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THE LEUCOGRANITES OF SOUTHERN BRITTANY: ORIGIN BY FAULTING, FRICTIONAL HEATING, FLUID FLUX AND FRACTIONAL MELTING

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ABSTRACT

Muscovite–biotite leucogranites that occur along the South Armorican Shear Zone of Brittany were repeatedly intruded along dextral shear belts, mainly during Hercynian (340–300 *Ma*) orogenesis. The zone is marked by an amphibolite-facies culmination in regional metamorphic grade, and by *in situ* formation of the leucogranites by anatexis of metasediments. The leucogranites are homogeneous in major element composition, with no pronounced difference between plutons. Trace elements and $^{87}Sr/^{86}Sr$ initial ratios do show some differences, which may result from both minor variations in source materials and degrees of partial melting. The formation of these leucogranites can be explained by means of models involving fractional melting along fault zones either by temperature increase due to frictional heat production, or by lowering of melting temperatures owing to periodic flux of water through the fault zone.

Keywords: two-mica granite, shear belts, chemistry, petrogenesis, fractional melting, leucogranite, Brittany, France.

SOMMAIRE

Des massifs leucogranitiques à muscovite et biotite de Bretagne ont été mis en place épisodiquement le long de ceintures de cisaillement dextre dans la zone de l'Armoricain méridional, et surtout pendant l'orogénèse hercynienne (de 340 à 300 *Ma*). Cette zone atteint le facies métamorphique amphibolite, d'où la formation *in situ* des leucogranites par anatexie de métasédiments. En ce qui concerne les éléments majeurs, ces granites sont homogènes et sans grande différence entre massifs. Certaines variations observées dans la teneur en éléments traces et le rapport initial $^{87}Sr/^{86}Sr$ refléteraient à la fois des variations mineures dans les matériaux originels et différents degrés de fusion partielle. On peut attribuer l'origine de ces leucogranites à une fusion fractionnée le long de zones faillées, résultant de l'accroissement de la température dû à la chaleur de friction, ou de l'abaissement du solidus dû au flux périodique d'eau dans les failles.

(Traduit par la Rédaction)

Mots-clés: granite à deux micas, zone de cisaillement, composition, pétrogénèse, fusion fractionnée, leucogranite, Bretagne, France.

INTRODUCTION

Peraluminous (corundum-normative) leucocratic granites–granodiorites ("leucogranites") are typical of the deeply dissected parts of orogenic terrains, where they tend to form minor portions of larger biotite- or amphibole-bearing metaluminous granitoid bodies, but they also occur as individual plutons of significant volume. They are characterized by primary muscovite and biotite, with minor garnet, rarely cordierite, and very rarely andalusite, all of which have been used as indicators of pressures of crystallization (*e.g.*, Cawthorn *et al.* 1976, Cawthorn & Brown 1976, Green 1976, 1977, 1978, Flood & Shaw 1975, Clarke *et al.* 1976). Possible mechanisms for their formation include amphibole fractionation from less siliceous melts (Cawthorn *et al.* 1976), partial melting of pelitic metasediments (Green 1976), vapor-phase transport of alkalis (Luth *et al.* 1964), secondary alteration (Heming & Carmichael 1973) and magma contamination (Ewart & Stipp 1968).

The Hercynian orogen of western Europe is characterized by abundant peraluminous two-mica leucogranites, which are well known for their associated mineral deposits (*e.g.*, Chauris 1977, 1978). Such rocks are poorly represented in the adjacent Caledonian orogen, leading Hall (1971, 1972) to suggest that a difference in geothermal regime was responsible for the contrasting granitoid suites.

This paper focuses on the leucogranite plutons of the Armorican Massif in southern Brittany, where they were emplaced during a span of at least 250 million years along the South Armorican Shear Zone (S.A.S.Z.) and its sub-

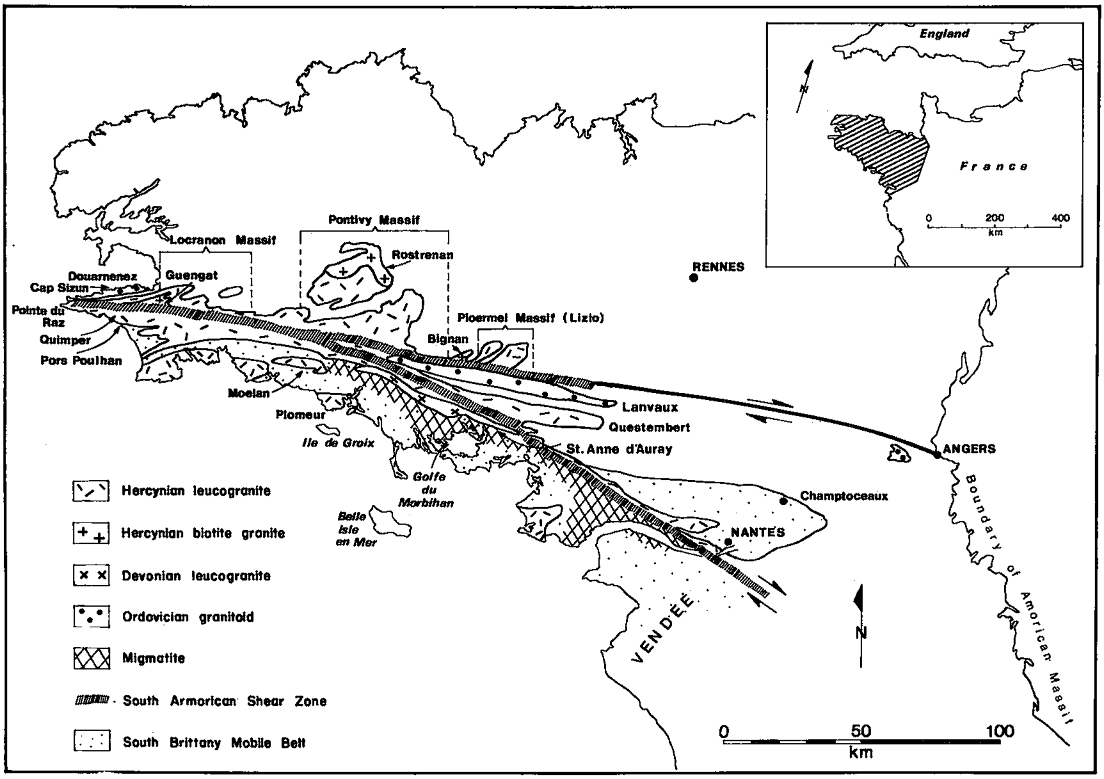

FIG. 1. Geological setting of the granitic rocks of southern Brittany, showing granitic plutons and massifs discussed in text.

sidiary faults. These rocks contrast with other granitoid plutons of widely differing petrochemical and metallogenic characteristics but of similar age, which were emplaced in the same overall Appalachian–Caledonian–Hercynian orogenic terrains (Strong 1980). An understanding of the formation of these leucogranites in the clearly defined geological setting of southern Brittany may lead to petrogenetic models applicable to similar rocks in other areas.

GEOLOGICAL SETTING

The geology of southern Brittany (Fig. 1) is dominated by two major features: the South Armorican Shear Zone (Cogné 1957, Berthé *et al.* 1979) and large volumes of Paleozoic granite. To the north of the S.A.S.Z. lies the Brioverian greenschist-facies metasedimentary sequence, deformed and metamorphosed during the Hercynian (Le Corre 1977, Hanmer *et al.* 1980); to the south lies the amphibolite-facies South Brittany mobile belt. The latter was deformed, metamorphosed and migmatized during the Ligerian (Siluro-Devonian) and Hercynian (Carboniferous–Permian) orogenies (Cogné 1977, Hanmer 1977a) and grades southward into greenschist-facies metasediment of the Belle-Ile-en-Mer Group (Audren & Lefort 1977). The S.A.S.Z. is a branching transcurrent fault whose latest movement (pre-Westphalian "D"/Cantabrian: Cogné 1957, Hanmer 1977b) was dextral (Berthé *et al.* 1979). Older and younger granites are located along the trace of the S.A.S.Z.: the Cambro-Ordovician Lanvaux gneiss (Vidal 1972), the Ordovician Douarnenez plagiogranite (trondhjemite) complex (Barrière 1970, 1972, Barrière *et al.* 1971, Hanmer 1977b), the Devonian Ste-Anne d'Auray granite (Vidal 1973) and the voluminous Carboniferous (Hercynian) leucogranites (Barrois 1930).

Pre-Hercynian granitoid bodies

The penetratively foliated Douarnenez complex is composed of predominant biotite trondhjemite, plus granodiorite, tonalite and leucogranite. It is intrusive into the Brioverian metasediments, which were cleaved and metamorphosed to staurolite grade before or during pluton emplacement. The western quarter of the complex is distinctive in comprising a locally garnetiferous plagiogranite carrying a dextral shear fabric (Berthé *et al.* 1979). The eastern part consists of trondhjemite cut by leucogranite and large rafts of granodiorite; these eastern lithologies all share a common fabric. Samples from all lithologies of the complex plot on a single Rb/Sr whole-rock isochron, giving an age of 473 ± 20 *Ma* with an initial ^{87}Sr/^{86}Sr of 0.7047 (Barrière *et al.* 1971). (All Rb/Sr isochron ages quoted here are recalculated with λ ^{87}Rb $= 1.42 \times 10^{-11}$.)

Relatively little is known about the Lanvaux "gneiss", a foliated biotite–muscovite granite with minor inclusions of granodiorite or diorite at its western end (P. Jegouzo, pers. comm. 1979); the gneiss becomes more isotropic at its eastern end. Six samples from the western end of the gneiss (Lanvaux I) lie on a composite Rb/Sr isochron yielding an age estimate of 554 ± 10 *Ma* (^{87}Sr/^{86}Sr$_o$ = 0.7031), whereas the central (Lanvaux II) and eastern (Lanvaux III) parts of the "gneiss" yield isochron ages of 472 ± 8 *Ma* (^{87}Sr/^{86}Sr$_i$ = 0.7041), and 433 ± 4*Ma* (^{87}Sr/^{86}Sr$_i$ = 0.7061), respectively (Vidal 1972, 1976).

The Ste-Anne d'Auray granite (*granite d'anatexie*) was emplaced in migmatites along the south side of the S.A.S.Z., is syntectonic with respect to penetrative deformation of these migmatites, and appears to have been derived from them (Le Métour 1978, Audren & Le Métour 1976, Le Métour & Audren 1977). Vidal (1976) gives an isochron age of 370 ± 10 *Ma* and an initial ^{87}Sr/^{86}Sr ratio of 0.7062 for the granite. However, as pointed out by J.J. Peucat (pers. comm. 1978), the initial ^{87}Sr/^{86}Sr ratio of the less-metamorphosed lateral equivalents of the migmatites and those of the granite are incompatible with this hypothesis. According to these workers (Peucat & Cogné 1977, Le Métour & Audren 1977), migmatization occurred between 460 and about 380 *Ma.*

Hercynian granites

Hercynian biotite–muscovite leucogranites occur in an elongate belt 30 km wide by 300 km long between Pointe-du-Raz and the Vendée (Barrois 1930), along the trace of the southern branch of the S.A.S.Z. The southern margin of the belt and a number of isolated elliptical leucogranite plutons (*massifs circonscrits*) intrude the South Brittany mobile belt. On its northern margin, the granite belt comprises four irregular lobes, the Locronan, Pontivy, Ploermel (Lizio) and Questembert leucogranite massifs, all intruded into the Brioverian and Paleozoic sedimentary country rocks. Three biotite granites are intimately associated with the leucogranites: the equigranular Bignan granite and the megacrystic Guengat (Hanmer 1977b) and Rostrenan granites.

Coarse grained muscovite pegmatites and fine grained muscovite ± garnet aplites intrude the leucogranites and the country rocks on either side of the belt. Some pegmatites in the country rocks adjacent to the Locronan, Pontivy and Lizio massifs contain abundant kyanite or andalusite or both (Cogné 1961, Barrière *et al.* 1973).

The leucogranites have been dated in several areas by the Rb/Sr whole-rock isochron method. The Questembert massif yields 327 ± 10 *Ma* with an initial ^{87}Sr/^{86}Sr value of 0.7088 (Vidal 1973). Rafts and sheets of highly deformed leucogranite ["homogeneous gneiss" and "fine-grained gneiss" of Hanmer (1977b, p. 85-87); Cap Sizun Older and Cap Sizun Younger of this study], intruded by and included within the main, mildly foliated leucogranite at Cap Sizun, yield an age of 301 ± 11 *Ma* (0.7102) (Cap Sizun Younger: Hanmer & Peucat, unpubl. data). Other Rb/Sr ages for the Ploermel, Pontivy and Quimper massifs fall within the 300–330 *Ma* interval; initial ^{87}Sr/^{86}Sr values for Ploermel and Quimper lie within the range 0.708–0.710, but Pontivy is somewhat low at about 0.7060 (Peucat & Jegouzo, pers. comm. 1979, Peucat & Berthé, pers. comm. 1979). These leucogranites appear to have been intruded along an older plutonic line, possibly extending in the subsurface along the S.A.S.Z. (northern branch) and under the Paris basin (Weber 1967). After their emplacement, transcurrent movement in pre-Westphalian "D" or Cantabrian time produced mylonite belts, up to a kilometre in width, along the S.A.S.Z. axial zone (Cogné 1957, Berthé *et al.* 1979).

A number of field and laboratory observations demonstrate that the Locronan, Pontivy, Ploermel and probably the Questembert massifs were emplaced contemporaneously with both the metamorphism and deformation of their envelope rocks (Hanmer 1978, Hanmer & Vigneresse 1980, Hanmer *et al.* 1980): (1) the metasediments were regionally deformed and metamorphosed during the Hercynian orogeny (Le Corre 1977); (2) trajectory patterns of the single cleavage in the envelope rocks indicate interaction between a local strain-field related to radial expansion of the diapiric leucogranites during emplacement and the contemporaneous regional strain field (see Brun *et al.* 1976, Ledru & Brun 1977); (3) metamorphic grade in the envelope rocks increases from the regional lower greenschist facies away from the granite margins to lower-to-middle amphibolite facies (staurolite–kyanite–sillimanite–andalusite ± garnet) near the granites; (4) the metamorphic isograds and phyllosilicate isocrystallinity contours parallel the irregularities in the leucogranite outcrop; (5) metamorphic mineral growth is pre-, syn- and post-tectonic with respect to the penetrative cleavage in the envelope (Hanmer 1979). Syntectonic assemblages include kyanite–sillimanite–andalusite. Although nowhere have all three aluminosilicates been identified within a single thin section, their syntectonic textures with respect to the single regional cleavage suggest that temperatures of 550–600°C at 5–6 kbar $P(H_2O)$ obtained in the envelope rocks during granite emplacement (see Fig. 9).

Tectonic interpretations

A number of regional tectonic models have been proposed for the Paleozoic history of southern Brittany (*e.g.*, Nicolas 1972, Cogné 1977). Cogné proposed that northward-dipping subduction occurred beneath southern Brittany during the Siluro-Devonian, resulting in the "Ligerian" orogeny. Radiometric dating and structural study of the South Brittany blueschists tend to refute this model and to link their genesis to northward-directed Hercynian thrusting (Carpenter & Civetta 1976, Quinquis 1979). Cogné's (1977) model terminates with a continent–continent collision during the Hercynian. Recent paleomagnetic reconstructions, however, do not indicate a major suture in southern Brittany (Scotese *et al.* 1979). The close spatial relationship between the leucogranites and the S.A.S.Z. suggests a genetic relation between them. Because of the disposition of the leucogranites in vertical sheets, Cogné (1957, 1960, 1967) considered granitic melt production and emplacement to be syntectonic with respect to transcurrent movement along the S.A.S.Z. The presence of rafts of highly deformed leucogranite within mildly foliated leucogranite close to the S.A.S.Z. at Cap Sizun, and of leucogranite protomylonite cut by subisotropic leucogranite between Locronan and Pontivy, supports this hypothesis. Furthermore, strain in leucogranitic Hercynian gneisses within the Baie d'Audierne schists and amphibolites, which are themselves cut by the Quimper leucogranite massif (Hanmer 1977b), is compatible with dextral transcurrent movement along the S.A.S.Z. (Berthé, pers. comm. 1978). More recently, Hanmer & Vigneresse (1980) and Hanmer *et al.* (1980) have interpreted the Locronan, Pontivy and Lizio massifs as diapirs, emplaced during the deformation of their metasedimentary envelopes.

The relationship between the older (pre-Hercynian) granite and deformation is less clear. The Ste-Anne d'Auray granite is known to have been emplaced during folding of the country rocks, but its possible genetic relationship with the S.A.S.Z. has never been considered. The Douarnenez complex carries a synemplacement foliation compatible with dextral wrench-faulting, *i.e.*, the sense of Carboniferous movement along the adjacent S.A.S.Z. The range of emplacement ages of the Douarnenez complex and the central and eastern parts of the Lanvaux gneiss (470–430 *Ma*) overlaps the older time constraints bracketing the syntectonic migmatization event within the mobile belt (460–376 *Ma*, Peucat & Cogné 1977). We tentatively suggest that the Douarnenez and Lanvaux granites were emplaced during deformation along the South Brittany mobile belt and were accompanied by dextral movement along the S.A.S.Z.

In summary, it appears that the line of the S.A.S.Z. has been the site of granite emplacement during Lower Paleozoic and Hercynian times. The fact that deformation patterns within the earlier Hercynian leucogranite are compatible with movement along the S.A.S.Z. and with the emplacement and subsequent mylonization of the bulk of the leucogranite along the S.A.S.Z. axial zone indicates a close spatial and temporal relationship between the leucogranites and activity along the shear zone.

PETROGRAPHY

The plutons studied vary mainly in grain size, degree of deformation, and muscovite content. However, since these variations are as great within a single pluton as between different plutons, it is not necessary to describe each pluton separately. Most of the "leucogranites" would be classified mainly as transitional between granite and granodiorite based on the classification of Streckeisen (1973).

Plagioclase is generally the coarsest mineral in these rocks, ranging up to several cm long but typically between 0.5 and 5 mm. The coarsest plagioclase crystals are most strongly zoned, with cores typically replaced by muscovite and calcite. In deformed rocks the larger plagioclase crystals are typically recrystallized, with abundant small, euhedral, secondary albite crystals. Myrmekitic textures are locally present in groundmass grains and along the rims of larger plagioclase crystals.

Alkali feldspar occurs typically as twinned crystals up to 1 cm long, and as an interstitial

TABLE 1. AVERAGE COMPOSITIONS OF BRITTANY LEUCOGRANITES

SAMPLE	QUIMPER(12)	PLOMEUR(9)	PONTIVY(7)	PLOERMEL(5)	CAP SIZUN YOUNGER(3)	CAP SIZUN OLDER(8)
Si02	72.68	72.84	72.46	73.50	74.17	72.13
Ti02	0.17	0.22	0.20	0.17	0.07	0.20
Al203	14.53	14.64	14.58	14.64	14.47	14.64
Fe203	0.32	0.09	0.12	0.22	0.21	0.38
Fe0	0.87	0.67	1.04	0.86	0.61	0.74
Mn0	0.01	0.02	0.02	0.02	0.01	0.01
Mg0	0.30	0.23	0.40	0.35	0.21	0.36
Ca0	0.64	0.58	0.70	0.73	0.59	0.83
Na20	3.22	3.72	3.58	3.36	3.40	2.83
K20	5.20	4.78	4.70	4.75	5.18	5.71
P205	0.30	0.24	0.31	0.30	0.34	0.28
LOI	1.36	1.25	1.13	1.47	0.99	1.12
TOTAL	99.60	99.28	99.24	100.37	100.25	99.28
Zr	87	50	82	75	46	93
Sr	86	53	76	73	57	83
Rb	317	348	292	274	242	255
Zn	64	44	81	60	29	46
Cu	6	7	6	5	5	5
Ba	256	169	269	247	187	349
Th	11	3	10	7	1	11
Nb	15	12	9	11	14	11
Ga	27	25	24	23	23	23
Pb	30	34	26	30	32	41
Ni	18	17	18	15	14	16
La	36	32	34	31	27	31
Cr	18	16	19	19	17	16
V	3	0	8	5	1	3
Y	14	10	11	13	12	14
Ce	93	108	123	87	81	96

SAMPLE	LANVAUX III (6)	STE-ANNE D'AURAY(9)	QUESTEMBERT (16)	DOUARNENEZ (3)	LANVAUX II (5)
Si02	74.13	72.17	73.37	73.10	74.38
Ti02	0.12	0.21	0.10	0.26	0.06
Al203	13.47	14.71	14.73	14.13	13.26
Fe203	0.46	0.32	1.06	0.44	0.33
Fe0	1.04	1.12	0.07	1.84	0.72
Mn0	0.03	0.02	0.03	0.04	0.03
Mg0	0.32	0.50	0.12	0.54	0.22
Ca0	0.73	1.21	0.51	2.41	0.45
Na20	3.90	3.34	3.47	3.98	3.15
K20	3.55	4.49	4.41	1.60	4.68
P205	0.15	0.12	0.05	0.07	0.08
LOI	1.11	0.82	1.38	0.69	1.33
TOTAL	99.01	99.03	99.30	99.10	98.69
			(2)	(2)	
Zr	80	95	43	165	69
Sr	80	186	38	98	42
Rb	108	178	416	60	234
Zn	21	33	62	41	29
Cu	7	28	5	6	12
Ba	493	531	131	219	153
Th	9	10	5	5	13
Nb	7	9	18	6	9
Ga	19	20	24	18	21
Pb	16	37	24	10	38
Ni	13	30	21	11	21
La	41	35	35	28	39
Cr	15	156	16	207	15
V	7	10	0	24	2
Y	37	13	14	25	46
Ce	177	44	36	45	149

NUMBERS IN BRACKETS REFER TO NUMBER OF ANALYSES groundmass phase, but locally it forms megacrysts. The larger crystals are generally perthitic, and some contain primary inclusions of the other phases, especially quartz and plagioclase. In some cases, plagioclase is partially replaced by alkali feldspar.

Quartz is comparable in grain size to the feldspars, with larger grains typically strained or, like the feldspars, showing varying degrees of recovery or recrystallization. Fluid-inclusion trains are ubiquitous, marking fractures and boundaries of deformation lamellae.

Both muscovite and biotite occur as euhedral plates, poikilitic megacrysts, interstitial groundmass grains and secondary mattes and microlites replacing feldspars. Biotite is brown-yellow and may be oxidided or chloritized. In some rocks muscovite is replaced by biotite, whereas in others the reverse is true.

Accessory tourmaline, garnet and apatite are common, with less abundant zircon, fluorite and rutile. Some zircons are composite, with euhedral overgrowth on rounded cores.

CHEMISTRY

Seventy-five rocks were analyzed for the major and trace elements; their distribution and the average compositions of each of the twelve plutons are given in Table 1. Major elements were determined by atomic absorption, trace elements by X-ray-fluorescence spectrometry, and P_2O_5 and FeO by titration, with precision and accuracy as given by Strong *et al.* (1978). Thirteen major-element analyses of the Questembert pluton are taken from Charoy (1970).

There is a striking consistency in composition among the plutons (Table 1), and this is further illustrated by their normative quartz–albite–orthoclase proportions. All pluton averages, except those for Douarnenez, Lanvaux III and Cap Sizun Older, cluster on the experimentally determined quartz–plagioclase–alkali feldspar piercing point in the system $Ab_{97}An_3$–Or–Q–H_2O, as determined by James & Hamilton (1969) at 1 kbar $P(H_2O)$. This correspondence is somewhat surprising, since it appears from the petrographic and field evidence that the plutons crystallized at substantially higher pressures, around 5 kbar. However, as shown on Figure 2c, there are a number of opposing factors that affect the position of this piercing point, such as the An content of the system, differing coexisting phases and fluorine content. Until the interaction of these variables is understood, it is not possible to choose the exact phase-relations ap-

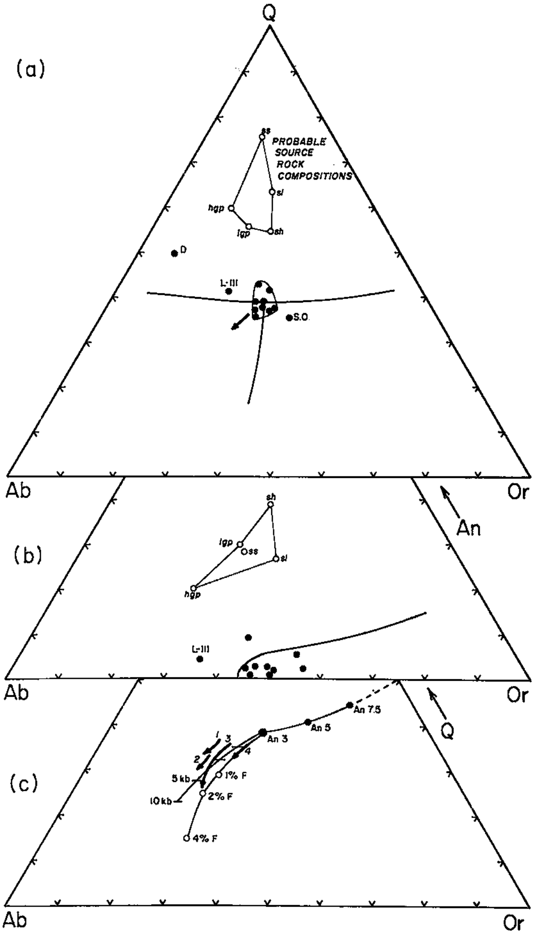

FIG. 2. *a,b.* Proportions of normative Ab–An–Or–Q in average compositions of Brittany leucogranites (dots) and in sedimentary–metasedimentary rocks (circles) as given by Garrels & MacKenzie (1971), with abbreviations as follows: ss sandstone, sl slate, sh shale, lgp low-grade pelite, hgp high-grade pelite, D Douarnenez, S.O. Cap Sizun older, L-III Lanvaux-III plutons. Cotectic lines are from James & Hamilton (1969) for the system $(Ab_{97}An_3)$–Or–Q–H_2O. The arrow in *a* shows the trend of piercing-point compositions from 2.3 to 4 kbar $P(H_2O)$ for granite melt in equilibrium with muscovite, as given by Brown & Fyfe (1970). *c.* The effects of different variables on the "eutectic" compositions as follows: dots, differing An contents; dashes, differing $P(H_2O)$, as compiled by Wyllie (1977); circles, differing fluorine contents (Manning 1979); arrows, differing melt compositions resulting from differences in the coexisting hydrous phase, bulk composition and $P(H_2O)$ (arrowheads at highest pressures), with numbers referring to 1 hornblende granite (1–4 kbar), 2 hornblende diorite (2–4 kbar), 3 biotite granite (2–10 kbar), 4 muscovite granite (2.5–4 kbar).

plicable to these granites. However, we consider their near-correspondence with granite compositions coexisting with muscovite at 1–4 kbar (Brown & Fyfe 1970) to be significant, and we use the 1 kbar cotectic curves for the following petrogenetic discussion.

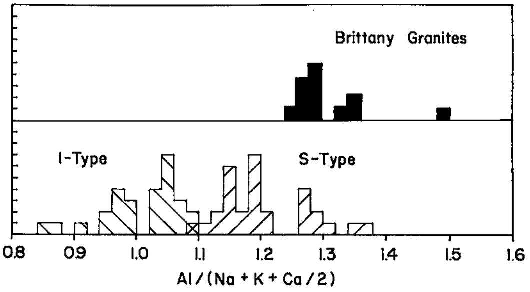

FIG. 3. Histogram showing frequency of Al/(Na+K+Ca/2) (cation %) for the Brittany leucogranites, compared with the I- and S-type granitoid rocks of the eastern side of the Kosciuscko batholith of New South Wales (after Hine *et al.* 1978).

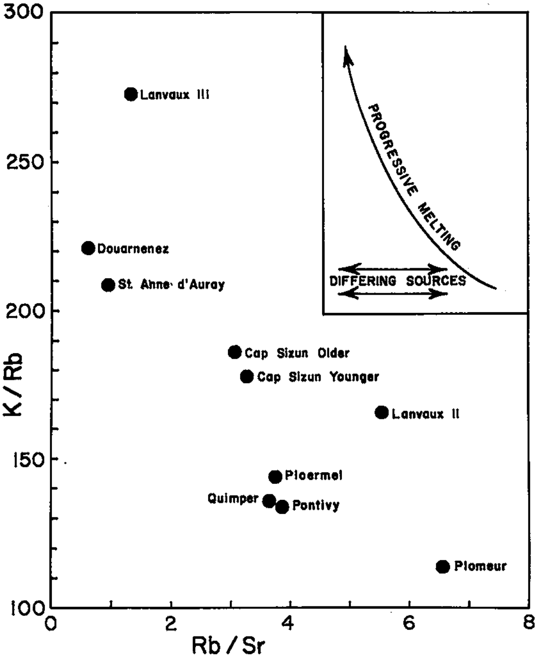

FIG. 4. Variation in average ratios K/Rb *versus* Rb/Sr in Brittany leucogranites. The inset shows trends that might result either from differing degrees of partial melting of a fixed source-composition or from differing source-compositions.

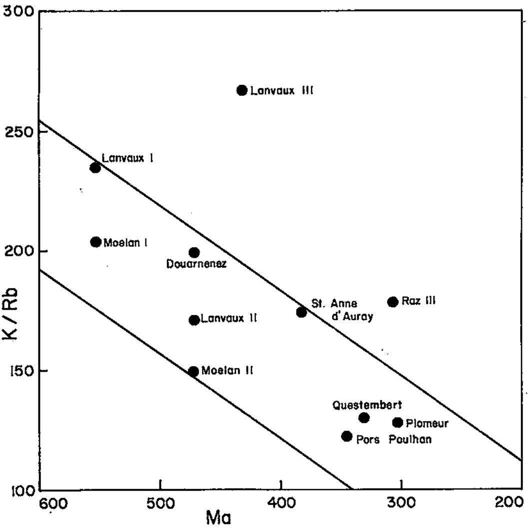

FIG. 5. Temporal variation in K/Rb ratios in granites of southern Brittany.

Figure 3 shows a diagram used by Hine *et al.* (1978) to illustrate differences between "I-type" (igneous-derived) and "S-type" (sedimentary-derived) granitoid rocks of the Kosciusko batholith of eastern Australia. The Brittany leucogranites typically plot at the more peraluminous part of this diagram, as they contain about 3% normative corundum. They are thus comparable to the S-type granitoid rocks, in line with the field evidence for their metasedimentary origin described above.

Most trace elements, like the major elements, vary little from one pluton to another (Table 1). There are some differences, however, as illustrated in Figures 4 to 7. On a plot of K/Rb *versus* Rb/Sr (Fig. 4), the Cap Sizun gneisses and the Ploermel, Quimper and Pontivy plutons cluster in two separate groups; the others are more dispersed. There are no particular spatial or temporal relations to explain why some of these plutons should be grouped as they are, *e.g.*, in terms of common sources, but there is a tendency towards lower K/Rb ratios in younger rocks (Fig. 5). The trend of higher K/Rb with lower Rb/Sr (Fig. 4 insert) could result from higher degrees of partial melting of a fixed source, with variations off that trend resulting from minor differences in the source.

Because K, Rb and Sr concentrations have been altered by the secondary processes that affected these rocks, the supposedly less mobile elements Zr, Ti, Ce and Nb are plotted in Figure 6. These show the same grouping of Pont-

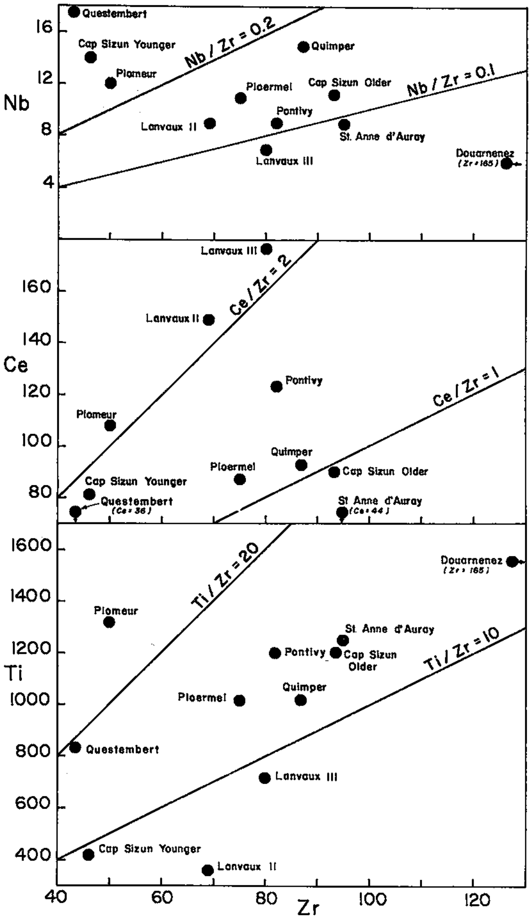

FIG. 6. Variation in average concentrations (ppm) of Nb, Ce and Ti with Zr in leucogranites from Brittany. The apparently random pattern is presumed to reflect differences in source compositions.

but there is an apparently random scatter of these data for the other plutons. This cannot be explained by differing degrees of melting or by crystal fractionation, and might also reflect differing source materials.

ivy–Ploermel–Quimper plutons as in Figure 4,

Initial $^{87}Sr/^{86}Sr$ ratios (Fig. 7) likewise show significant systematic variations with time. This may indicate derivation from sources with a steadily increasing input of crustal material, or it could simply reflect derivation from a source with high Rb/Sr ratios around 0.6. The drop in K/Rb ratios with time (Fig. 5) can be explained by progressively lower degrees of partial melting, or by the melting of rocks with progressively lower K/Rb ratios.

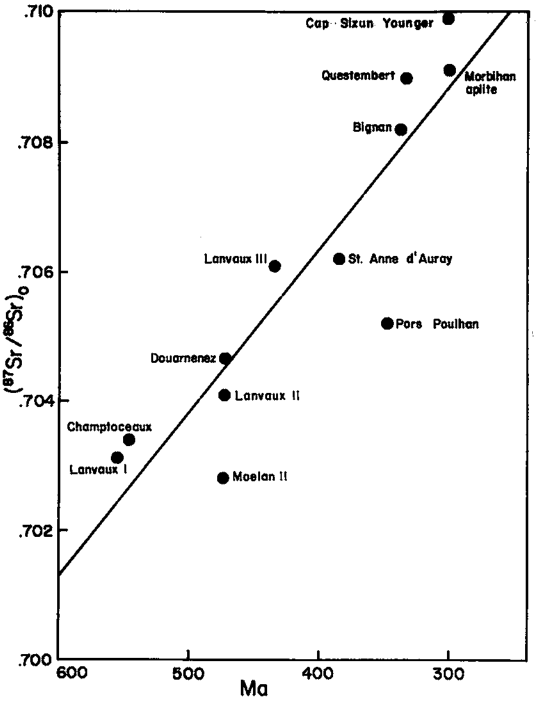

FIG. 7. Temporal variations of initial $^{87}Sr/^{86}Sr$ in southern Brittany leucogranites. Data sources cited in text; other data in Vidal (1976).

PETROGENESIS

Any model for the petrogenesis of the Brittany leucogranites must explain both the chemical and physical processes responsible for (1) their more or less constant mineralogical and major element compositions; (2) their systematic variation in concentrations and ratios of trace elements and initial Sr isotopic ratios (Figs. 4–7) without appreciable corresponding change in major elements; (3) repeated production of melts of relatively constant major element composition; (4) linear distribution of the leucogranites along the S.A.S.Z. and its subsidiary faults; (5) syntectonic emplacement of the leucogranites; (6) localization in a metamorphic culmination, and (7) the absence of obvious tectonic effects recorded in the overlying sedimentary rocks of the same age to the north of the S.A.S.Z.

CHEMICAL MODEL

The following chemical model is based on the field and isotopic evidence, presented above, indicating that the granites were formed by partial melting of crustal materials, probably metasediments. Because we have no data on the exact composition of the metasediments from which the melts were formed, the following discussion is based on the average sedimentary rock compositions given by Garrels & MacKenzie (1971).

Presnall (1969) has presented an elegant theoretical discussion of the variations of melt compositions with differing processes of partial melting, *e.g.*, fractional melting or equilibrium melting. The essential point for the present model is that, given a fixed composition for the source in a chemical system (Fig. 8), progressive (equilibrium) melting will produce a range of melt compositions approaching progressively closer to the source, along the path *x*–*y*–*z*. However, fractional melting can produce successive batches of melt of constant (eutectic) composition *x* as long as the source composition remains within the system *ABC*. During this process, the composition of residual source-material will change progressively away from melt *x* along *zn* within the system *ABC*. At the point where the residual source-composition leaves the system *ABC* (*i.e.*, component *C* is exhausted), melting will cease until temperatures reach those of the eutectic *m*, at which point a second fractional melt of composition *m* will be produced until all of component *B* is melted out of the system. Within the system *ABC*, the composition of melt (*i.e.*, at *x*) will be the same whatever the source composition, although the amount of melt that can be produced will vary with source composition.

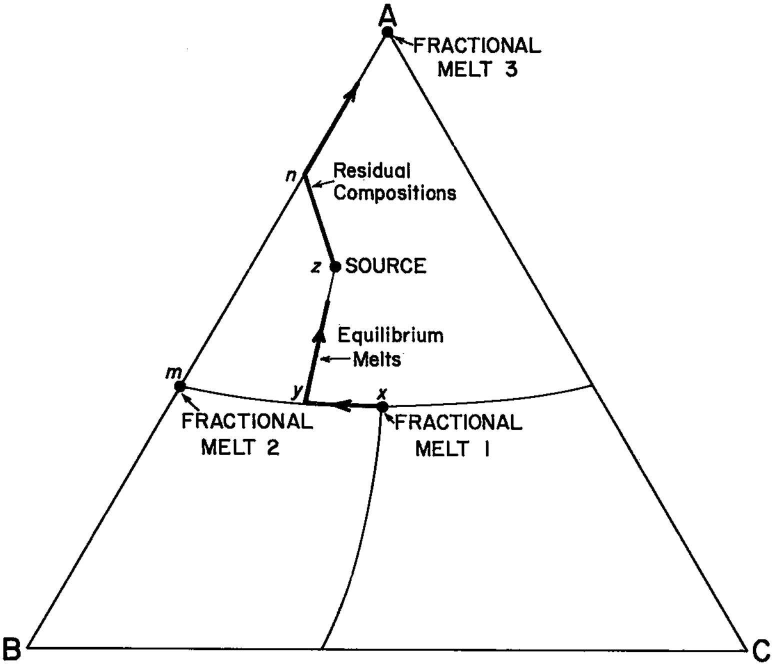

FIG. 8. Schematic outline of the differences in equilibrium melting and fractional melting in the system *ABC*. For equilibrium melting of source composition *z*, the liquid initially will have eutectic composition *x* and change continuously toward the source along *xyz*, with the residual solid compositions of the source changing continuously along *znA*. With fractional melting of *z*, the first liquid produced will have composition *x*, and repeated melting will give repeated melts of this composition, until all of component *C* is removed from the system. At this time the source will have changed composition to the *AB* sideline at *n*, and further heating will be required to raise the temperature to produce the eutectic melt composition at *m*. Repeated melting will give liquid fractions of composition *m*, until all of *B* is removed, so that the final fractional melt will then be of composition *A* (see Presnall 1969 for a more detailed discussion of fractional melting processes).

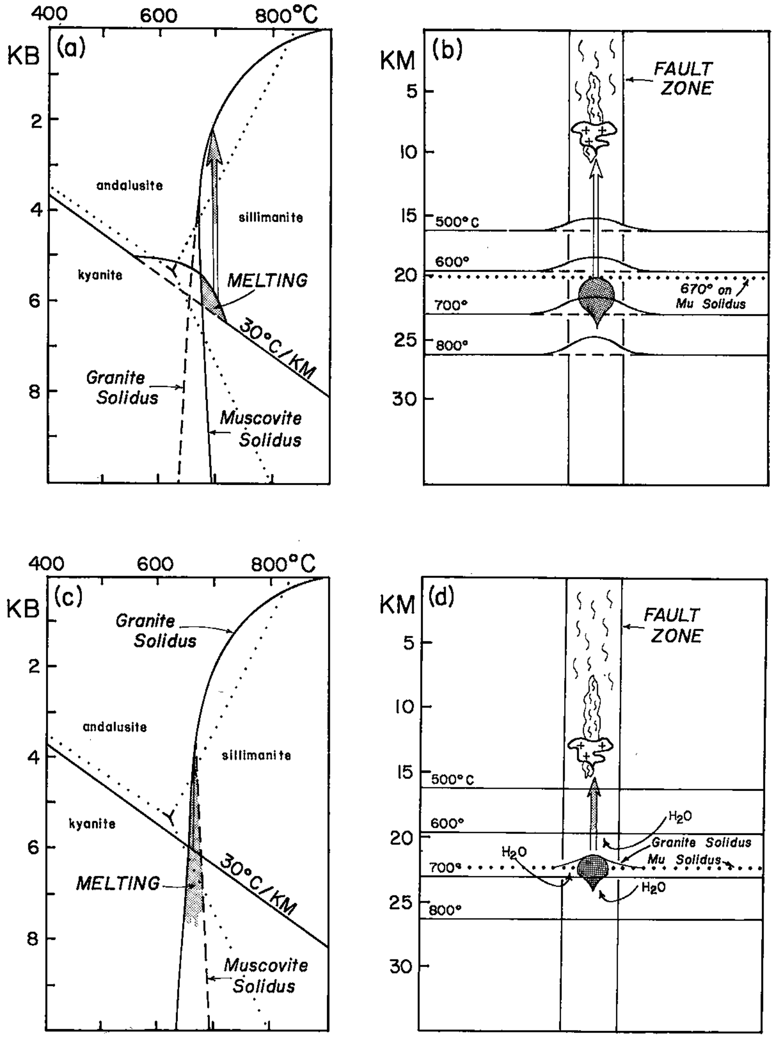

FIG. 9*a*. Pressure–temperature projection of some melting and reaction relations relevant to the genesis of Brittany leucogranites. The granite and muscovite solidus are from Burnham (1979), the aluminosilicate triple point after Richardson *et al.* (1969), and 100°C perturbation of the 30°C/km geotherm caused by frictional heating according to the calculations of Reitan (1968a, b). The shaded area shows a zone of muscovite melting as a result of such frictional heating, with the arrow showing an adiabatic rise to depths of about 7 km. *b*. Thermal model of a fault zone, based on *a*, showing batches of granitic melt periodically produced by the frictional heating, rising and freezing at shallower levels and being deformed in the fault zone and intruded by later melts. *c*. As for *a* but with melting caused by lowering of the melting temperatures to the water-saturated granite solidus by influx of water into the fault zone. *d*. Thermal model of the fault zone based on *c*. Note that melts produced in *a* could rise to shallower depths than those of *c* before freezing, and that those of *c* could be formed at slightly lower temperatures, although the presence of such elements as Li, B and F could lower the melting temperature by as much as 100°C in either case.

This process of fractional melting can be applied to interpretation of the Brittany leucogranites using the phase relations outlined in Figure 2. It can be shown, using Figures 2 and 8, that the leucogranites could represent eutectic melts derived from common sedimentary rocks by fractional melting (Fig. 2 caption).

Although sophisticated models using trace elements are available for evaluation of anatectic processes (*e.g.*, Shaw 1978), these models are critically dependent on a knowledge of the source concentrations, the stable residual phases (hence, the conditions of melting) and the element partition-coefficients between melt and residual phases. Such data are not yet available, but we can say that the variations in trace element and isotopic ratios of Brittany leucogranites require variations in source compositions, and may also reflect different degrees of melting.

Physical model

Any physical model for the production of Brittany leucogranites must provide for their control by strike-slip faulting, a relationship so intimate as to require a genetic relationship. Such a relationship has been suggested by Nicolas *et al.* (1977), who proposed frictional heating as the main cause of production of granitic melt. Melting in other fault zones by a similar process has also been suggested by Reitan (1968a, b), and McKenzie & Brune (1972), both of whom estimated possible temperature-increases of up to 100°C.

These concepts have been incorporated in the model illustrated in Figure 9. Melt production is assumed to occur at pressures of 5 kbar or more because of the field evidence described above. Figure 9 incorporates a frictional temperature increase of 100°C above an ambient 30°C/km geotherm and water-deficient melting at the upper stability limit of muscovite. Figures 9a and b show the extreme case of adiabatic ascent of the melt along the fault zone, which allows intrusion at shallow depths where muscovite is unstable on the granite solidus, although the presence of abundant primary muscovite indicates much shorter paths of ascent. This model allows for repeated fractional melting (as discussed for Fig. 8) by either intermittent seismic shearing or continuous aseismic shearing. In the latter case, fractional melting could result in lubrication of the fault zone by melt, which would cause a drop in production of frictional heat. Melting would then cease until upward migration and freezing of the melt allowed further frictional heating. Melting temperatures could be lowered by more than 100°C by such elements as boron, lithium and fluorine (Chorlton & Martin 1978, Wyllie & Tuttle 1961, Stewart 1978), all of which are relatively abundant in the Brittany leucogranites (Chauris 1977, 1978).

Although frictional heating models have been criticized from a theoretical point of view, *e.g.*, because of inadequate viscosities of the rock, rates of movement or times involved (*e.g.*, Sibson 1977, Yuen *et al.* 1978, Brun & Cobbold 1979), it is probable that both the models and the criticisms are based on oversimplified assumptions. For example, Fleitout & Froidevaux (1979) pointed out that in an inhomogeneous layered sequence, the temperature in the less ductile rocks can increase sufficiently to melt the neighboring more ductile material. Nevertheless, other processes operative in fault zones must also be considered, and perhaps the most important is the role of fluids, especially water.

Many workers (*e.g.*, Beach & Fyfe 1972, Berry 1973, Sibson 1975, Beach 1979) have emphasized the importance of fault zones as conduits for hydrous fluids. It appears that the large volumes of water that diffuse into fault zones not only promote hydration reactions (*e.g.*, Beach 1979) but also move upward along the fault zone to the surface, *e.g.*, by "seismic pumping" (Sibson 1975, Fyfe *et al.* 1978). It is thus reasonable to suggest that such water ingestion could promote saturation conditions within the fault zone.

According to the model shown in Figure 9c, melting along a 30°C/km geotherm at about 6 kbar or more could be caused by a lowering of melting temperature from that of the upper stability of muscovite to the water-saturated granite solidus owing to hydration along the fault. Again, fractional melting could be caused by variations in water pressure as a result of "seismic pumping" or other processes. It is unclear which of these two extreme processes may be more important in controlling the production of leucogranites along shear zones, but either or both seem necessary to explain the shear-zone association and the constant compositions in the leucogranite belt of southern Brittany.

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