 Location of studied areas in France.

I. THE FRENCH MASSIF CENTRAL

In the French Massif Central, systematic variation in the distribution of the plutonic rocks can be observed from west to east (fig. 9, 10) with a succession of aluminous leucogranites ($\bar{T}$ = 295), parautochthonous monzogranites and granodiorites ($\bar{T}$ = 358) (which constitute a larger zone partially overlapping the main leucogranite zone), a main zone of aluminous intrusive monzogranites (subgroup 3 with $\bar{T}$ = 352), and a zone consisting mainly of calc-alkaline gran-

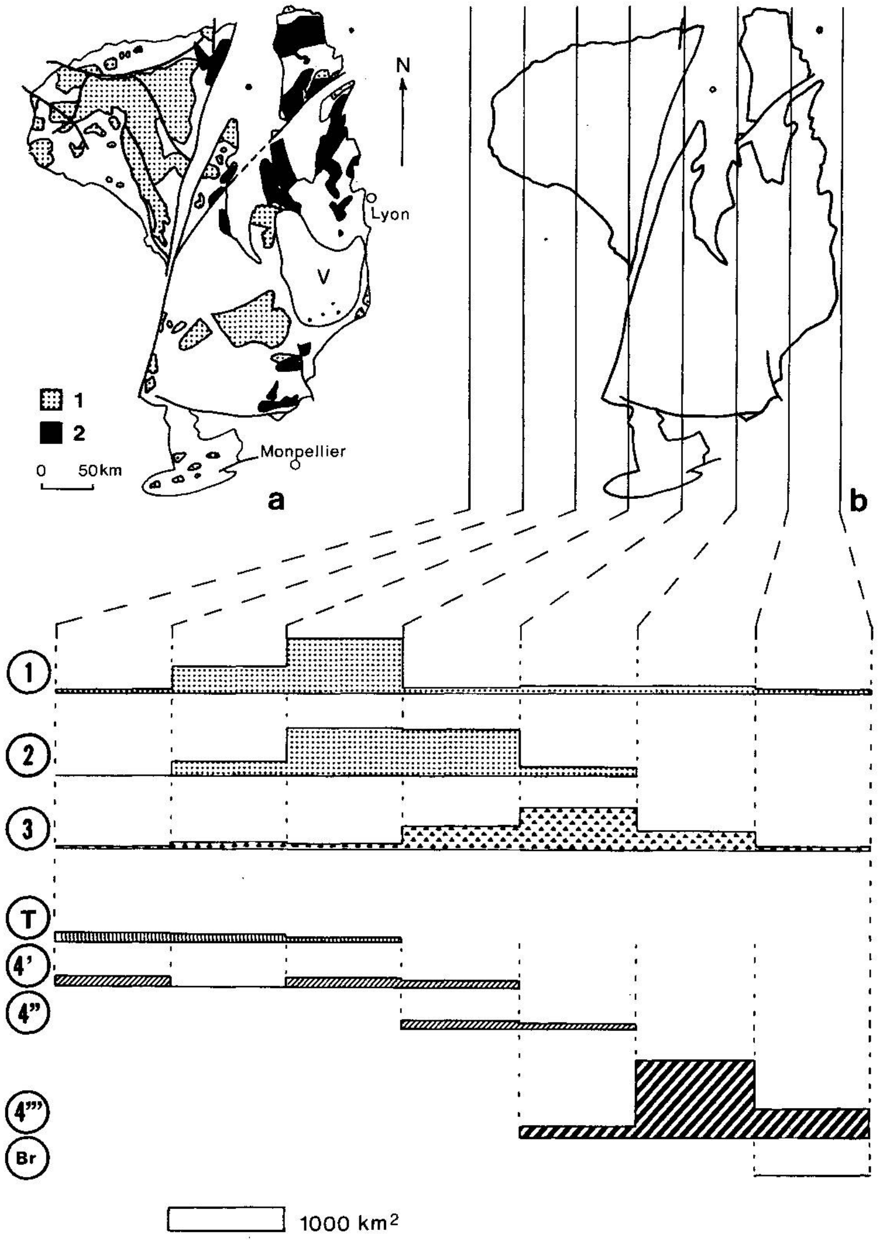

Fig. 9 Zoned distribution of hercynian granitic rocks in the French Massif Central:

a) Distribution of granites with $\bar{T}$ values of zircon populations $<$ 450 *(shaded* [1]) and $>$ 450 *(black* [2]); V = the late hercynian emplaced Velay anatectic diapiric dome (Autran and Peterlongo, 1979).

b) Relative areas of outcrops of the different hercynian granitic rocks in the French Massif Central: ① aluminous leucogranites (subgroup 1; 24 samples); ② (par)autochthonous monzogranites and granodiorites (subgroup 2; 15 samples); ③ aluminous intrusive monzogranites and granodiorites (subgroup 3; 26 samples); Ⓣ tonalites; ④' calc-alkaline western granites derived from water-rich magmas (subgroup 4; 15 samples); ④" calc-alkaline granites of the middle of the Massif Central (subgroup 4; 3 samples); ④''' calc-alkaline and K-calc-alkaline eastern granites derived from drier and hotter magmas (subgroup 4; 30 samples); Ⓑr Brevenne sodic granites (2 samples).

Reconstitution of the French Massif Central as it could be before displacement along «Sillon Houiller» fault (Grolier, 1971).

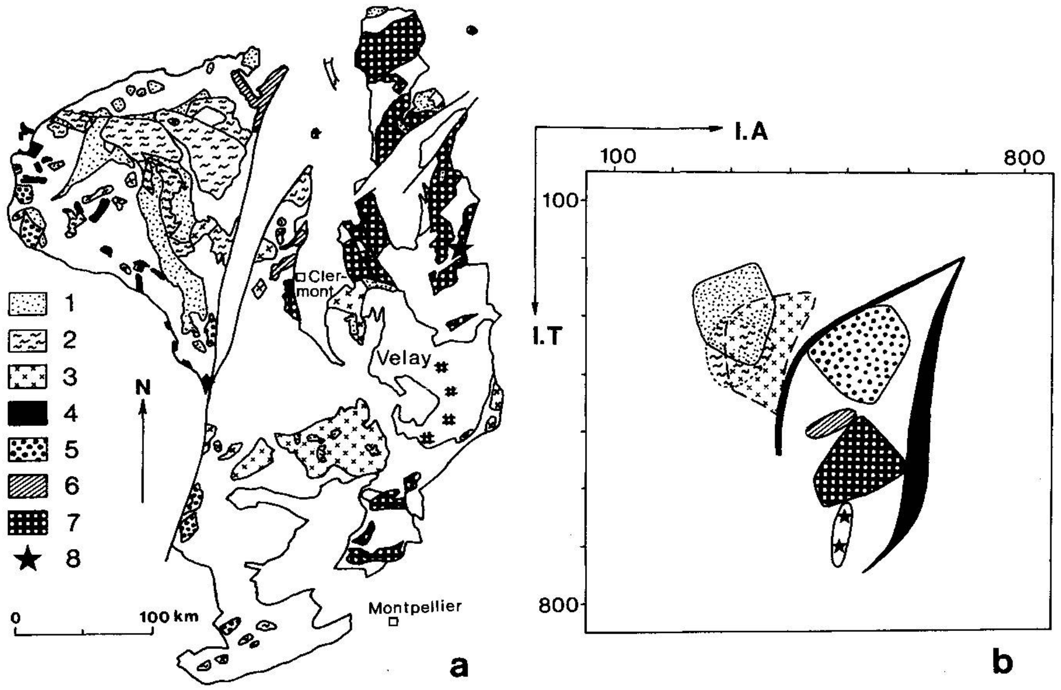

Fig. 10 General distribution of the main hercynian plutonic granitoids of the French Massif Central (a) and their corresponding zircon populations (b).
(1) aluminous leucogranites; (2) (par)autochthonous monzogranites and granodiorites; (3) aluminous intrusive monzogranites and granodiorites; (4) tonalites; (5) calcalkaline western granites derived from water rich magmas; (6) calc-alkaline granites of the middle of the Massif Central; (7) calc-alkaline and K-calc-alkaline eastern granites and microgranites derived from «hot and dry» magmas; (8) Brevenne sodic granites.
In the Velay anatectic dome are indicated the presence of numerous enclaves of porphyritic calc-alkaline granites belonging to the eastern unit (PUPIN and TURCO, 1975b) and probably fragments of bodies dislocated by the emplacement of the dome.

ites (subgroup 4 derived from dry magmas, $\bar{T}$ = 562). Minor amounts of tonalites (tonalitic line of DIDIER and LAMEYRE, 1971), are restricted to the western part of the Massif Central and calc-alkaline granites ($\bar{T}$ = 492) are present in the middle part of the Massif. Also, calc-alkaline granites derived from water-rich magmas ($\bar{T}$ = 353) occur at the western part of the Massif Central as well as between the tonalite zone and the previously mentioned calc-alkaline rocks ($\bar{T}$ = 492). Finally, sodic granites (BEURRIER et al., 1980) are present at the eastern part of the Massif Central, where they are represented by the Brevenne granites ($\bar{T}$ = 677).

This zoning shows the following major characteristics:

A) Zoning of the crustal anatectic granites: in the western part of the Massif Central, granites of lower temperature ($\bar{T}$ = 295) predominate; in the central part, granites of higher temperature ($\bar{T}$ = 358, 352) predominate. Because the temperature of such granites is about equal, these two different rock types (subgroups 2 and 3) can be considered as the result of the same process (anatexis) acting on different source rocks.

B) Zoning of the calc-alkaline granites: from west to east, a regular increase in the $\bar{T}$ values (= crystallization temperature) can be observed, with relatively low temperature granites derived from water-rich magmas occurring in the western part and high temperature granites derived from "dry" magmas occurring in the eastern part. Even higher temperature rocks are represented by the sodic granites at the eastern limits of the Massif Central.

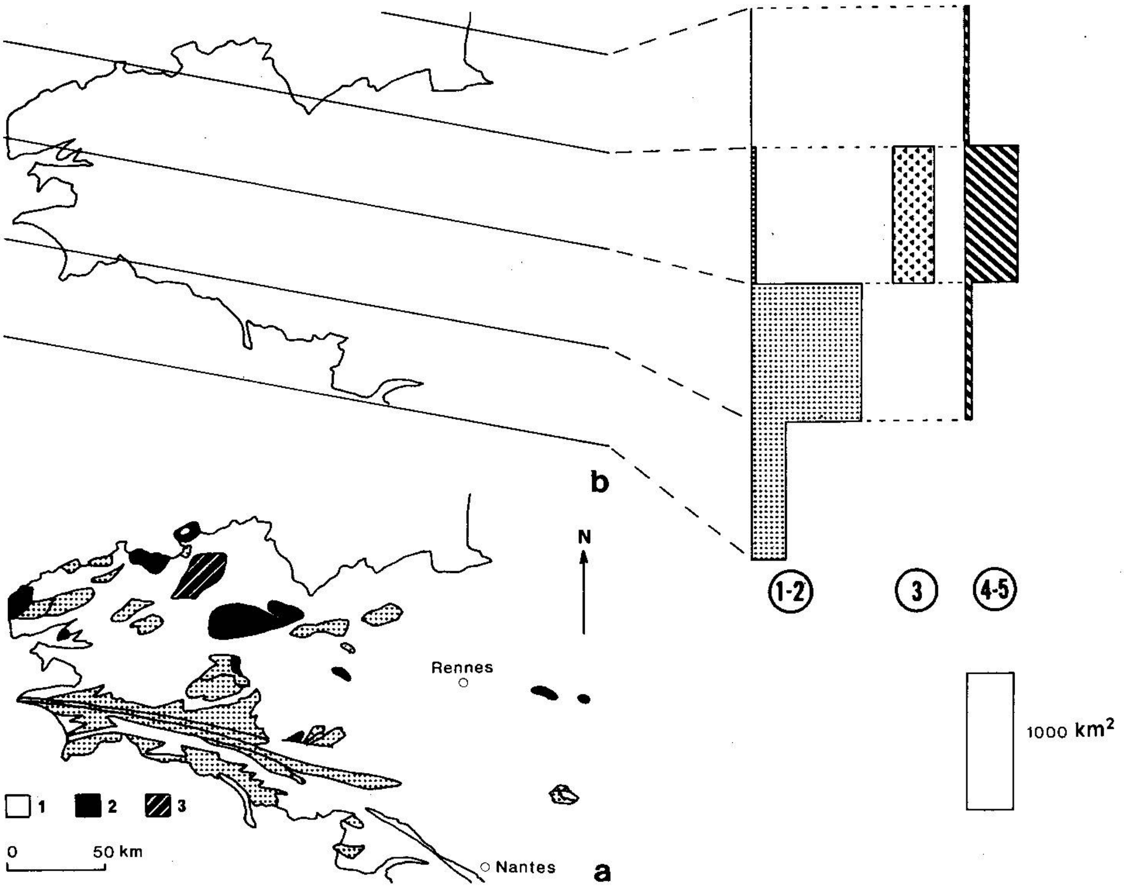

Fig. 11 Zoned distribution of hercynian granitic rocks in Brittany:
a) Distribution of granites with $\bar{T}$ values of zircon populations < 450 (*shaded* [1]) and > 450 (*black* [2]); (3) = the Plouaret Massif with zircon populations < and > 450.
b) Relative areas of outcrops of the different hercynian granitic rocks in Brittany.
(1–2) anatectic granites of subgroups 1–2 (19 samples); (3) aluminous intrusive monzogranites and granodiorites (subgroup 3; 9 samples); (4–5) calc-alkaline and K-subalkaline granites (subgroups 4–5; 26 samples).

II. BRITTANY

The magmatic zoning of the Hercynian plutonic granitoids of Brittany is outlined in figures 11 and 12. From south to north, the following main granitic zones can be recognized:

1. Aluminous anatectic granites (subgroups 1 and 2) with $\bar{T}$ = 302;

2. Aluminous anatectic granites (subgroup 3) also with $\bar{T} = 307$;
3. Hybrid granites (subgroups 4 and 5) with $\bar{T}$ values greater than 450 or with mixed zircon populations with $\bar{T}$ values greater or smaller than 450 as in the case of the Plouaret Massif (for all samples analysed, $\bar{T} = 553$).

In a general way, the magmatic zoning of Brittany displays the same major characteristics visible in the Massif Central: crustal anatectic granites (with relatively low $\bar{T}$ values) are followed by a sequence in which the subgroups 1 and 2 both occur, and this assemblage is then replaced by granites of the subgroup 3. As in the Massif Central, granites from subgroup 3 overlap spatially with hybrid granites of subgroups 4 and 5, with overall higher $\bar{T}$ values indicating higher crystallization temperatures for the zircon populations.

III. CORSICA

The general disposition of the main Hercynian plutonic granitoids of Corsica and the distribution of their corresponding zircon populations are shown in figures 13 and 14. Contrary to the French Massif Central and Brittany, there is a general lack of crustal anatectic granites in Corsica.

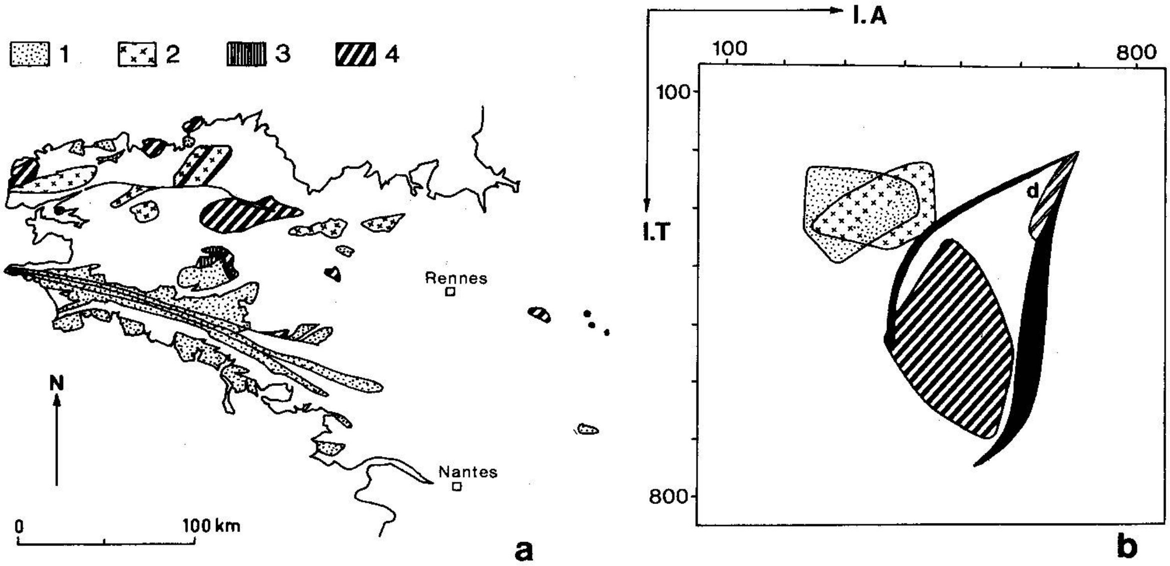

Fig. 12 General distribution of the main hercynian plutonic granitoids of Brittany (a) and their corresponding zircon populations (b). (1) anatectic granites of subgroups 1–2; (2) aluminous intrusive monzogranites and granodiorites (subgroup 3); (3) amphibole granite usually associated with tonalites; (4) calc-alkaline and K-subalkaline northern granites (subgroups 4–5); (d) very localized differentiates (veins, small bodies of aplites or hololeucocratic granites) associated with calc-alkaline and K-subalkaline northern granites (6 samples).

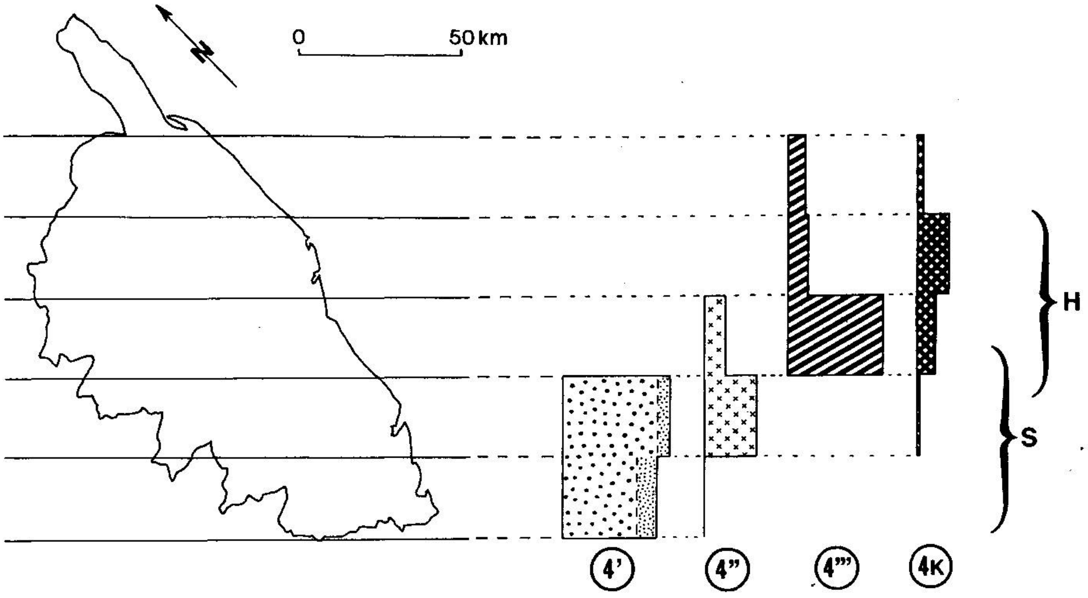

Fig. 13 Zoned distribution of hercynian granitic rocks in Corsica. Relative areas of the outcrops of different calc-alkaline granites: ④’ calc-alkaline southern granites with intrusions (small dotted) derived from water rich magmas (17 samples); ④” calc-alkaline granites associated with tonalites of the middle part of Corsica Island (8 samples); ④”’ calc-alkaline northern granites derived from drier and hotter magmas (11 samples); ④K calc-alkaline north-western granites (4 samples).
H = domain of hypersolvus alkaline permian granites;
S = domain of subsolvus alkaline permian granites (about these granites, see MARTIN and BONIN, 1976; BONIN, 1980).

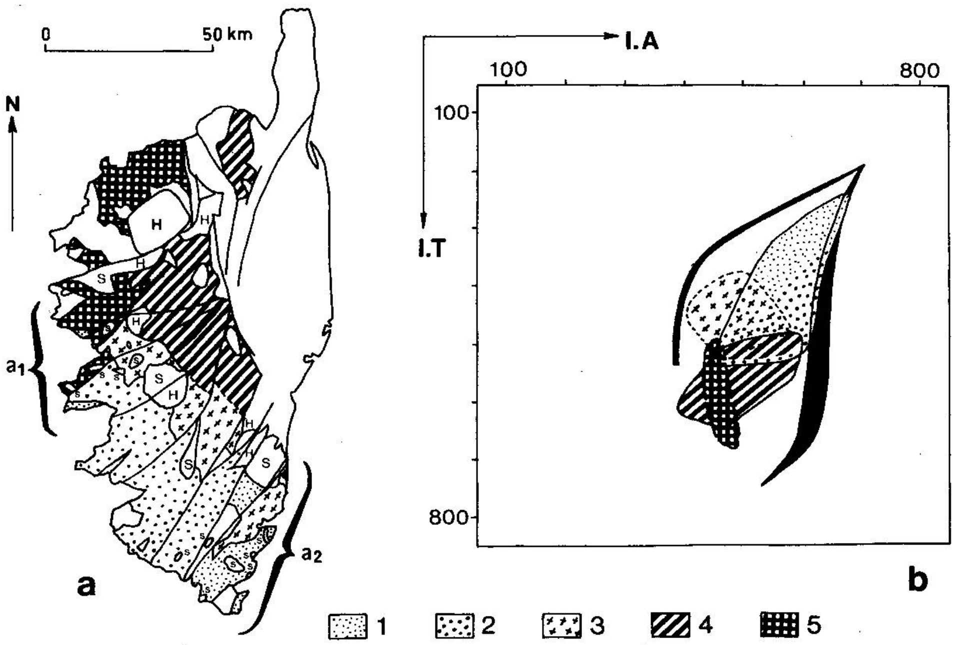

Fig. 14 General distribution of the main hercynian plutonic granitoids of Corsica (a) and their corresponding zircon populations (b). (1) calc-alkaline granites derived from water rich magmas localized in two main areas: (a1) Ajaccio area; (a2) Bonifacio-Porto Vecchio area. H, hypersolvus alkaline granites; S, subsolvus alkaline granites.

Among the hybrid granites, the following zoning occurs from southwest to northeast:

1. Calc-alkaline granites of subgroup 4 derived from water-rich magmas with low $\bar{T}$ values ($\bar{T} = 388$).
2. Calc-alkaline granites of subgroup 4 associated with tonalites (Orsini, 1980) ($\bar{T} = 438$).
3. A zone characterized by the overlapping between calc-alkaline ($\bar{T} = 558$) and K calc-alkaline ($\bar{T} = 610$) granites of subgroup 4 (Pupin, 1981) derived from "dry" magmas with high $\bar{T}$ values.

The Permian alkaline granites (fig. 15 d) will be discussed in a separate paper (Pupin, in preparation).

IV. DISCUSSION AND CONCLUSION

The Hercynian magmatic zoning of the French Massif Central, Brittany, and Corsica recognized by the zircon method shows a regular pattern in all three areas which can be summarized in the following manner:

1. Two main types of granitoids occur: (A) anatectic crustal granites and (B) hybrid granites. Both types show fairly distinctive features on a zircon typologic diagram (fig. 3, 15, 16).
2. The different subgroups (1, 2, 3) of the anatectic crustal granites display approximately the same $\bar{T}$ values (fig. 4, 10, 12). Therefore, the differences between the subgroups (see table 1) must result from differences in the composition of their source rocks as well as the type of anatexis (regional metamorphism as opposed to magma-induced melting).
3. The zircon typologic diagram allows the granitoids of subgroups 1, 2, and 3 to be easily distinguished from nearby eutectic-cotectic granites (Wernick, 1982) evolved from subgroups 4, 5, and 6. All of these granites have low R. E. E. content, high Sr 87 / Sr 86 initial ratios, and high $\delta\ ^{18}O$.
4. Where relatively voluminous anatectic crustal granites occur, for example in the French Massif Central and Brittany, they consistently show zoning with subgroups 1 and 2 followed by subgroup 3. Such zoning is reflected by a slight increase in the mean $\bar{T}$ values from subgroup 1 to subgroup 3. This is perhaps the result of a significant increase in the anatexis of sialic crust and (in the case of subgroup 3) already some slight mixing with basic magmas which play a more important role in the genesis of calc-alkaline granites (subgroup 4).
5. Hybrid granites also show a regular spatial distribution, beginning with calc-alkaline granites of subgroup 4 derived from water-rich magmas. Such granites have generally low $\bar{T}$ values, comparable to the $\bar{T}$ values of the anatectic granites of subgroups 2 and 3. These "hydrous" granites overlap or are fol-

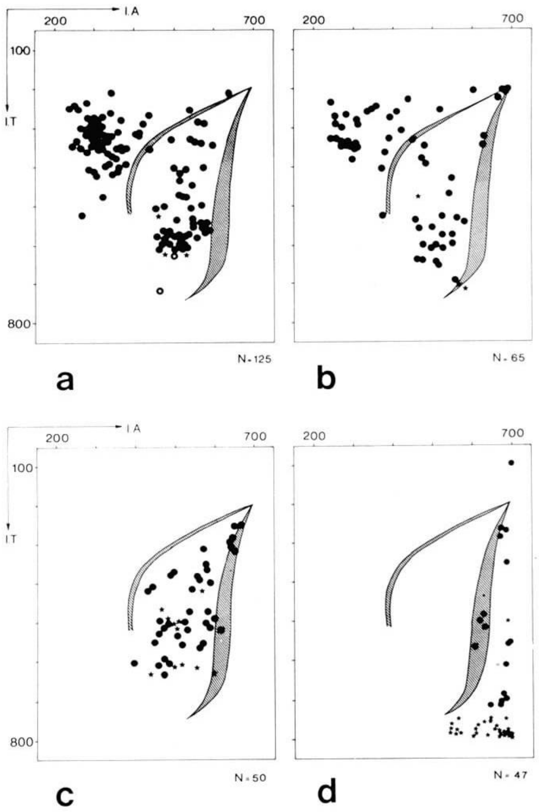

Fig. 15 Mean points distribution of zircon populations from hercynian granitic rocks from the French Massif Central (a), Brittany (b) Corsica (c) and permian alkaline pluto-volcanic rocks from Corsica-Esterel (d). *Black circles* = granites; *encircled stars* = Brevenne granites; *black stars* = rhyolites. N = number of examined samples. For the permian alkaline province of Corsica-Esterel (d), data from Tessier et al., 1978 and Pupin, 1978.

lowed by calc-alkaline granites of subgroup 4 and by the K-subalkaline granites (i.e., Ploumanac'h, Brittany; Barrière, 1977) of subgroup 5 derived from "hot" and "dry" magmas. High temperature is indicated by the fairly high $\bar{T}$ values of their zircon populations, a characteristic of these types of calc-alkaline granites. These last granites are also associated with extremely active volcanism (Bebien and Gagny, 1980; Paquette, 1980; Vellutini, 1977).

6. Where sodic granites (with geochemical affinities with tholeiitic granites) are present, they follow the dry and high temperature calc-alkaline granites of subgroup 4.
7. An overlap exists between the different types of crustal anatectic granites and hybrid granites, but in a general way the dry and high temperature calc-alkaline granites of subgroup 4 occur spatially behind the main zone of anatectic granites of subgroup 3, even though in Brittany both zones of distribution overlap. The existence of anatectic granites in the area of hybrid granites may be explained by the induced melting due to rising magmas related to certain kinds of subgroup 4 granites.

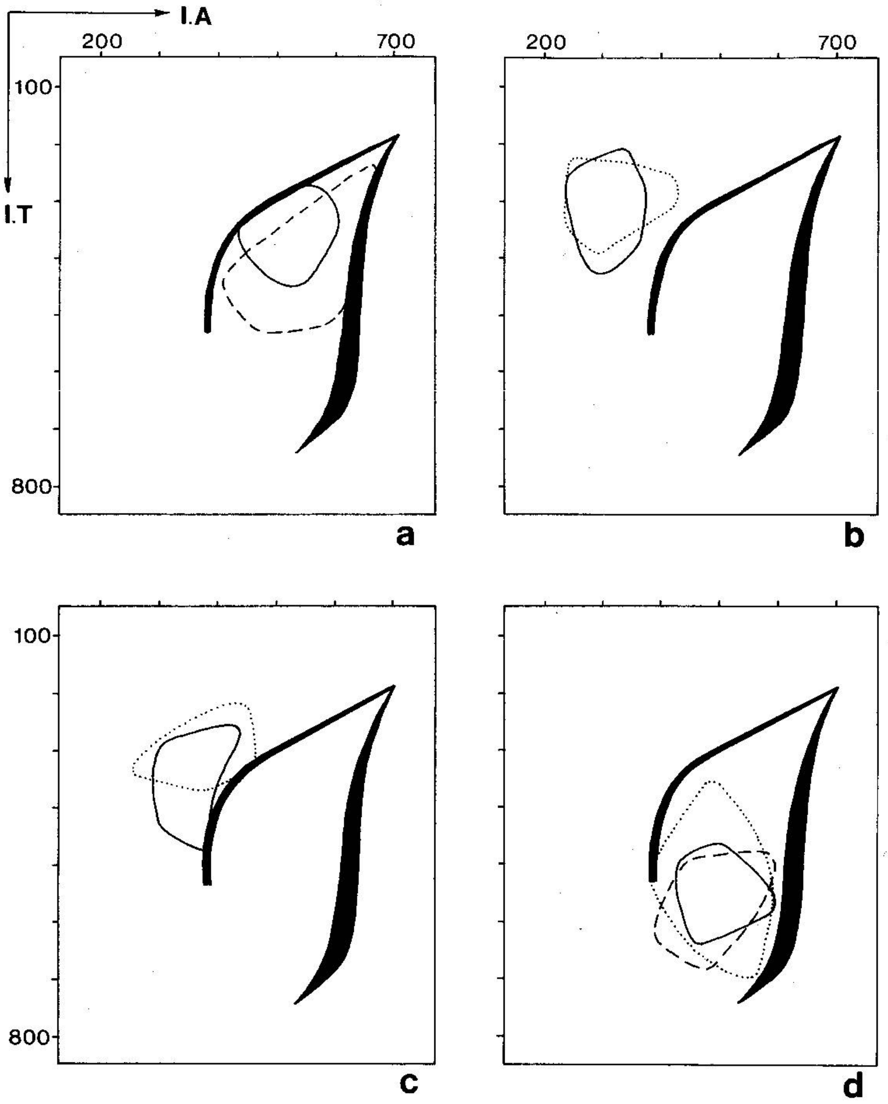

Fig. 16 Relative positions of the main types of granites when going away from the suture zone (*heavy lines* = French Massif Central; *broken lines* = Corsica; *dotted lines* = Brittany): (a) calc-alkaline granites derived from water rich magmas (low $\bar{T}$ in subgroup 4); (b) anatectic granites of subgroups 1–2; (c) aluminous intrusive monzogranites and granodiorites (subgroup 3); (d) calc-alkaline, K-calc-alkaline and K-subalkaline granites derived from "hot and dry" magmas (high $\bar{T}$ in subgroups 4–5).

8. The above schematic succession of different crustal anatectic granites, hybrid granites, and sodic granites, as well as their mutual spatial relations, can be considered in terms of subduction zones in which the sequence of subgroups 1, 2, and 3 and the subgroups 4 and 5 (with the succession of calc-alkaline granites derived from water-rich magmas, calc-alkaline granites associated with tonalites, and calc-alkaline / K-calc-alkaline-subalkaline granites derived from hot and dry magmas) correspond to progressively deeper positions of the subduction zone.

Granites of these subgroups actually possess progressively higher $\bar{T}$ indices for their zircon populations. Taking into account the relationships we have established with the $\bar{T}$ index (cf. paragraph 4), one can say that generally these granites are derived from magmas which are progressively hotter and drier, richer in R. E. E. and in certain trace elements (V, Co, Ni, Zr), and with progressively lower initial strontium isotope ratios and $\delta\,^{18}O$. A zonation somewhat comparable has been suggested by ISHIHARA (1977, 1982) in Japan based on study of "magnetite-ilmenitegranites".

This progressive zonation of granites can be the result of progressive anatexis of sialic crust in areas near suture zones (subgroups 1 to 3) as well as the result of mixing, to a greater or lesser degree, of sialic magmas with basic materials derived from the mantle adjacent to the subducting plate, producing calc-alkaline granites more or less hot and saturated with water (subgroups 4 and 5). The mobilization of the majority of anatectic granites is probably due to the phenomenon of collision because these magmas are systematically missing from active margins without collision.

The intrusion of granites, notably calc-alkaline, is perhaps only the result of a long process, during which sufficient time is available for mixing in lower-crustal or intracrustal sites, because geochronology (DUTHOU, 1977; LAMEYRE and AUTRAN, 1980; MIALHE, 1980) indicates that the ages of intrusions clearly occur after the final subduction in the zones analysed. This late intrusion of magmas in post-subduction periods has already been pointed out (SMITH, 1977; DI GIROLAMO et al., 1976; in GIROD, 1978). The disappearance of the relict structures of geodynamic polarity and the entire process of evolution-intruding these magmas require a very long period of time. Among the possible indicators, magmas, especially acid magmas of the Hercynian type (PITCHER, 1979) are likely to provide excellent criteria of polarity capable of solving the problems of paleogeodynamics.

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