

Peralkaline granites in Corsica: some petrological and geochemical constraints

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ABSTRACT. — Among the Permo Triassic alkaline plutonic-volcanic complexes of Corsica three of them contain peralkaline granites. They yield radiometric ages of 245 m.yr. (Permo-Triassic boundary) and a mantle origin (low Sr-initial isotopic ratios). Peralkaline granites are characterized by a high albitic ratio ($(Na + K)/Al$ up to 1.25, with the presence of CIPW normative sodium disilicate) and a sodic mineral paragenesis (albite, arfvedsonite, aegirine, elpidite).

In order to discriminate between magmatic processes and post-magmatic mineral resettings, modal analyses, mineral chemical compositions, major element geochemistry as well as trace element geochemistry have been performed. The role of hydrothermal fluids is emphasized, inducing the crystallization of Ti-Zn enriched aegirine and arfvedsonite and a moreless complete subolidus metasomatism. These processes are marked by the dissolution of early prismatic zircon and late-stage precipitation of elpidite and/or octahedral zircon, a complete low-temperature ordering of alkali feldspars (maximum microcline and low albite) and the incorporation of Li and F in arfvedsonite. Chemical zonations in arfvedsonite crystals and trace element data substantiate the role of F-rich mantle-derived fluids, carrying Na, Li, Fe, Sr, Th, ..., resulting in a complete Sr isotopic homogenization (initial ratio of 0.703).

These hydrothermal alteration processes are completely differing from those suffered by earlier and synchronous alkaline peraluminous biotite granites, where a significant crustal component is involved in the percolating hydrothermal fluids.

The alkaline plutonic-volcanic series is composed of basic, intermediate and differentiated rock-types. Evolved rock-types can be classified into three evolutionary trends: metaluminous, peraluminous and peralkaline and, according to their contrasting silica saturation behaviour, can be granites,

syenites and feldspathoidal syenites (for a comprehensive review of the nomenclature, see SØRENSEN, 1974). Actually, alkaline rocks are difficult to define, as the term «alkaline» is ambiguous and has been used with many different senses (BATES and JACKSON, 1980).

If the view of SHAND (1922) is adopted taking into consideration the molecular proportions $Na_2O + K_2O : Al_2O_3 : SiO_2$, then: «an alkaline rock should be one in which the alkalis are in excess of 1:1:6, either alumina or silica or both being deficient». According to this classification, alkaline rocks comprise silica-saturated (syenitic) to oversaturated (granitic) rocks which are peralkaline ($(Na_2O + K_2O)/Al_2O_3 > 1$). However, in many alkaline provinces, silica-oversaturated (per)aluminous rocks (biotite granites), which are not strictly alkaline, do occur in the same complexes as the alkaline rocks.

This is the case in the Corsican alkaline province, where the peraluminous granite is the most abundant rock-type, occurring in about twenty complexes (BONIN, 1980). Peralkaline granites are more restricted, as they have been recognized so far in only four complexes: Cauro-Bastelica (BONIN, 1972), Evisa-Calasima (NENTEN, 1897; DEPRAT, 1905; ORCEL, 1924; QUIN, 1968; VELLUTINI, 1977; BONIN et al., 1978), Bonifatto (DEPRAT, 1905; QUIN, 1968; VELLUTINI, 1977) and Capo Rosso (QUIN, 1968; VELLUTINI, 1977).

The Evisa-Calasima peralkaline complex is

probably the most famous, because of its mineralogy which has given to Lacroix the matter of numerous articles in his monumental «Minéralogie de la France» (1962). First described by Gueymard as «tourmaline granite» in 1820, the peralkaline granites of the Evisa area have been recognized as bearing blue amphibole and aegirine by NENTIEN (1897). The petrographic term *lindinosite*, which will be discussed later, was proposed and defined by LACROIX (1923) after Nentien's samples in the Lindinosa Forest, in the middle of the Evisa complex.

This complex is one among others of the Corsica province, which is made up of numerous, high level, anorogenic and granitic ring-complexes. Descriptions of the province have been made by VELLUTINI (1977) for its northern part and by BONIN (1980) for the rest, summaries of the geology can be found in BONIN and ORSINI (1980) and in BONIN (1982, 1986). Accordingly, the present paper deals briefly with the general aspects of Corsica ring-complexes and is largely concerned with the petrography, geochemistry and petrogenesis of the peralkaline granites.

Nomenclature. The peralkaline granites have a distinctive mineralogy, characterized by sodic species, with acmite (ac) and sometimes sodium-disilicate (ns) appearing as CIPW normative minerals. These granites have been described previously as riebeckite granites (NENTIEN, 1897; QUIN, 1968), but this term requires revision in the light of mineralogical studies.

According to their feldspathic contents, the granites will be referred as *hypersolvus* for the mesoperthitic varieties, and *albitic* for the albite-bearing varieties (BONIN, 1982, 1986).

Lindinosite is a term for mesocratic to melanocratic sodic granite, bearing sodic amphibole as the major constituent (LACROIX, 1923). *Rockallite* refers to an aegirine-bearing mesocratic to melanocratic granite (JUDD, 1897).

1. Mode of occurrence and associations

Corsican alkaline ring-complexes vary greatly in size and structural complexity (BONIN, 1982, 1986). Their most typical ones

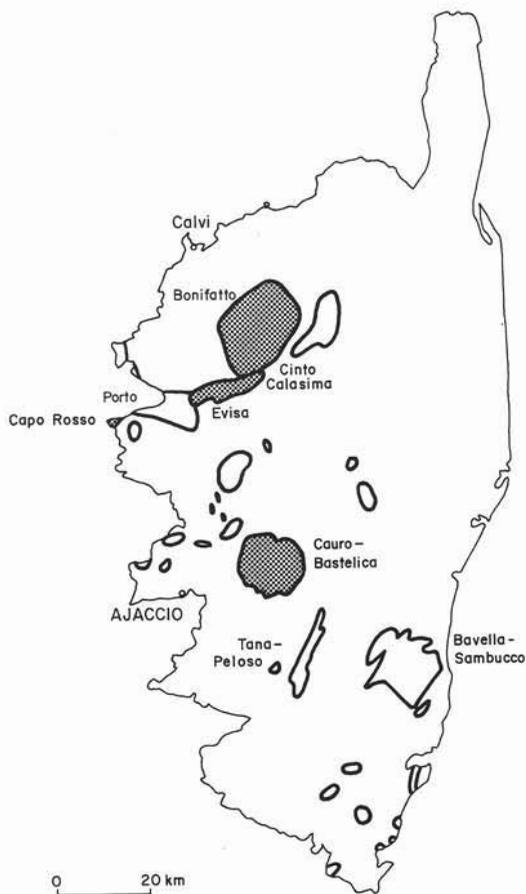


Fig. 1. — Location of the peralkaline granite-bearing complexes (crossed areas) among the Permo-Triassic alkaline province of Corsica (peralkaline complexes labelled).

are circular or elliptical in outline, 5 to 20 km in diameter, and are composed of either caldera-filling volcanic formations or a series of concentric granitoid intrusions or both. Overlapping ring-complexes have a linear arrangement, as in the cases of Tana-Peloso (BONIN, 1980) or Porto-Evisa-Calasima (VELLUTINI, 1977).

Such alignments are accompanied by linear dyke swarms, filled by bimodal (basic and felsic) magmatic hypabyssal rocks, like the Niolo (QUIN, 1968; VELLUTINI, 1977), Sotta-Porto Vecchio and Santa Maria Sicché-Olivese (BONIN, 1980) dyke swarms.

The elliptical outlines of many ring-complexes have been interpreted as signs of

active transcurrent faulting process during their emplacement: for example, the Porto-Evisa-Calasima alignment provides evidences of a sinistral sense of movement during Porto ring-complex emplacement and a reverse dextral sense during Evisa-Calasima ring-complexes emplacement (BONIN, 1982, 1986). The almost perfectly circular ring-complexes (Cauro-Bastelica, Bonifatto) are comparatively rare and could have been emplaced during a relatively steady period.

Peralkaline granites have been recognized in four complexes: Cauro-Bastelica and Capo Rosso, where they are in subordinate amounts, Bonifatto and Evisa-Calasima, where they predominate (Figure 1).

1.1. *Cauro-Bastelica*

Located in the centre of Corsica, at about 20 km at the east of Ajaccio, this complex was the first ring-complex discovered in Corsica and was studied in detail by BONIN (1972, 1980). Radiometric ages by the Rb-Sr isochron method on whole rocks (BONIN et al., 1972, 1987) substantiate a magmatic activity during the Permo-Triassic boundary.

Two petrographic groups are present. A first ensemble of hypersolvus granites was emplaced in a ring-structure of 15 km diameter and is composed of the intrusive sequence: 1) fayalite granite; 2) biotite granite, 3) sodic amphibole granite. Rhyolitic domes and breccias containing basement xenoliths constitute the associated volcanic formations. Hypersolvus biotite granites have yielded a 241 m.yr. age.

The second ensemble is made up of peraluminous transsolvus and subsolvus biotite granites, which intrude the first ensemble and form ring-structure of the same diameter but emplaced in the north-western part of the massif. These granites have yielded a 236 m.yr. age.

The hypersolvus fayalite and sodic amphibole granites belong to the peralkaline evolutionary trend. They display metaluminous to peralkaline chemistry and are characterized by a complete crystallization sequence of dark minerals, from a magmatic fayalite-hedenbergite-iron oxide assemblage to a

complex post-magmatic paragenesis comprising sodic amphibole (barroisite to winchite), mafic amphibole (sodic grünerite), biotite of the annite-lepidomelane series and fluorite (BONIN, 1980; GIRET et al., 1980).

Recently (1984), during the works performed to increase the capacity of production of the hydro-electric works at Ocana, pegmatitic dykes issued from the sodic amphibole granite and intruding the fayalite granite of the Punta di Mazzoni have been discovered in tunnels. They are made up of a quartz-K feldspar-albite assemblage and exhibit well developed (up to 10 cm long) euhedral amphibole crystals of richterite-arfvedsonite composition (see Table 3), which will be discussed later.

1.2. *Capo Rosso*

This complex, the most western one in Corsica, is located in the southern part of Golfe de Porto, where it appears as red cliffs (Capo Rosso means «red cape») at the sunset. It is made up of two distinct intrusions (VELLUTINI, 1977); a peralkaline one at the summit of the cliffs, and a peraluminous one at the lowest part of the cliffs.

The peraluminous intrusion comprises a main biotite granite body and numerous and spectacular inclusions of gabbro, near the outer contact and in the centre of the intrusion. Evidences of synchronous injections of basic and acid magmas are pillow-like outlines of gabbroic masses, lobate and cusped contacts and some features of magma-mixing (PLATEVOET et al., 1988). The peralkaline intrusion is made up of an arfvedsonite hypersolvus granite.

1.3. *Bonifatto*

This massif is located 30 km south of Calvi. It was mapped in some details by VELLUTINI (1977), who has given convincing evidences that the Bonifatto granite intrudes the Monte Cinto volcanic formations. No Rb-Sr radiometric age on whole rocks is available to date and previous K-Ar data have substantiated a significant rejuvenation effect during the Alpine tectonic episodes (MALUSKI,

1977; VELLUTINI, 1977). However, some K-A and $^{39}\text{A}/^{40}\text{A}$ data on minerals suggest a 245 M.yr. cooling age (MALUSKI, 1977). Field evidences indicate that the Monte Cinto caldera postdates the Evisa complex (VELLUTINI, 1977).

The complex is made up by a 18 km-diameter caldera filled by volcanic products (pyroclastic breccias, pumice flows and ignimbric piles) of comenditic affinity and lacustrine detrital formations. A granitic cupola, the Bonifatto peralkaline granite, intrudes the basal volcanic formations. The peralkaline granite is far from being homogeneous and, at the Spasimata vertical sections, this sequence can be observed, from top to bottom:

— a marginal fine-grained facies, red in colour and about 50 m-thick, just below the ignimbric pile. The horizontal prismatic in the ignimbric formations disappears, along with a complete recrystallization of the groundmass, 50-100 m above the contact;

— a complex zone where large rafts of ignimbric formations are dissected and enclosed in the fine-grained facies, showing horizontal fluidal structures;

— a medium-grained facies, red in colour, with chlorite as the major dark mineral, passing progressively into a coarse-grained facies, also red in colour and with chlorite, but containing numerous miarolitic cavities, about 0.5 to 5 mm in diameter, filled with yellow and orange mineral products. The coarse-grained facies is the dominant one and is commonly found along the road to Bonifatto and in adjacent valleys;

— a coarse-grained facies, light green to grey in colour, sometimes with miarolitic cavities, where the major dark mineral is the blue sodic amphibole (arfvedsonite). This facies is represented by scarce exposures and can be found only as local remnants of the previous magmatic hypersolvus granite, before its complete alteration into the main reddened chlorite granite. No sharp contact has been observed between the green amphibole-bearing and the red chlorite-bearing facies. A 20 cm-wide transitional facies actually observed at the contacts strongly suggest an hydrothermal oxidizing process, probably

prograding from the jointings of the granitic massif and invading pervasively the plutonic formation.

Associated with the hydrothermal alteration, miarolitic cavities and hydraulic fissures, filled with quartz, haematite and fluorite, can be observed at the Spasimata Bridge as well as along the road to Bonifatto.

1.4. Evisa-Calasima

This massif is located at the east of Porto and is composed of numerous intrusions in a SW-NE trending alignment (VELLUTINI, 1977). Peralkaline granites are predominating but rare biotite granites have been discovered in 1984 during a comprehensive mapping of the complex. Radiometric data, using the Rb-Sr isochron method on whole rocks, have yielded similar ages of 246 m.yr. and similar Sr initial ratios of 0.703 for the different units, evidences for a very short time interval for the complete intrusive sequence, an identical mantle origin for the magmas and a complete lack of crustal contamination during the differentiation, ascent and cooling of the peralkaline granites (BONIN et al., 1978). The Sr isotopic ratio of 0.703 is the lowest recorded so far for this type of granite in the Phanerozoic, it provides a good indication that it is unlikely that anatexis of the upper crust can play a significant role in the genesis of such peralkaline granites.

Three petrographic units compose the complex. The earliest is represented by biotite subsolvus granites, either as small cupolas (above Verghio Pass) or as large rectilinear dykes (Lonca Forest) which may be related to the neighbour Porto ring-complex (Figure 2).

The others are peralkaline. The second ensemble is represented by a number of small cupolas, located from SW to NE at Capu di u Vitullu, Capu a e Mancenule, Spelunca, N of Evisa and Casterica Crest, above Verghio Pass. They are made up of a green hypersolvus arfvedsonite granite, displaying a fine-grained marginal facies and a coarse-grained core facies. At the roof of the cupolas, the rock is reddened, with chlorite replacing arfvedsonite, and pegmatitic pockets are



Fig. 2. — Sketch map of a part of Evisa complex. 1. Ota biotite subsolvus granite; 2. Ota gabbro; 3. Porto biotite transolvus granite; 4. Evisa arfvedsonite hypersolvus granite; 5. Evisa arfvedsonite-aegirine albitic granite; 6. Calc-alkaline basement; 7. Geological contact; 8. Fault.

enclosed in the marginal facies. The most spectacular exposure (ORCEL, 1924) is located along the road from Porto to Evisa, about 1.5 km before Evisa: large pegmatitic pockets, with sharp contacts against the red marginal facies (BONIN, 1980), are composed of huge crystals of fayalite (up to 50 cm-long and 10 cm-wide), of quartz (up to 80 cm), growing toward the centre in a matrix composed of pink skeletal K-feldspar crystals. Evidences of a high fluid activity are provided by inclusions of sulphides (pyrite) in the fayalite crystals and of purple fluorite (up to 1 cm) in the core of zoned quartz crystals. These pockets are fed by pegmatitic dykes displaying the same paragenesis.

The last intrusive unit is composed of an albitic arfvedsonite-aegirine granite, located in the Lindinosa Forest. It intrudes the hypersolvus arfvedsonite granitic cupolas and is represented along the vertical contacts by a fine-grained facies, gradually coarsening towards the core of the intrusion and passing into the main medium-grained facies, greenish grey in colour, with dark minerals clustered in centrimetric pockets where arfvedsonite is rimmed by aegirine. At the roof of the intrusion, as shown by the Salto Pass vertical

section, the granite is far from being homogeneous and the following sequence can be observed:

- a fine-grained to aplitic marginal zone, pink in colour and with scarce quartz-alkali feldspar pegmatitic pockets;
- a fine-grained arfvedsonite-aegirine facies, moreless reddened with some zones completely red passing into greyish zones with red spots in the alkali feldspars;
- aplite-pegmatite layered sheets, made up of a pegmatitic border zone, where alkali feldspar and arfvedsonite crystals are growing toward the core, and an aplitic layered core, sometimes including some large arfvedsonite crystals. Poikilitic 5 to 10 cm-long amphibole crystals are often rimmed by acicular 1 mm-long aegirine crystals. Aegirine can also constitute discrete up to 1 cm-large crystals, arranged as radial aggregates;
- toward the core of the intrusion, the granite becomes medium- to coarse-grained, greenish grey in colour, with dark pockets of arfvedsonite rimmed by green aegirine and 1 mm-large miarolitic cavities filled with yellowish elpidite.

Late-stage formations are represented by *lindinosites*, characterized by a quartz-

microcline-arfvedsonite assemblage (ORCEL, 1924) and emplaced along tensile joints, when the granitic mass, almost completely crystallized, presented a ductile habit. This result in rectilinear dykes, curvilinear schlieren (Lindinosa Forest) and rounded enclaves (Bergeries de Mazze), with a conspicuous mechanical mixing of the granitic host rock and the lindinositic synplutonic dykes.

Hydraulic fissuration and brecciation are widespread, especially under the roof formations, and are filled by a groundmass chiefly composed of albite, arfvedsonite and aegirine, enclosing angular or rounded host rock fragments. Hydraulic fissurations have also produced haematite-fluorite vertical veins (QUIN, personal communication, 1977). Previously described as «cataclastic granite» (DEPRAT, 1905), they look like the so-called «tuffisite-veins» (HUGHES, 1971) and show evidences of the high activity of an oxidizing peralkaline fluid rich in fluorine at the end of the consolidation, when the granitic mass has become brittle.

Radial and concentric dyke swarms are numerous around the Evisa complex. Some are linked with hypersolvus granitic cupolas and display aplite-pegmatite associations with quartz-mesoperthitic alkali feldspar-arfvedsonite assemblage.

The most abundant are issued from albitic granite and are characterized by very high apaiitic Na + K/Al ratios (up to 2.0), and a sodic mineralogy (aegirine, arfvedsonite, albite). They all belong to the grorudite-paisanite series (QUIN, 1968) and some contain so many aegirine that they are true «rockallites» (DEPRAT, 1905). These peralkaline dykes intrude both basement formations and peraluminous granites of Porto complex and induce strong «fentization» processes within a few centimeters of the peraluminous granite/rockallite interface (BONIN and PLATEVOET, 1988).

2. Petrography and mineralogy

Texture and typical parageneses have been described previously by DEPRAT (1905), QUIN (1968), VELLUTINI (1977), BONIN et al. (1978), BONIN (1980). Representative modal data are

reported in Table 1. The peralkaline granites, despite their extreme variations in texture (hypersolvus or albitic) and dark mineral content (hololeucocratic to melanocratic), have an overall unity through the dominance of alkali feldspars and of sodic mafic minerals. Peralkaline granites differ in relative order of crystallization of felsic and mafic components from metalluminous fayalite granites: fayalite and hedenbergite are early formed, as prismatic euhedral grains, while sodic amphibole and aegirine are often late formed and poikilitic, enclosing crystals of quartz and alkali feldspar. This sequence is the same as in the apaiitic crystallization of the alkaline silica-undersaturated rocks.

TABLE 1
Average modal compositions of Evisa peralkaline granites

	1	2
Quartz	36.2 (1.2)	39.4 (3.4)
Mesoperthite	55.8 (6.2)	
K-phase	27.5 (2.5)	
Na-phase	28.3 (3.7)	
Microcline		24.6 (1.6)
Albite	3.6 (1.8)	27.2 (4.8)
Aegirine	tr.	1.6 (0.6)
Arfvedsonite	2.3 (2.7)	7.0 (3.0)
Accessories	1.9 (3.1)	0.2 (0.8)
Coloration Index	4.2 (5.8)	8.8 (4.4)

1. Arfvedsonite hypersolvus granite, Casterica (6 analyses).
2. Arfvedsonite-aegirine albitic granite, Lindinosa Forest (5 analyses).

All the rocks have suffered a variable degree of late magmatic and post magmatic recrystallization. Therefore, it is difficult to recognize the original magmatic parageneses, obliterated by post-magmatic mineral resettings. Modal data can provide a rough idea of the magmatic light/mafic mineral rations whereas the actual chemical and crystallographical data on single crystals are good indicators of subsolidus reequilibration processes. Alkali feldspars, mafic minerals and Zr-bearing minerals are among the most highly sensitive silicates.

2.1. Alkali feldspars

The Corsican anorogenic granites can be classified into three groups which are defined according to the classic nomenclature of TUTTLE and BOWEN (1958) and as modified by BONIN (1972):

- the hypersolvus granites with separate Na- and K-phases into a single feldspar (mesoperthite);

- the subsolvus granites with discrete Na- and K-phases in two feldspars;

- the transsolvus granites with three feldspars (mesoperthite plus the two subsolvus type feldspars).

The peralkaline complexes display the hypersolvus type (Cauro-Bastelica, Bonifatto, Evisa) and an albitic type (Elvisa albitic granite), where early mesoperthites are replaced by late-stage chessboard albite and interstitial microcline. This type can be ascribed as transsolvus to subsolvus, providing that this terminology is employed for descriptive purposes only without any genetic implication.

The feldspars of the hypersolvus granites are generally light green («malgachitic») in fresh sections, but, after exposure to the air, they turn into grey green to yellow. In fracture zones, they become red. They are composed of crystals showing complex twinning combining Manebach, Baveno and not so commonly Carlsbad laws. Some oligoclase cores have been observed (QUIN, 1968; BONIN, 1980). The most important feature is that albite films and lamellae show evidences of epitaxial and rhythmic syncrystallization with the potassic phase (WILHELM, 1977). The abundance of fluorite inclusions and of cavities filled with quartz and fluorite inside the crystals, the moreless continuous fringe of quartz and albite, associated with fluorite, around the large mesoperthitic crystals are signs of the presence of a discrete fluorine-rich fluid phase.

The origin of coarse albite lamellae is still under debate: WILHELM and BONIN (1980) has disputed the classic view of the exsolution origin from a primary single feldspar, suggesting microcline and albite both grew episodically from a liquid, the two feldspars defining an epitaxial relationship as evidenced

by the recognition of prominent growth faces of the microcline. MARTIN (1982) has proposed that this controversial proposal could be reconciled with an ultimate origin by exsolution: the albite lamellae would be physically rafted and thus become aligned onto growth faces as the microcline undergoes the solution and redeposition steps that accompany Si-Al ordering. Thus, microcline does not crystallize directly from the melt but from a fluid during the complex solution stage.

The feldspars of the albitic granite are generally white in the core of the intrusion and become pink to at the top. The reddening is provoked by haematite, either as discrete pockets or as pervasive minute inclusions. Early mesoperthites, fully comparable to those of hypersolvus granites, are replaced by chessboard albite. These late albite are synchronous with the destabilization of arfvedsonite into aegirine as they form symplectic growths with the quartz that results from this reaction. Interstitial microcline is synchronous with late albite and thus later than the mesoperthites. The replacement is controlled by a fluorine-rich fluid, as exemplified by synchronous crystallization of interstitial quartz, fluorite, albite and microcline. Chemical analyses of the alkali feldspars in the albitic granite show the distinctive differences of the different types of feldspars (Table 2): the mesoperthitic feldspars are significantly higher in FeO (0.50 wt% in the K-phase, 0.90 wt% in the Na-phase) than late-stage albite (0.30-0.10% wt%) and microcline (0.30-0.10 wt%). In the lindinosite, microcline is always low in FeO (less than 0.20 wt%). Coarse albite lamellae (N Ab = 0.98) closely approach the NaAlSi₃O₈ end-member, and the microclitic phase of mesoperthites (N Or = 0.97 - 0.98) the KAlSi₃O₈ end-member, suggesting a very low temperature for equilibration processes. Replacement chessboard albite (N Ab = 0.99-1.00) and late microcline in the albitic granite, as well as microcline in the lindinosite (N Or = 0.98-1.00), are always very pure.

From X-ray data (BONIN, 1982, 1986), it can be concluded that the alkaline feldspars have maximum microcline + low albite assemblages (for analytical results, see BONIN,

TABLE 2
Selected analyses of alkali feldspars

N° anal	1	2	3	4	5	6	7	8
SiO ₂	65.47	68.34	65.30	68.44	69.20	65.15	69.56	64.93
Al ₂ O ₃	18.36	18.67	18.15	19.20	19.34	18.47	19.35	18.46
FeO t	0.50	0.90	0.43	0.25	0.29	0.10	0.23	0.12
CaO	0.00	0.00	0.00	0.07	0.00	0.00	0.02	0.05
Na ₂ O	0.20	11.49	0.30	12.31	11.82	0.12	11.43	0.12
K ₂ O	15.46	0.41	15.29	0.06	0.07	16.08	0.10	15.64
Total	99.99	99.84	99.47	100.33	100.72	99.92	100.69	99.32
Or	98.15	2.30	97.10	0.30	0.40	98.85	0.60	98.60
Ab	1.85	97.60	2.90	99.30	99.60	1.15	99.30	1.20
An	0.00	0.00	0.00	0.40	0.00	0.00	0.10	0.20

Arfvedsonite-aegirine albitic granite, Lindinosa Forest: early mesoperthitic feldspar: 1. K-phase, 2. Na-phase; late albitized feldspar: 3. K-phase relict, 4. albitic core, 5. albitic rim.

Zone of mechanical mixing of albitic granite and lindinosite, Lindinosa Forest: 6. microcline, 7. albite.

Lindinosite, *locus typicus*, Lindinosa Forest: 8. microcline.

1980). The degree of ordering increases from the hypersolvus to the albitic granite. The microcline-dominated lindinosite and the albite-dominated hydraulic breccia are characterized by extreme values of ordering.

2.2. Sodic amphiboles and aegirine

Alkali amphiboles in Corsica have been previously described as riebeckite (LACROIX, 1962; QUIN, 1968) with a strong pleochroism (X = very deep blue, Y = light blue, Z = light yellow). But all alkali amphiboles in alkaline granites actually belong to a continuously varying series ranging from barroisite in fayalite granites (BONIN, 1980) to arfvedsonite, through winchite and richterite (GIRET et al., 1980). Representative analyses are reported in Table 3.

Analytical procedures

Chemical analyses have been performed on an automatized CAMEBAX electron microprobe (15 KV, 12 nA, 5 s counts, natural silicate or oxide minerals as standards), at the Service de Microscopie Analytique, Orsay (BIZOUARD and PICHON). Because Li was not

determined, the 23 oxygen basis of calculation results in an overall overestimation of analyzed cations (Si content may reach unrealistic high values of 8.40). In the cases where calculated Si content is more than 8.00 and Ca + Na + K more than 3.00, this classical basis of calculation was discarded. Thus, assuming that all Si and Al are in the tetrahedral site Z (HAWTHORNE, 1982), structural formulae were computed on the basis of Si + Al = 8.00. By this scheme of calculation, problems arising from the lack of knowledge of the valence state of Fe and of the amounts of non-analyzed elements are avoided.

The chemical evolution during the crystallization of alkali amphiboles is well illustrated by euhedral crystals of the Punta di Mazzoni pegmatite, in the Cauro-Bastelica ring-complex: cores and prismatic rims are true arfvedsonite, whereas pyramidal rims are riebeckite-arfvedsonite. On a Ca + Al_{IV} vs. Si + Na + K diagram (Figure 3a), they follow two successive evolutionary trends:

— a first one, parallel to the richterite-arfvedsonite join, according to the substitution: $\square \text{CaX Fe}_3 + \text{Al} \rightleftharpoons \text{NaA NaX Fe}_2 + \text{Si}$,

TABLE 3
Selected analyses of sodic amphiboles and aegirine

N° anal	1	2	3	4	5	6	7	8	9
SiO ₂	48.77	49.73	50.10	50.69	50.65	51.80	52.90	52.65	51.98
TiO ₂	0.09	0.13	0.07	1.00	0.37	0.96	0.36	0.30	1.29
Al ₂ O ₃	1.44	1.18	1.04	0.66	0.19	0.42	0.49	0.33	0.31
FeO t	35.18	34.20	34.55	33.60	33.80	32.27	37.22	36.27	29.24
MnO	1.01	0.91	0.68	0.47	0.53	0.39	0.24	0.09	0.03
MgO	0.04	0.02	0.03	0.02	0.03	0.00	0.34	0.13	0.03
CaO	0.57	0.53	0.24	0.69	0.14	0.10	0.25	0.09	0.29
Na ₂ O	7.50	7.70	6.87	9.03	7.32	9.36	7.06	6.93	13.58
K ₂ O	0.96	1.12	1.00	1.83	3.83	1.78	0.62	0.39	0.02
Total	95.56	95.52	94.87	97.99	96.85	97.08	99.48	97.18	96.76
Structural formulae calculated on the basis of Si + Al = 8.00 (see text).									
Si	7.73	7.79	7.81	7.88	7.97	7.92	7.91	7.94	7.96
Al	0.27	0.21	0.19	0.12	0.03	0.08	0.09	0.06	0.06
Ti	0.01	0.02	0.01	0.12	0.04	0.11	0.04	0.03	0.15
Fe	4.65	4.46	4.52	4.35	4.43	4.11	4.64	4.56	3.74
Mn	0.14	0.12	0.09	0.06	0.07	0.05	0.03	0.01	0.00
Mg	0.01	0.00	0.01	0.00	0.01	0.00	0.08	0.03	0.00
Ca	0.10	0.09	0.04	0.11	0.02	0.02	0.04	0.02	0.05
Na	2.31	2.34	2.07	2.72	2.23	2.77	2.05	2.02	4.03
K	0.20	0.22	0.19	0.36	0.77	0.35	0.12	0.07	0.00
Y'	4.91	4.60	4.63	4.53	4.55	4.27	4.79	4.63	
A	0.64	0.65	0.30	1.19	1.02	1.14	0.21	0.11	

Y' = Ti + Fe + Mn + Mg (in amphiboles).

A = (Ca + Na + K) - 2.00 (in amphiboles).

Amphiboles from pegmatitic dykes, tunnel through the Punta di Mazzoni, Cauro-Bastelica ring-complex: 1. prismatic core (arfv), 2. prismatic rim (arfv), 3. pyramidal rim (riebe).

Amphiboles in arfvedsonite-aegirine albitic granite, boulder in the Lonca River, Evisa complex: 4. core (arfv) with 1.96 ± 0.08 wt % F and no detected Cl, 5. rim (arfv) with no detected F and 160 ± 60 ppm Cl.

Amphiboles in lindinosite, *locus typicus*, Lindinosa Forest: 6. core (arfv), 7 and 8. pyramidal rims (riebe).

arfv = arfvedsonite, riebe = riebeckite.

Aegirine from arfvedsonite-aegirine albitic granite, boulder in the Lonca River, Evisa complex: 9.

— a second one, parallel to the arfvedsonite-riebeckite join, according to the substitution: $\text{NaAlFe}_2\text{O}_6 \rightleftharpoons \square\text{Fe}_3\text{O}_6$. The two trends can be explained in terms of reduction, then oxidation processes in Na and Fe-enriched hydrothermal environment.

In the albitic granite, arfvedsonite is the common sodic amphibole, with low contents of Al, Ca, high contents of Na, Fe, K, and fairly high contents of minor elements such

as Ti, Mn, Zn. Chemical zonation from core to rim are marked by a decrease in Al, Na, Ti and F and an increase in K and Cl (Figure 3b). Aegirine is commonly associated with arfvedsonite. Analyses of aegirine closely approach the acmite end-member and show a fair enrichment in Ti.

In the lindinosite, arfvedsonite is K-rich (0.35 in the structural formulae), quite similar to arfvedsonite in the albitic granite.

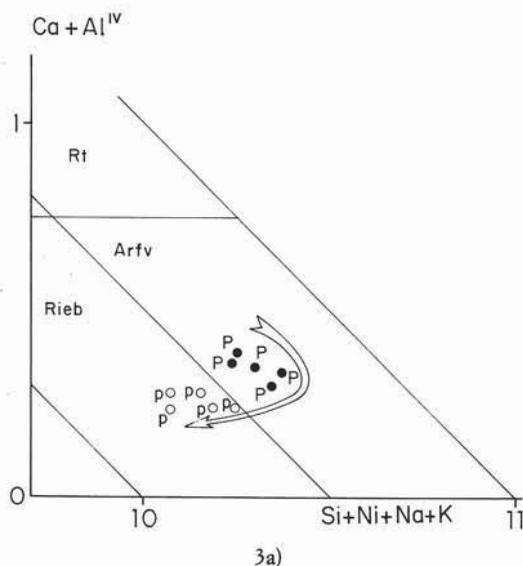
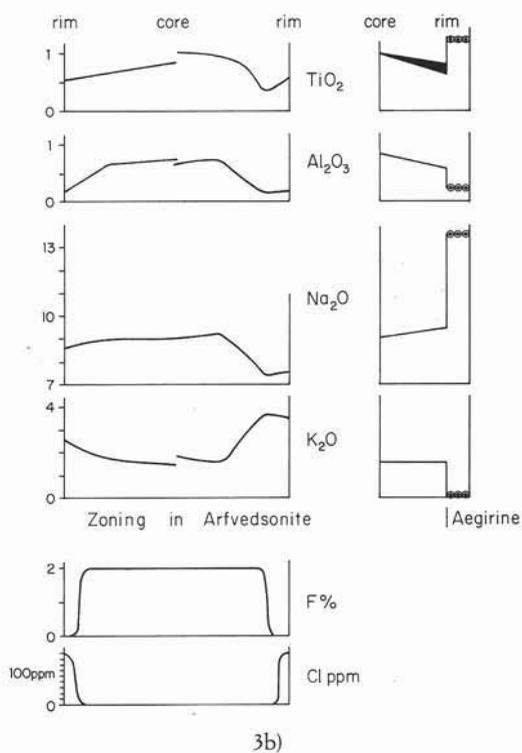


Fig. 3. — Alkali amphiboles in Corsica.

3a. Zoning in pegmatitic amphiboles, Punta di Mazzone Tunnel, Cauro-Bastelica ring-complex, represented in a Ca + Al vs. Si + Na + K plot. Fields of richterite (rt), arfvedsonite (arf) and riebeckite (rieb) are outlined. The large arrow indicates the compositional variations from prismatic (P) to riebeckitic pyramidal zones (p) in the same crystal.

3b. Zoning in rock-forming amphiboles of the albitic granite (sample in the Lonca River as a boulder) represented as a cross-section in a single crystal for TiO₂, Al₂O₃, Na₂O, K₂O, F and Cl. A contact between arfvedsonite and aegirine is also represented.



However, arfvedsonite crystals exhibit rims of riebeckitic composition, marked by a strong depletion in Na (2.02 in structural formulae) and K (0.07).

In all cases, calculations of structural formulae on the basis of Si + Al = 8.00 result in the depletion of Y site (Ti + Fe + Mn + Mg < 5.00), owing to the probable presence of Li in the unit-cell (inferred as 0.10 to 0.75).

As noted previously by BOWDEN and TURNER (1974) for the Nigerian Younger Granites, sodic amphiboles trend with increasing alkali substitution whilst their host granites also show a parallel increase in normative *ac* and *ns*. From chemical analyses in the albitic granite and in the lindinosite, it may be added that after a first and complete Na substitution follows a second and limited K substitution.

2.3. Accessory minerals: zircon and elpidite

Zr-bearing minerals have been proved to be highly sensitive to the alkalinity of the medium in which they crystallize (WATSON, 1979). In the majority of igneous rocks, zircon is the unique Zr mineral. However, in peralkaline rocks, the behaviour of Zr become less orthodox and zircon can be replaced by one or many complex zirconsilicates (VLASOV, 1966).

The metaluminous and peraluminous alkaline granites in Corsica are all rich in zircon (BONIN, 1980; PUPIN, 1980; TESSIER, 1979). The peralkaline hypersolvus granites display also large amounts of early and prismatic zircon. The peralkaline albitic granite of the Evisa complex is characterized by high amounts of Zr (Table 5) and a more complex Zr-bearing mineralogy:

- late octahedral zircon, included by fluorite and quartz (PUPIN, 1976),
- spherulitic zircon in complex aggregates, around arfvedsonite and included by quartz (QUIN, 1968),
- elpidite, yellowish in colour, as radial

TABLE 4
Selected analyses of elpidite

'No. anal'	1	2	3	4	5	6	7	8	9
SiO ₂	59.57	60.27	59.15	60.26	61.53	61.21	60.78	63.24	64.42
ZrO ₂	19.95	19.63	19.91	20.13	20.31	19.86	21.05	21.93	21.83
Al ₂ O ₃	0.17	0.19	0.33	0.30	0.28	0.23	0.49	0.58	0.39
CaO	0.21	0.11	0.27	0.23	0.25	0.25	0.34	0.28	0.26
Na ₂ O	10.01	9.98	9.57	9.52	8.29	7.27	4.94	4.52	3.01
K ₂ O	0.09	0.08	0.09	0.10	0.08	0.22	0.20	0.35	0.11
Total	90.00	90.26	89.32	90.54	90.74	89.04	87.80	90.90	90.02

The analysed sample is a boulder on the Lonca River, near Deux Ponts d'Ota (Bonin, 1980).

Ti, Fe, Mn, Mg, F and Cl below detection limits.

1 to 4: centre of a miarolitic cavity; 5 to 7: rims of the miarolitic cavity; 8 and 9: interstitial crystals. Note the strong compositional variations in Na₂O from interstitial crystals (3.00 to 4.50 wt %) through rims of the miarolitic cavity (4.95 to 8.30 wt %) to the core (9.50 to 10.00 wt %).

needles filling miarolitic cavities of the granite and growing toward the centre. No pseudomorph of earlier mineral has been found, indicating that the crystals have grown freely in the cavities and the interstices of the rock. Elpidite aggregates have never been observed in connection with mafic minerals.

First identified by X-ray diffraction (MARTIN, 1978, personal communication), elpidite was confirmed by chemical analyses by electron microprobe. Major elements, Zr, F and Cl were analysed. No R.E.E. has been detected.

About 1 mm³ of sample was devised for X-ray diffraction techniques, using the Cu K α ray on a Guinier-Hag camera, at McGill University, Montreal. With 60 indexed reflections of a powder-pattern, cell-dimensions have been calculated by the least square method on the McGill computer:

- a = 14.6073 (10) Å
- b = 14.6854 (10) Å
- c = 7.1200 (10) Å

and can be compared favourably with data from elpidite-type (CANNILLO et al., 1973).

Severe analytical constraints (sudden and complete losses of H₂O and alkalis under the electron beam) result in a special procedure, devised by BIZOUARD, at the Service de Microscopie Analytique, Orsay (1982): only 2 s counts using a defocussed beam of 40 nm \times 40 nm. Analytical data and

structural formulae on the basis of 15 oxygen are reported on Table 4. The total of analyses elements approximates 90.00 wt%. As computed structural formulae are correct and as neither F nor Cl was detected, it is inferred that elpidite closely approach the H₂O-bearing end-member.

3. Geochemistry

Representative analyses of peralkaline granites from Evisa complex and of selected representants of the other types (metaluminous and peraluminous) are tabulated in Table 5. Major elements as well as trace elements have been investigated. Previously published isotopic data (BONIN et al., 1978) will be discussed briefly.

3.1. Major element geochemistry

If only the CIPW normative salic minerals are considered, the peralkaline granites define a closely unified group, trending towards the minimum temperature composition at a water vapour pressure of 500 b in the haplogranitic system. The albitic granite, however, does not lie near this minimum, the observed deviation being probably due to the effects of hydrothermal modification. The most significant chemical feature of peralkaline

TABLE 5
Trace element data (in ppm) for alkaline rocks of the Corsican magmatic province

Sample	NC28	224	29	49	61	234	5	42	182	184	176
									4957	4964	
Li			25					25	10	10	
Ba	1938	1530	125	82	44	76	2	4	9	35	10
Rb	44	71	211	246	317	231	159	162	234	197	269
Sr	88	83	25	18	15	16	1.5	0.5	6.6	9.7	4
Pb		15	24	26	30		13	13	53	19	48
Th	2.9	9.5	24	48	35	29	22	17	39	24	32
U	1	2	6.5	9.5	10.5	10	5	4.5	11	6	11
Zr	1378	1420	293	154	82	178	245	207	393	425	322
Nb		29	23	26	13		23	19			54
Y		45	59	48	34		91	73			100
La	29								56	52	
Ce	57	295	96	52	37	38	90	69	90	93	111
Sc	19	16	2	< 1	2	1.6	< 1	< 1			< 1
Cu		2	< 1	19	< 1		< 1	< 1	< 1	< 1	1
Zn	48	127	90	55	22	62	143	117	100	34	152
Ga		19.5	20.5	20	14		22	22.5	29.4	25	31
A.I.	0.90	0.92	0.97	0.89	0.88	0.88	0.97	0.96	1.07	1.01	1.00

Samples:

1) *Tana-Peloso complex*.

NC28: monzonite, Monte Peloso (m)

224: syenite, Arbellara quarry (m)

234: subsolvus biotite granite, Col de Sio (al)

2) *Cauro-Bastelica ring-complex*.

29: hypersolvus biotite granite, Ocana Hydro-electric Works (al)

49: transsolvus biotite granite, La Vanna (al)

61: subsolvus biotite granite, Aragnasco (al)

5: hypersolvus fayalite granite, Tolla Dam (alc)

42: hypersolvus amphibole granite, Punta di Mazzoni (alc)

3) *Evisa complex*.

182: hypersolvus arfvedsonite granite, chilled margin, Aitoni Forest (halc)

184: hypersolvus arfvedsonite granite, chilled margin, U Castagnone (alc)

176: hypersolvus arfvedsonite granite, chilled margin, Aitoni swimming-pool (alc)

175: hypersolvus arfvedsonite granite, road to Bocca a u Saltu (alc)

177: to 181: hypersolvus arfvedsonite granite, Aitoni Forest (halc)

186: arfvedsonite-aegirine albitic granite, chilled margin, road to Bocca a u Saltu (halc)

granites, as previously outlined by JACOBSON et al. (1958) for the Nigerian Younger Granite province, is that slight differences in the atomic proportions of Na, K and Al can produce such striking changes in the mineralogical composition of the suite.

As peralkaline granites are highly evolved

rocks, with a strong depletion in Ca and Mg, the distribution of Na, K, Al and Fe is a good criterium to discriminate between the different behaviours of peraluminous and peralkaline rocks (BONIN, 1982, 1986). JACOBSON et al. (1958) have already pointed out that, despite the alkaline nature of the granites, the Na and

TABLE 5

Trace element data (in ppm) for alkaline rocks of the Corsican magmatic province

Sample	175	177	178	179	180	181	186	187	193	190	191	192
		4958	4959	4960	4962	4963			4965	4966	4967	4968
Li		35	15	40	30	50			135	170	170	210
Ba	16	< 1	6	9	10	12	10	4	6	6	10	2.1
Rb	215	243	206	228	232	257	362	429	423	475	444	539
Sr	3	3	4.2	1.8	3	2.5	3	5.5	4	10	10.5	5
Pb	141	41	26	33	46	32	13	50	72	55	54	82
Th	25	23.3	21	22.3	28	27	51	33.5	35	73	87	48
U	8	5.2	5.5	4.8	9	9.4	23	11	12.6	15.6	15.2	12.4
Zr	476	369	402	368	417	441	920	1020	976	1751	1514	1410
Nb	40				48	44	64	48	63	84	77	
Y	92				91	94	63	76	104	174	190	
La		47	65	72	52	51			51	107	108	88
Ce	124	81	101	96	96	106	95	96	129	194	208	141
Sc	< 1				< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cu	< 1	< 1	< 1	< 1	< 1	3	1	< 1	< 1	< 1	2	< 1
Zn	139	113	138	105	145	138	269	272	296	291	300	273
Ga	26	25	23.2	25.2	27.5	27	36.5	34	35.5	35	35	34.1
A.I.	1.02	1.05	1.06	1.05	1.00	1.03	1.13	1.14	1.10	1.16	1.16	1.19

- 187: arfvedsonite-aegirine albitic granite, core zone, Bocca a u Saltu (halc)
 193: arfvedsonite-aegirine albitic granite, Capu a Cuccula (wrongly labelled as Punta di Cricché, in BONIN et al., 1978) (halc)
 190 to 192: arfvedsonite-aegirine albitic granite, road to Bocca a u Saltu (halc)

m = metaluminous, al = peraluminous, alc = weakly peralkaline, halc = highly peralkaline, some with CIPW normative *ns*.

Numbers refer to major elements analyses published by BONIN et al., (1978) (4957 to 4968, 2nd line) and BONIN (1980) (5 to 234, 1st line). Except for Li (analysed by XRF techniques at Clermont-Ferrand, BONIN et al., 1978), all trace element data are new analyses:

— for NC28 (unpublished major element analysis) and 234, trace elements analysed by INAA at Laboratoire Pierre-Süe, C.E.N. Saclay (France) (Ba, Rb, Sr, Th, U, Zr, La, Ce, Sc, Zn),

— for other samples, XRF analyses at Memorial University, St. John's (Newfoundland) (Prof. D.F. Strong, personal communication) (Ba, Rb, Sr, Pb, Th, U, Zr, La, Ce, Cu, Zn, Ga) and Geological Survey of Canada (WHALEN et al., 1987a and 1987b) (Ba, Rb, Sr, Pb, Th, U, Zr, Nb, Y, Ce, Sc, Cu, Zn, Ga). V, Cr, Ni are below or near detection limits (1 ppm) (WHALEN et al., 1987b).

K values are not particularly high. The peralkaline character is due to a deficiency of Al relative to Na + K and JACOBSON et al. (1958) have therefore favoured the term «hypoaluminous» for peralkaline granites.

The deficiency of Al is well depicted in a DI (differentiation index) versus AI (agpaitic

inde Na + K/Al) diagram (figure 4): the higher the agpaitic index, the lower the differentiation index. This paradoxical feature can be explained by the scheme of calculation of the differentiation index (sum of CIPW normative quartz + orthoclase + albite, for granitic rocks). If Al is deficient relatively to

Na and K, then aegirine $\text{NaFeSi}_2\text{O}_6$ is calculated at the place of albite $\text{NaAlSi}_3\text{O}_8$. As aegirine is not considered in the definition of the differentiation index, peralkaline granites would yield a somewhat «less differentiated» character, which is an artefact. Extreme cases would be that of the strongly peralkaline differentiates: lindinosite (AI up to 2.5, DI less than 48) and rockallite (DI as low as 7.9, extreme AI of 13.7, and 87% of normative aegirine).

BARKER (1978) drew the attention of the same features illustrated on an alkalis-iron-magnesium diagram for agpaitic rocks from Ilimaussaq (Greenland) and BONIN (1980) has shown for granitic rocks from Corsica that peralkaline granites follow a trend (from alkalis to iron apex) which is different from the normal alkaline series (trending towards alkalis apex) and that the strongly peralkaline differentiates (lindinosite and rockallite) deviate significantly towards the Fe + Mn pole.

No systematic attempt to determine anionic composition of peralkaline granites has been performed. Previously published data (BONIN et al., 1978) have substantiated that F is an important constituent of the bulk rocks, whilst Cl is always below detection limit. The mafic and accessory parageneses comprise minerals that contain in their structural cells either H_2O or OH^- , F^- , Cl^- : arfvedsonites, fluorite and elpidite. The distribution of the anions in the albitic granite has been estimated by microprobe analyses: F and Cl have been directly analysed, OH^- and H_2O are calculated assuming a perfect stoichiometry.

Arfvedsonite display a strong zonation from core to rim: F is present in the cores (2 wt%), whereas some Cl (about 200 ppm) can be detected at the rims. Elpidite is always F-free and a little Cl (less than 30 ppm) has been detected only at the margins of the miarolitic cavities. The crystallization sequence: F-rich arfvedsonite core - OH, Cl-rich arfvedsonite rim - H_2O -rich elpidite, is therefore a good indicator of fluid phase compositional variations during the cooling of the pluton. Note that all the considered minerals are sodic and that their crystallographic structures are

similar (silica tetrahedral chains, HAWTHORNE, 1982; CANNILLO et al., 1973).

3.2. Trace-element geochemistry

It has long been recognized that certain trace elements such as Zr are selectively concentrated in peralkaline rocks whilst other elements like Li and Rb exhibit a dual role concentrating both in peralkaline and in peraluminous granites (BOWDEN and TURNER, 1974). In addition, significant levels of rare earths (La and Ce) and the highly charged cations such as Pb, Nb, Y, U and Th are also found. In contrast, there is a marked depletion in Sr, Ba, V, Sc and Cu. The highly differentiated character is marked by the extreme depletion in compatible elements, such as Ni, Cr.

Some trace element data on Evisa complex have been previously published (BONIN and CARRON, 1977; BONIN et al., 1978; WHALEN et al., 1987a, 1987b). A representative set of data is given in Table 5.

Granites can be classified by statistical analyses of large numbers of chemical data of granites from well defined tectonic setting (PEARCE et al., 1984). This approach leads to discrimination diagrams which can be used in identifying the tectonic settings of other granite suites. PEARCE et al. (1984) have indicated that Nb, Y, Ta, Tb and Rb trace element data can provide good criteria to discriminate between syn-collision (SYNCOLG), volcanic-arc (VAG), ocean ridge (ORG) and within -plate (WPG) type granites. With a set of 148 analyses, including 15 from Evisa complex, WHALEN et al. (1987) have shown that the alkaline granites are well defined by Ga/Al ratios, Y, Ce, Na and Zr contents.

Plots of data collected for Corsican peralkaline and peraluminous granites on Nb - Y and Rb - Y + Nb diagrams (figure 5) show that most samples lie in the field of WPG-type of PEARCE et al. (1984), near the average of A-type granites computed by WHALEN et al. (1987), with the unique exception of the highly evolved biotite subsolvus granite of Cauro-Bastelica ring-complex. This result can be compared

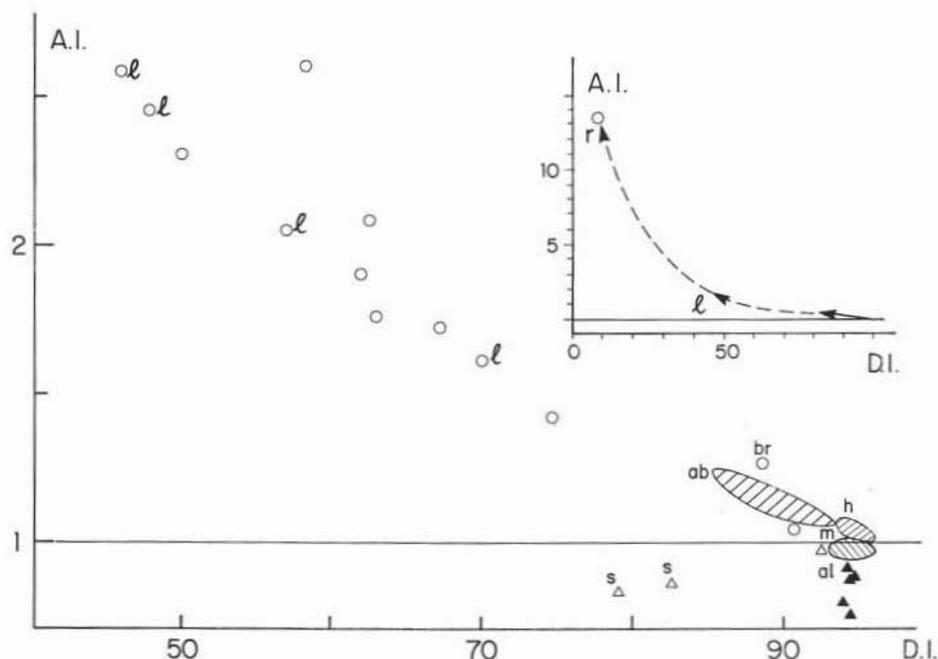


Fig. 4. — Peralkaline rocks of Corsica plotted in a A.I. ($\text{Na} + \text{K}/\text{Al}$) vs. D.I. (CIPW normative $\text{qz} + \text{or} + \text{ab}$) diagram. Symbols: s = monzonite - syenite, al = peraluminous suite, m = metaluminous (fayalite- and amphibole-bearing) granites, h = peralkaline hypersolvus granite, ab = peralkaline albitic granite, br = hydraulic breccia, l = lindinosite, r = rockallite, other open circles: peralkaline dykes.

favourably with geological evidences and there is no obvious reason to cast doubt on the anorogenic environment for this type of granites, unless it is supposed that a post-orogenic distensive regime is not truly «anorogenic» (for reviews of this problem, see BOWDEN, 1974; DI GIROLAMO, 1984; BONIN, 1987; BONIN et al., 1987).

The evolution of the alkaline suites can be illustrated by numerous variation diagrams. Variation diagrams with LIL elements are currently used in order to describe the modes of differentiation. The LIL elements versus Th is the most popular one (TREUIL, 1973).

A diagram using Ga and Th (figure 6) illustrates the contrasting roles of Th: metaluminous, peraluminous and peralkaline hypersolvus granites follow a linear trend marked by a constant Ga/Th of 1.0. Careful examination of the plot indicate a weak if any differentiation from metaluminous to peraluminous liquids and a significant fractionation process from metaluminous to peralkaline liquids.

Peraluminous transsolvus and subsolvus granites as well as the peralkaline albitic granite exhibit strong variations of Th contents with slow variations of Ga contents. In the Evisa complex, Th variations are not erratic. In the hypersolvus granites, the Ga/Th ratio remains near the 1.0 value. In the albitic granite, the Ga amount is near the 35 ppm value, but Th contents, if relatively low (35 ppm) in the core and near the top of the cupola, reach maximum values (87 ppm) in the intermediate zones where aplito-pegmatitic sheets are widespread.

This would suggest a dual role of Th: first incompatible and concentrated into the residual liquids during the differentiation at the magma chamber level, then concentrated into the fluid phase at the subvolcanic level during the cooling of the epizonal cupolas.

Other trace elements display the same behaviours as Th: Li, Rb, Nb, Y, La, Ce, Zn and Sr show extreme variations in the peralkaline albitic granite, with strong enrichments in the middle zones of the cupola,

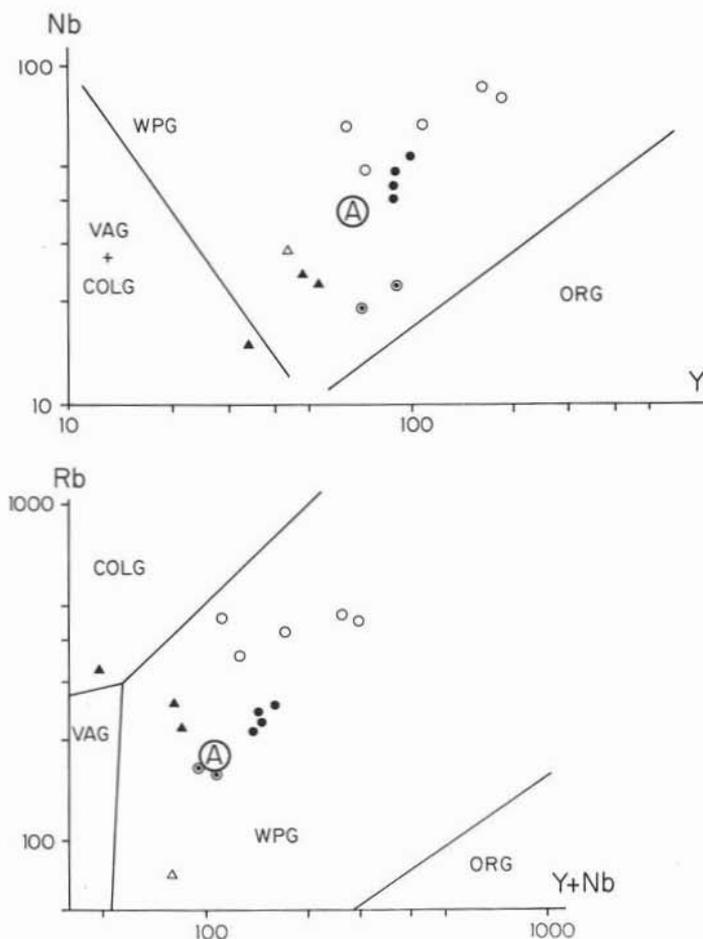


Fig. 5. — Trace element discrimination diagrams of PEARCE et al. (1984). Two of them are represented: Nb vs. Y and Rb vs Nb + Y. Circled A: average of A-type granites, as calculated by WHALEN et al. (1987a). Open triangle: monzonite - syenite. Full triangle: peraluminous suite (hypersolvus, transsolvus and subsolvus granites). Peralkaline suite: double circle: metaluminous granites (fayalite and amphibole hypersolvus granites), full circle: hypersolvus granite, open circle: albitic granite.

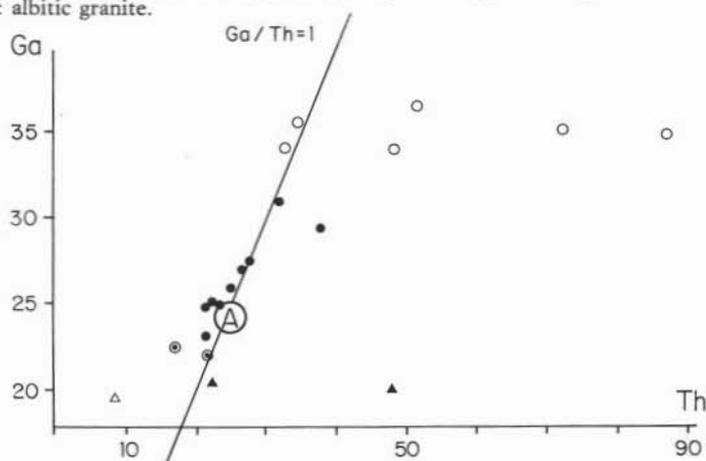


Fig. 6. — Ga vs. Th plot. Same symbols as in Figure 5. The straight line is for a constant Ga/Th ratio of 1.00.

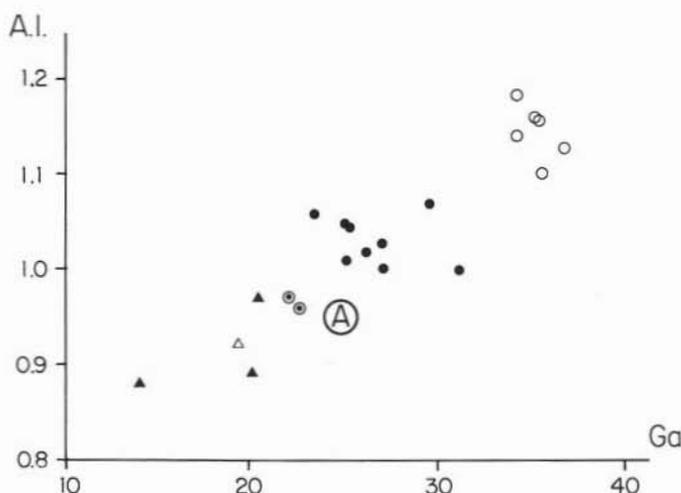


Fig. 7. — A.I. vs. Ga plot. Same symbols as in Figure 5.

where fluorite-rich fluids were particularly at work during the consolidation and cooling of the pluton. Log-log plots of these elements cannot therefore be used as indicators of fractional crystallization processes. This type of evolution controlled by hydrothermal fluids has already been stressed for fenitization processes (e.g. MARTIN *et al.*, 1977, for the fenites of the Borralan complex, N. Scotland), suggesting that peralkaline fluids can provide similar types of alteration and trace elements enrichments in peralkaline granite environments as well as in silica-undersaturated environments (MARTIN, 1977).

WHALEN *et al.* (1987a) have proposed that the Ga/Al ratio can provide the best way to discriminate alkaline granites. If their set of data is carefully considered, it appears that this ratio increases either by increasing of Ga contents, or depletion of Al or both. What happens in peralkaline granites is that Ga increases from 24 to 37 ppm and Al is strongly depleted (normative and modal aegirine), whereas in peraluminous granites Ga is constantly lower (16-22 ppm) and Al is strongly enriched (normative corundum). This relationship, already illustrated by a Ga/Al - appaiitic index diagram by WHALEN *et al.* (1987), can be evidenced in a Ga-AI diagram (figure 7): not only Ga/Al ratios but also Ga contents are strongly linked with the appaiitic

index. Thus, Ga is better an appaiitic index than a differentiation index.

3.4. Zr behaviour and zirconosilicates

Zr is a trace element highly sensitive to the alkaline environment. Many authors (SIEDNER, 1965; BOWDEN, 1966; QUIN, 1968) have pointed out that in peralkaline granites there are less zircon crystals than expected from Zr contents of bulk rocks, implying that zircon can be dissolved into peralkaline melts. At Evisa, the zircon-free samples of the albitic granite can yield high Zr concentrations up to 1700 ppm. BOWDEN and TURNER (1974) have proposed that the Zr concentration may be used as an index of peralkalinity, as exemplified by Zr - Ga and Zr - AI plots (figures 8a and 8b).

The solubility of zircon into granitic melts has been tested experimentally by WATSON (1979): in metaluminous and peraluminous liquids, zircon saturation is attained for less than 100 ppm Zr. In peralkaline liquids, zircon solubility increases as a linear function of appaiitic index. Small amounts of CaO and Fe_2O_3 in the liquid would lower the zircon solubility by 25%. According to WATSON (1979), zircon solubility in a silicate melt is governed by the formation of soluble M4 Zr (SiO_4)₂ complexes («Watson's molecule»),

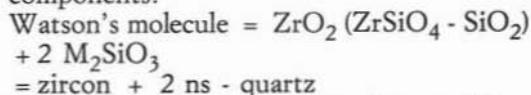
where M is an alkalic element. Thus, in highly peralkaline liquids, Zr has an incompatible behaviour and can crystallize only as late and complex zirconosilicates. Chemical and modal data on Evisa massif confirm this scheme: early zircon (0.36 vol%) crystallized in the slightly peralkaline hypersolvus granites (AI less than 1.1, Zr = 400 ppm), whilst, in the albitic granite (AI higher than 1.1, 950 ppm < Zr < 1800 ppm), zircon is rare or lacking, always late, and the main Zr-bearing minerals is elpidite (up to 1 vol%) filling miarolitic cavities.

If Watson's hypothesis is valid, elpidite formation is governed by the reaction:
 $\text{Na}_4 \text{Zr} (\text{SiO}_4)_2 + 4 \text{SiO}_2 + 4 \text{H}_2\text{O} = \text{Na}_2 \text{Zr} \text{Si}_6\text{O}_{15} \cdot 3 \text{H}_2\text{O} + 2 \text{NaOH}$, which supposes a high silica activity in the presence of water and a remobilization of alkalis in an aqueous fluid phase characterized by low pH.

Elpidite-bearing rocks are therefore characterized by Na excess, relatively to Al and Fe^{3+} , which is marked in CIPW normative assemblage by the presence in little quantities of sodium disilicate *ns* Na_2SiO_3 . The appearance, during the calculation of the

CIPW norm, of *ns* is a good indicator of the presence of late zirconosilicates.

Experimental works by WATSON (1979), performed for silica - (over) saturated liquids (from 5 to 45 wt% of normative quartz), have given zircon and, in some cases, inclusions of baddeleyite ZrO_2 . The «Watson's molecule» can be subdivided into CIPW normative components:



indicating a silica-undersaturated composition.

The most frequent zirconosilicates in peralkaline environments are (SØRENSEN, 1974):

- zircon Zr SiO_4
- elpidite $\text{Na}_2 \text{Zr Si}_6\text{O}_{15} \cdot 3\text{H}_2\text{O}$
- vlasovite $\text{Na}_2 \text{Zr Si}_4\text{O}_{11}$
- catapleite $\text{Na}_2 \text{Zr Si}_3\text{O}_9 \cdot 2\text{H}_2\text{O}$
- keldyshite $\text{Na}_2 \text{Zr Si}_2\text{O}_7$
- eudialyte - eucolite $\text{Na}_4\text{Ca}_2 \text{Zr Si}_6\text{O}_{17} (\text{OH})_2$
- lavenite $\text{Na Ca}_2 \text{Zr Si}_2\text{O}_8 \text{F}$

These minerals can be plotted in a Na_2SiO_3 - ZrO_2 - SiO_2 diagram (figure 9).

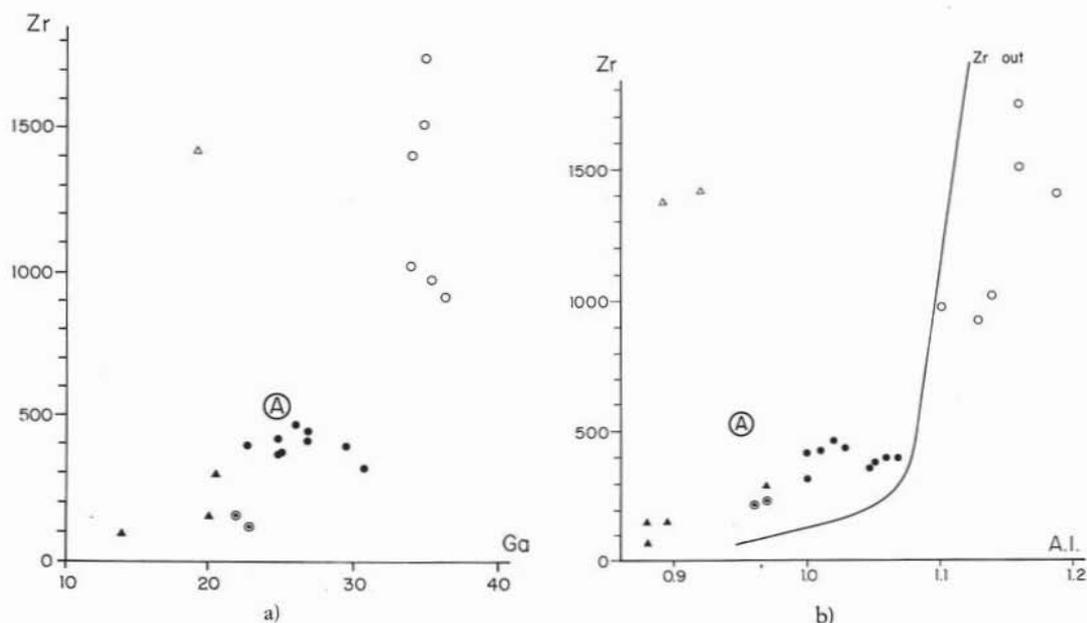


Fig. 8. — Zr behaviour in peralkaline granites. Same symbols as in Figure 5. 8a) Zr vs. Ga plot. 8b) Zr vs. A.I. plot. The zircon-out curve is outlined.

With the exceptions of lavenite and of «Watson's molecule», all the minerals lie inside the ns - zircon - quartz triangle. Some of them are anhydrous: zircon, vlasovite and keldyshite, the others are H₂O - or OH - bearing: elpidite, catapleite and eudialyte. All of them could theoretically crystallize in a silica-(over)saturated liquid.

Elpidite has been recorded so far:

— in apaiitic rocks: in the *locus typicus* of Narsarsuk, Greenland (LINDSTRÖM, 1894), in the Kola Peninsula (VLASOV, 1966) and at Mont Saint-Hilaire (CHAO, 1967).

— in peralkaline granites: at Rockall Island (SABINE, 1960), at Tarbagatai, Kazakhstan (VLASOV, 1966), at Tuva, E. Siberia (KAPUSTIN, 1967), at Ilimaussaq, Greenland (SØRENSEN, 1970), at Gjerdinher, Oslo rift (RAADE, 1972), at Ulan Erge, Mongolia (PAVLENKO, 1974), and at Shira, Nigeria (BENNETT, 1981). Other occurrences have been described in the Quebec province (CURRIE and ZALESKI, 1985).

With the exception of the exceptional formation of Tarbagatai, where elpidite occurs as huge crystals (up to 30 cm long) in quartz-

microcline-aegirine pegmatites, elpidite is present as filling miarolitic cavities in a moreless albitic arfvedsonite-aegirine granite, like at Evisa.

The relative stability of elpidite, an H₂O-bearing mineral, and of vlasovite, an anhydrous one, has been studied experimentally by CURRIE and ZALESKI (1985). These authors have found that, at low pressures (1-2 Kb), elpidite is stable for temperatures lower than, respectively, 595°C and 644°C. The reaction curve is unaffected by the presence of excess Na in the vapour phase. But the substitution of 1 N HCl for water decreases the stability field of elpidite by about 20°C, which is a further confirmation of the low pH necessitated by the precipitation of elpidite, as proposed earlier. Elpidite is unstable relative to keldyshite, another anhydrous mineral, in highly chlorinated assemblage. According to CURRIE and ZALESKI (1985), elpidite forms from high-temperature hydrothermal fluids, whereas vlasovite forms as a magmatic accessory or by metamorphism of elpidite.

Accordingly, as elpidite occurs in the Evisa

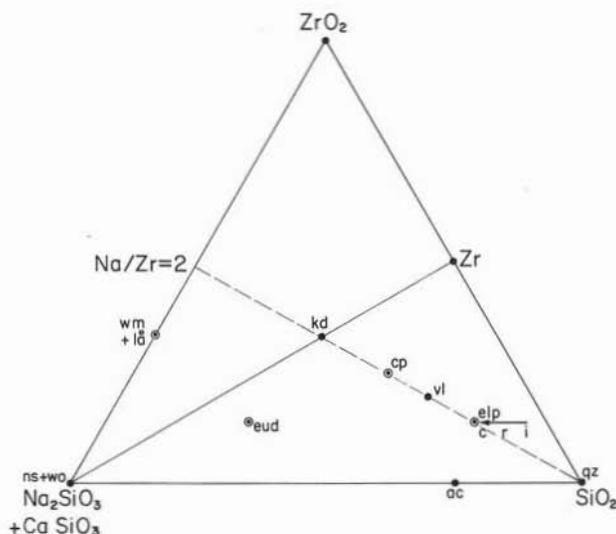


Fig. 9. — The system Na-Ca-Zr-Si-O-H projected onto the Na₂SiO₃ + CaSiO₃ - ZrO₂ - SiO₂ triangle. The natural zirconosilicates and associated minerals are represented: full circles for anhydrous minerals (qz = quartz, zr = zircon, bd = baddeleyite, vl = vlasovite, kd = keldyshite, ac = aegirine, ns = sodium disilicate, wo = wollastonite), double circles for hydrous minerals (el = elpidite, cp = catapleite, eud = eudialyte, lã = lavenite, wm = Watson's molecule). The arrow indicates the compositional variations of albitic granite elpidite, from interstitial crystals (i) through rims (r) of the miarolitic cavity to the core (c) of the miarolitic cavity.

albitic peralkaline granite as radial needles growing freely and fillingmiarolitic cavities, it is likely that elpidite does occur when an aqueous phase separated from a completely crystallized peralkaline granitic medium. The place of elpidite in the crystallization sequence after arfvedsonite and fluorite implies that the aqueous phase can be present in important amounts only after the overall precipitation of fluorine-rich minerals.

3.4. Isotopic studies

Ten samples of Evisa peralkaline granites provided Rb-Sr whole-rock isochrons for each rock-type (BONIN et al., 1978). The ages of the two granites: hypersolvus and albitic granites, are indistinguishable at 247 ± 7 m.yr., corresponding to the Permian - Triassic boundary.

The computed $^{87}\text{Sr}/^{86}\text{Sr}$ initial isotopic ratios are very low: 0.7034 ± 0.0011 , lying in the mantle range of values. This result precludes any important crustal contamination, as Sr isotopic ratios for the Corsican upper crust at 245 m.yr. are estimated at 0.715 ± 0.005 (BONIN et al., 1978).

Field, mineralogical, and trace element evidences substantiate the important role of deuteric changes, promoted by peralkaline fluid phases. The constantly low value of the Sr initial isotopic ratio for both rock-types indicate:

- the granitic melts have a mantle origin or a source low in radiogenic Sr,
- the fluid phases that have interacted with the crystallized albitic granite have an identical origin,
- they were active at the same time as the emplacement of the complex (within the 7 m.yr. time interval) and have provoked autometamorphic reactions.

Such isotopic data for a single complex provide strong constraints on the source and the evolution of peralkaline rocks. Consistently higher Sr initial ratios have been discovered elsewhere (e.g. in Nigeria, VAN BREEMEN et al., 1975). However, high Sr initial ratios cannot provide evidences of an upper crustal source for the melt, as claimed

by several authors (BOWDEN, 1970; COLLINS et al., 1982), but would rather imply an important crustal component in the percolating hydrothermal fluids (BLAXLAND, 1976; BONIN et al., 1979; BONIN, 1982, 1986).

The Evisa complex, among the peralkaline granite group, provides a rare example of an evolving closed system where evidences of a crustal component are notably lacking.

4. Concluding remarks

Peralkaline granites provide field, textural, mineralogical and chemical evidences for a high fluid activity:

A. The various structural and tectural features inside a single intrusion (e.g. Bonifatto hypersolvus granite cupola, Evisa albitic granite cupola) can be explained in terms of magmatic fluid behaviour. Initial crystallization at low pressures (less than 1 kb and most probably about 500 b) of a granitic magma close to ternary minimum temperature composition result in a quartz + alkali feldspar anhydrous assemblage. During progressive crystallization, the residual liquid becomes saturated in volatiles.

As BURNHAM (1979) has noted, the volume per unit mass of crystals + discrete fluid phase is greater than the volume of the same unit of volatile-saturated silicate melt. The change in volume resulting from the crystallization process in the volatile-saturated magma cannot be accommodated by progressive plastic deformation and expansion, owing to the effects of the low confining lithostatic pressure and the brittle character of the wall rock. Consequently the internal pressure in the already crystallized carapace increases as cooling and crystallization proceed. BURNHAM has calculated that internal pressures of the maximum order of 5 kb could theoretically be generated within pockets of magma undergoing pegmatitic crystallization. At depths corresponding to pressures of less than 1 kb, the rocks of the brittle envelope would fail long before pressures of this magnitude were achieved.

Eventual entrapment of volatile-rich pockets, beneath the top of the intrusions, is responsible of isolated pegmatitic bodies

containing giant euhedral crystals of quartz (80 cm) and fayalite (40 cm) in the hypersolvus granite, of arfvedsonite (25 cm) and aegirine (2 cm) in the albitic granite.

Within the apical zone, the system would fail by fracturing when the internal overpressure reached a value equal to the minimum principal stress plus the tensile strength of the rocks forming the brittle envelope. This condition is critical for the enlargement of the effective volume of the system by tensile hydraulic fracturing. The principal mechanical effect of increasing internal overpressure would be the creation of sets of subvertical tensile fractures with an orientation normal to the trajectory of the minimum principal stress in the brittle envelope in the apical region of the cupola.

When the internal pressure is sufficiently high, failure occurs and the propagation of hydraulic fractures takes place. Then, a portion of the fluids in the apical zones escapes and the internal pressure is temporarily relieved. The progressive build up of the internal pressure continues as a consequence of the crystallization of the magma and critical conditions are once again achieved so that renewed fracturing can take place.

Hydraulic breccia emplacement evidently marked the climax of the sequence of events in which fluorine-rich fluids escaped from the apical zone of the granitic cupolas. They reflect the escape of magmatic gas through the congealed parts of the intrusion with increasingly explosive effects.

Such mechanical processes have been described in other volatile-saturated environments, whatever the compositions of the fluid phases. Pertinent examples are abundant in copper-bearing breccia pipes (SAWKINS, 1969; KNUTSON et al., 1979) where boron is strongly enriched in the residual phase (tourmaline is consequently the main phase of the matrix of hydraulic breccias) (ALLMAN-WARD et al., 1982).

B. The composition of the volatiles can be estimated by the nature of the minerals precipitating directly from the fluids or formed by reaction with previously crystallized magmatic assemblages. The fluids

are dominantly sodic and fluorine-rich at near-solidus temperatures in a reducing environment: thus, arfvedsonite, fluorite and chessboard albite crystallize.

During the cooling steps, entrapment of fluorine by amphibole and fluorite results in a depletion in F in the remaining fluids. Arfvedsonite becomes unstable and is replaced into aegirine, according to the reaction: arfvedsonite + O₂ = aegirine + iron oxides + quartz + vapour (BONIN, 1982, 1986) implying a more oxidizing medium. This reaction is buffered in the granitic cupolas as closed systems, but can be enhanced in narrow dykes, which constitute typical open systems.

These first stages are characterized by a continuum between magmatic crystallization of the early anhydrous assemblage and hydrothermal precipitation of poikilitic, interstitial and replacement minerals.

When the volatiles make up a discrete fluid phase, emplacement of aplitic - pegmatitic sheets and pockets, hydraulic fracturing and brecciation take place with the precipitation of:

- sodic minerals: aegirine (+ arfvedsonite) + albite (rockallite), in associated dyke swarms,

- sodic minerals: arfvedsonite + albite, in the apical part of the cupola,

- more potassic minerals: K-rich arfvedsonite + microcline (lindinosite), in the internal parts.

Late stage fluids are moreless devoid of fluorine and would precipitate hydrated minerals (elpidite in the miarolitic cavities) and/or highly oxidized minerals (haematite filling fissures, forming red pockets or staining alkali feldspars, oxychlorites replacing arfvedsonite and aegirine), causing the typical pervasive reddening of the tops of alkaline granitic cupolas.

At a very late stage, quartz pockets and veinlets near the top of the intrusion indicate highly silicic fluids. No sign of argillization processes has been observed so far.

C. Fluids released from the apical part of the cupola and from peralkaline dyke swarms can react with wall rocks, especially when they yield strong chemical contrasts. Actually, reaction zones are very narrow,

confined to the vicinity of peralkaline dyke swarms (BONIN and PLATEVOET, 1988): metaluminous and peraluminous wall rocks are converted into discrete rims of aegirine + arfvedsonite-bearing rocks whereas biotite is replaced by silicic mica. Accordingly, a chemical and mineralogical zonation is obvious in few centimeters width.

D. Geochemical and isotopic data provide evidences of a mantle origin for the F-rich fluids, which carry some trace-elements such as Sr, Th, U, LREE, a.s.o. There is now a controversy for the interpretation of granite types and sources (BOWDEN et al., 1984). Whereas a mantle origin is currently inferred from geological and geochemical evidences for peralkaline volcanic formations (BOWDEN, 1974), WHALEN et al. (1987) have proposed that A-type granites result mainly from partial melting of F⁻ enriched dry, granulitic residue remaining in the lower crust after extraction of an orogenic granite. The origin of fluorine is also a matter of debate: following a suggestion of BAILEY (1970), HARRIS and MARRINER (1980) have invoked high fluxes of mantle-derived halogen-rich volatiles providing the high concentration of alkalis and high field strength elements in anorogenic granites.

Our isotopic data from Evisa complex, substantiating a mantle origin both for granitic liquids and associated fluids, are clearly in favour of the second hypothesis. Reviews of Sr-isotopic data on anorogenic granites have been performed elsewhere (BLAXLAND et al., 1978; BONIN, 1981, 1986): the major result is that a crustal isotopic signature is recorded only in mineralized alkaline rocks, peralkaline (granites and agpaites) as well as peraluminous (granites and miaskites). This would suggest that such mineralizing fluids are of multiple origins, F-rich volatiles from the mantle, other Cl-rich hydrated volatiles from the crust: pertinent examples have been described in Nigeria (VAN BREEMEN et al., 1975; BONIN et al., 1979; KINNAIRD, 1985).

In Corsica, peralkaline granites are relatively rare, compared with metaluminous and peraluminous alkaline granites and they exhibit some contrasting characteristics

(BONIN, 1982, 1986). Chemical and mineralogical data document different behaviours of major and trace elements. Moreover, peraluminous subsolvus granites yield significantly higher Sr-isotopic initial values (from 0.707 to 0.722, BONIN et al., 1987), suggesting a more important role of a crustal component. What crustal component? Calc-alkaline wall rocks display high Sr-values at the time of emplacement of alkaline ring-complexes and calculations indicate no more than 15% of contamination by wall-rock (BONIN et al., 1987). Another candidate is hypersolvus granites, that have been emplaced just before the subsolvus granites: a late, high level uptake of water by hot crystalline granite, characterized by high Rb/Sr ratios, would induce local remelting of the early granite (MARTIN and BONIN, 1976) and higher Sr-isotopic initial values; this process is likely to take place at the magma chamber level, as no sign of such anatexis has been observed in situ. A combination of both explanations — contamination by leaching of wall rocks and early granite remelting — necessitates large percolations of water, mobilized in a convective geothermal field (NORTON, 1978).

The most puzzling feature of Evisa peralkaline complex is, therefore, the lack of evidence of crustal-derived fluids. Elsewhere in Corsica, mantle-derived metaluminous alkaline magmas have interacted, at the magma chamber level, with water and have produced peraluminous granitic magmas yielding varying crustal isotopic signatures. In the case of Evisa, no interaction has occurred and peralkaline granitic magmas were produced, without any significant crustal contribution. The reason why is not yet clear. Current hypotheses favour differentiation processes, involving plagioclase and amphibole fractionation (JACOBSON et al., 1958; BONIN and GIRET, 1985) and/or contrasting sources (BARKER et al., 1975; WHALEN et al., 1987a).

Geochronological data obtained so far for the whole Corsican province substantiate a long-duration peraluminous granitic magmatism (from 270 to 200 m.a.) whereas peralkaline granites have been emplaced in a very short period (250 to 230 m.a.). The Corsican province has been proved to be a

part of a larger western Mediterranean province (BONIN et al., 1987), characterized by the extreme abundance of subsolvus biotite granites.

It is therefore likely that locally the emplacement of exceptional peralkaline granites was promoted, whereas typical subsolvus biotite granites are the rule elsewhere. This event was characterized by the inhibition of any crustal contribution and the subsequent behaviour of the magmatic system as a closed system.

Acknowledgements. — I wish to thank warmly the organizers of the S.I.M.P. Symposium on «Granites and their surroundings» (Prof. A. Boriani and Dr. V. Caironi, Milano) to have invited me to present my data on Corsican peralkaline granites. I have also benefitted from fruitful discussions and comments in the field with many colleagues: Profs. S. Ayrton (Lausanne), P. Bowden (St. Andrews), J.P. Carron (Brest), J. Didier (Clermont-Ferrand), A. Jauzein (Paris), J. Lameyre (Paris), R.F. Martin (Montréal), H. Sorensen (Copenhagen), A. Streckeisen (Bern), Drs. R. Dubois (Orsay), J.D. Giraud (Nice), C. Grelou-Orsini (Paris), A.T. Johansen (Copenhagen), the late H. Loup (Paris), B. Platevoet (Orsay), J.P. Pupin (Nice), S. Wilhelm (Paris), and many others. Among them, I include undergraduate students from Orsay and Paris, as well as persons attending field trips organized by the European Network on «Granites» and other organizations (1974, 1976, 1984, 1985, 1986). I was helped for mapping the Evisa area by Mrs. F. Bonin (Le Pecq), Dr. B. Platevoet and MM. P. Przysiecki, J.Y. Vétill (Orsay). Some samples and indications of areas of special interest were provided by Prof. J.P. Quin (Toulon). Mineralogical data have been collected with the aid of my friends Prof. R.F. Martin (Montréal) for X-rays and Dr. S. Wilhelm (Paris) for optics on alkali feldspars, Drs. H. Bizouard and R. Pichon (Orsay) for microprobe analyses, especially of elpidite. Geochemical trace elements analyses on my samples have been kindly provided by Prof. D.F. Strong (St. John's) and Dr. J.B. Whalen (Geol. Surv. Canada) and isotopic analyses by Dr. Y. Viallette (Clermont-Ferrand).

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