RENDICONTI DELLA SOCIETÀ ITALIANA DI MINERALOGIA E PETROLOGIA, 1988, Vol. 43-2, pp. 215-236

Granite settings and tectonics

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ABSTRACT. — Among the different geodynamic settings of granitic rocks attention is given to local situations both in the orogenic belts and in within-plate provinces of oceanic and continental domains.

The compressive regime associated with the late stages of the evolution of back-arcs may produce conditions of crustal melting without continental collision and favour mixing and mingling with mantle magmas.

In the Hercynian belt, as in the High Himalaya, post collisional thrusts have generated inverted metamorphic series. Leucogranitic melts, subsequent to this structure, rising as diapirs have opened tectonic windows in overlying nappes where inverted metamorphic grades display Buchan type series being overthrust by Barrovian.

Local tectonic conditions are also related in time and space to the activity of within-plate provinces. Their localisation is related to major crustal boundaries and faults and the distribution of their activity in time suggest an intra-lithospheric control.

Key words: Geodynamic settings, granite types, peraluminous granitoids, back-arcs, hypercollisions, within-plate provinces, shear systems.

RÉSUMÉ. — L'attention est portée plus particulièrement sur les conditions locales de mise en place des roches granitiques dans les différentes situations géodynamiques, que ce soit dans les orogènes ou dans les provinces intraplaques océaniques et continentales.

Le système compressif qui se manifeste dans les derniers stades de l'évolution des domaines arrière-arc peut réaliser, sans qu'une collision soit nécessaire, les conditions d'une fusion crustale et favoriser les hybridations et les mélanges avec les magmas mantelliques.

Dans la chaîne hercynienne, les chevauchements succédant à la collision ont produit des inversions de degrés métamorphiques. Les magmas leucogranitiques, consécutifs à cette dynamique, ont formé des diapirs dont la mise en place a ouvert des fenêtres tectoniques dans les nappes sus-jacentes. Des séries barroviennes se trouvent ainsi superposées à des séries de type Buchan apparaissant dans les fenêtres.

L'activité magmatique des provinces intraplaques peut également être mise en relation avec des conditions tectoniques locales. La situation de ces provinces qui paraît être conditionnée par les grandes frontières crustales et des accidents majeurs suggère un contrôle lithosphérique de leur position et de leur activité.

Mots clés: Situations géodynamiques, types de granitoïdes, arrière-arc et hypercollisions, provinces intraplaques et grands accidents.

When dealing with granites and their surroundings one should turn to the work of structural geologists in order to improve our knowledge of general and local conditions of magma generation, evolution and emplacement which is the task of the petrologists. Attention is particulary focused on plate boundaries which schematically are of two main types, convergent and divergent, to which one should add the transform. The first corresponds to a wide variety of active margins, it includes collisions, and most granitic rocks belong to these settings. The second is represented in mid-oceanic ridges and in continental rifts. The transform boundaries occur both in oceanic and continental areas such as the within-plate situation which, although typically anorogenic, must also be considered in a tectonic framework.

I - Granites in active margins. The question of peraluminous granodiorites within the orogenic series

The relationships between magmatism and orogenesis have been recognized for a long time. Streckeisen in his «Plutonismus und Orogenese» (1970) recalls the magmatic series defined by BURRI and NIGGLI (1946) and the classic phases of STILLE (1939), *ophiolites, sialic plutonism, andesite volcanism, and late basaltic activity*. Magmatism, and more particularly that with granitic components, is also an important parameter when defining types of orogens. ZWART (1967) distinguished *Alpinotypes* where granites are scarce and *Hercynotypes*, where they are abundant. On the basis of his experience in granitoids from different orogenic areas, PITCHER (1979) recognized four types: the *Pacific types* corresponding to Island Arcs with small «M type» plutons including gabbros and plagiogranites; the *Andinotype* in active continental margins with granodiorites, tonalites, associated gabbros and Cu-Mo porphyries; the *Hercynotypes* produced by continental collisions with peraluminous granites and Sn-W mineralizations; the *Caledonian type* in post-closure situations with magnetite-bearing granites allied with appinites and generally barren in mineral deposits. Petrological and geochemical characteristics have been also related to tectonic situations by LAMEYRE and BOWDEN (1982), PEARCE et al. (1984), BATCHELOR and BOWDEN (1985).

Returning to active margins two main modes of subduction have been distinguished by UYEDA (1982): *Chilean and Mariana*, with their proper tectonic and magmatic consequences. In most models importance is given to the relationship between the nature of magmatism and the distance to the trench (KUNO, 1968). This «magmatism at a plate edge» (PITCHER et al., 1985), described in a number of syntheses (GILL, 1981; BURKE et al., 1981; MCBIRNEY and WHITE, 1982) is

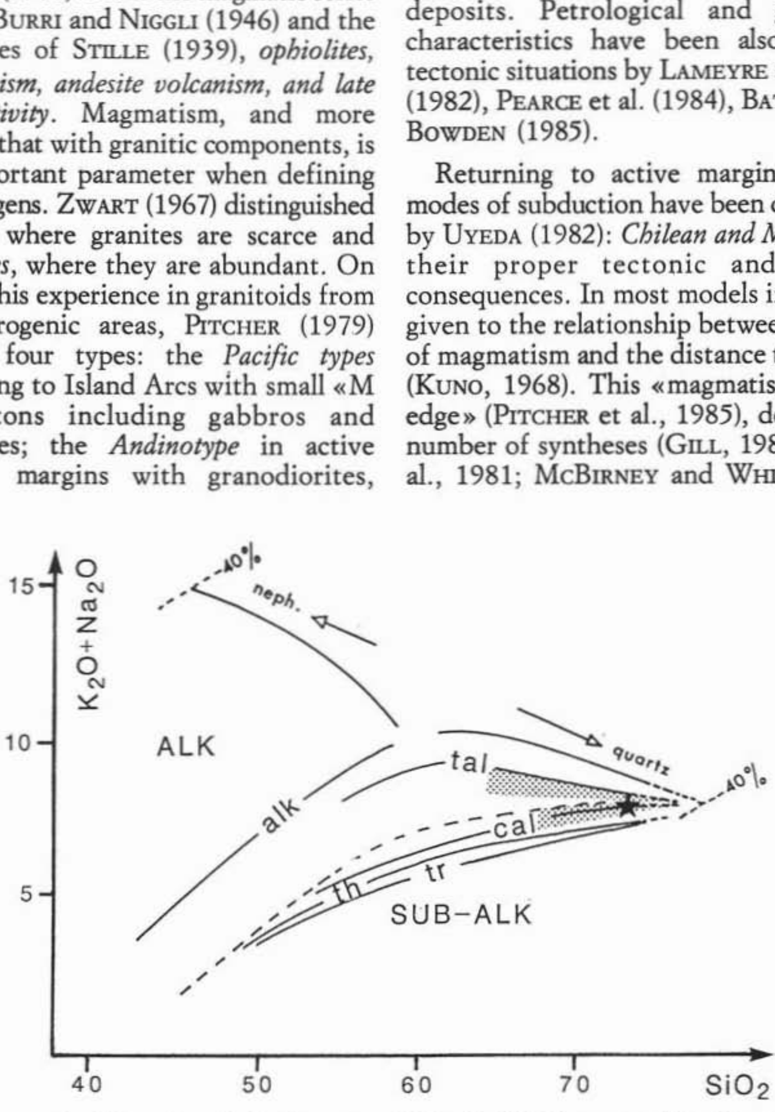

Fig. 1. — Main trends of plutonic series in the systems $K_2O + Na_2O/SiO_2$; **tr**: trondhjemitic; **th**: tholeiitic; **cal**: granodioritic or medium calc-alkaline; **tal**: monzonitic (or transalkaline)*; **alk**: alkaline with its two trends silica-undersaturated and silica-oversaturated; **black star**: average composition of Hercynian leucogranites from Massif Central; **ALK** and **SUBALK** indicate the alkaline and subalkaline fields separated by a broken line; **shaded areas**: distribution of the two main granitic series of the Hercynian belt in France. Between 60 and 70% SiO_2, they are easily distinguished by values of $K_2O + Na_2O$ over or under 8 (after LAMEYRE et al., 1982).

* This term has been proposed for orogenic series, silica oversaturated, situated within the alkaline field (LAMEYRE, 1987).

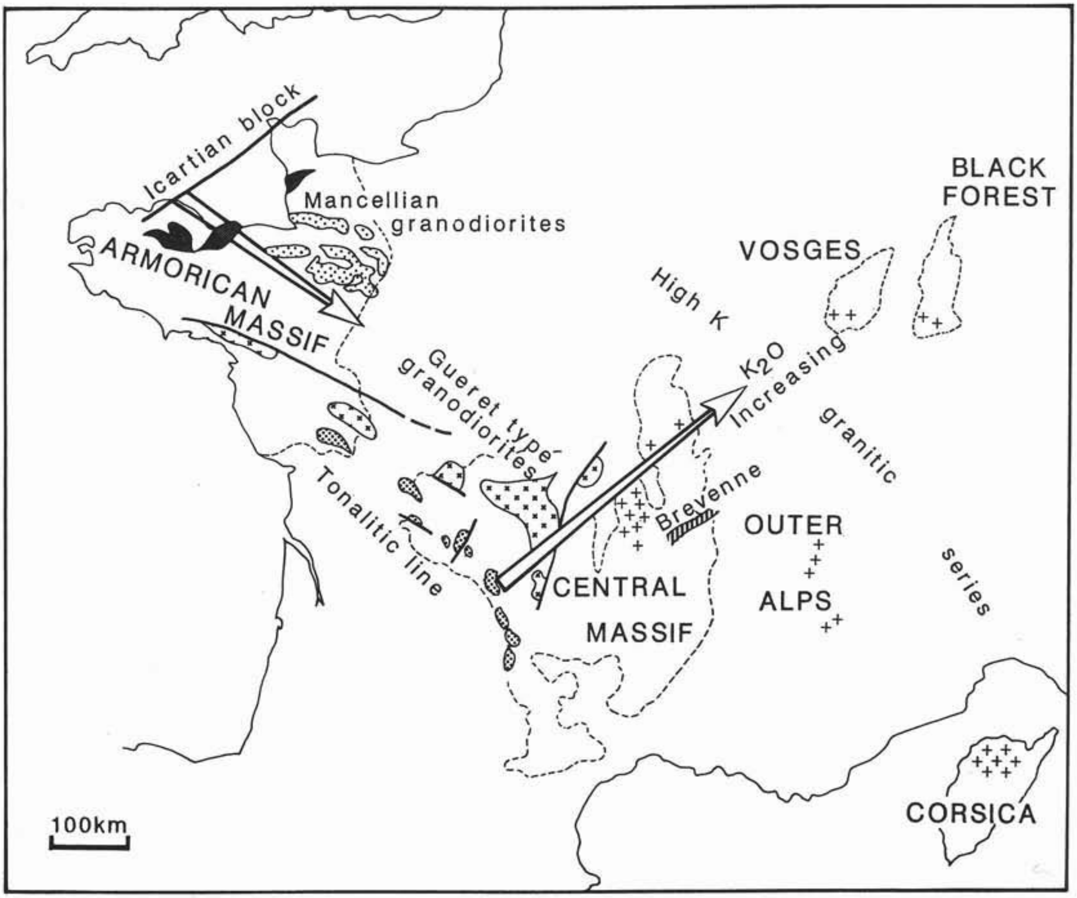

Fig. 2. — Distribution of Late Precambrian and Devono-Dinantian granitoids in France. In the Armorican massif, late Proterozoic calc-alkaline intrusions of St-Brieux - Coutance are followed in space and time by Mancellian peraluminous granodiorites. The south of Brittany and other Palaeozoic areas display a similar organization, with the Devonian tonalitic line of Limousin, then the cordierite-bearing granodiorites forming the Gueret laccolith, and finally the early Carboniferous High-K monzogranites. It is important to note that these formations are largely allochtonous.

characterized by an evolution from arc-tholeiitic types, to typical andesitic and granodioritic calc-alkaline suites, then to high K calc-alkaline and shoshonitic series. This conclusion has been particularly well documented in the Pacific areas of North and South America by petrological (BATEMAN et al., 1963; PITCHER et al., 1985) and also metallogenetic studies on Cu-Mo porphyries (SILLITOE, 1981; WESTRA and KEITH, 1981).

In the different generations of granitoids emplaced in France during the Palaeozoic, the variation of K_2O content is also a prominent feature. Using the $K_2O + Na_2O/SiO_2$ diagram as a discriminant (Fig. 1), ORSINI (1976) and BARRIÈRE (1977) have stressed the differences between two main trends, calc-alkaline and high K. The granitic rocks emplaced during the late-Devonian and early Carboniferous, change in K_2O content from the Devonian tonalites of the Limousine line (DIDIER and LAMEYRE, 1971; PEIFFER, 1986) to the high-K lavas and plutonites of Dinantian age, emplaced in the eastern part of the country (Fig. 2).

However an important difference from the magmatic sequences of western America occurs in this segment of the Variscan orogen.

Cordierite-bearing granodiorites and granites, known as «Gueret type», are interposed between tonalites and high K series rocks. The high values of 87/86 Sr_i .7098 ± .0004, indicate an important contribution of crustal components (BERTHIER, DUTHOU and ROQUES, 1979). The strong excess in alumina is chemically expressed by the A/B diagram of DEBON and LE FORT (1983) (Fig. 3). The compositions grade from a high Ca, Fe, Mg tonalite in the lower part, to a monzogranite at the top (Fig. 4), allowing a rather precise stratigraphy (VAUCHELLE and LAMEYRE, 1983). They form a large laccolith extending more than 5000 km^2, with a moderate thickness established by geological and geophysical methods and recently confirmed by drilling which found a sole of cordierite gneisses with a tectonic contact. Moreover tardi-magmatic deformation, whose intensity increases towards the roof, indicates syntectonic emplacement into the pile of nappes forming the western part of the French Massif Central.

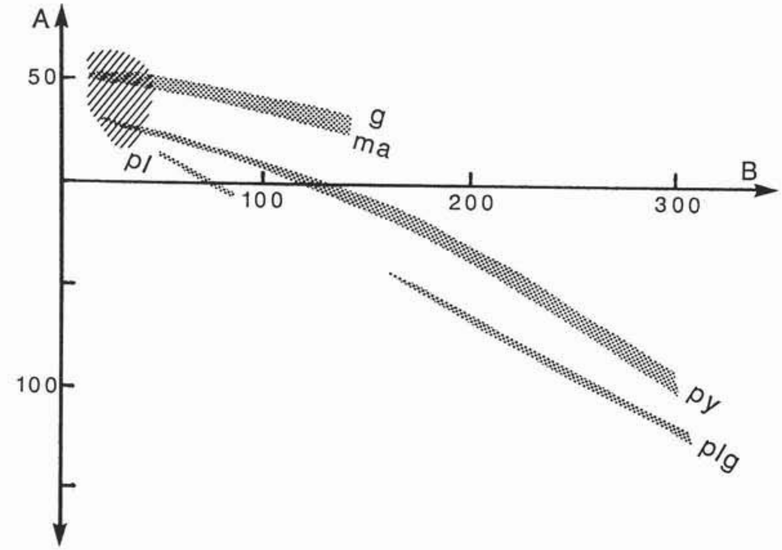

Fig. 3. — The A/B system proposed by DEBON and LE FORT. **A**: Al-(Na + K + 2 Ca); **B**: (Fe + Mg + Mn + Ti) Peraluminous granodiorites of Gueret (g) and Margeride (ma) are clearly distinguished from the calc-alkaline series from the Pyrénées (py) and the monzonitic (transalkaline) series of Ploumanach (pl) with its bimodal distribution between basic (plg) and acid (pl) terms. **Oblique lines** indicate the field of Hercynian leucogranites.

The geological history of France provides other examples of this group of granitoids. Late Proterozoic tonalites, granodiorites and andesites form an alignement between the bay of St-Brieux in Brittany and Coutance in Normandy, south-east of the edge of the 2 b.y. Icartian block. Their typical calc-alkaline characteristics have been related to a subduction process (AUVRAY and MAILLET, 1977) leading to the closure of the Celtic Ocean (COGNÉ and WRIGHT, 1980). They are followed towards the south-east by the Cambrian cordierite-bearing granodiorites and granites of the large Mancellian batholith which belong to the peraluminous family. (Fig. 2). Precise geochemical data indicate a mixed origin with a mantellic component, prominent in the basic enclaves, and a large contribution of crustal melts which are likely to have been produced from metágreywackes (GEORGET, 1986).

In the southern part of the Massif Central the Namuro-Westphalian intrusion of Margeride is also very similar to that of Gueret with cordierite-bearing types, large extension, limited thickness, vertical change in composition, strong foliation (COUTURIÉ, 1977). One should add some orbicular facies

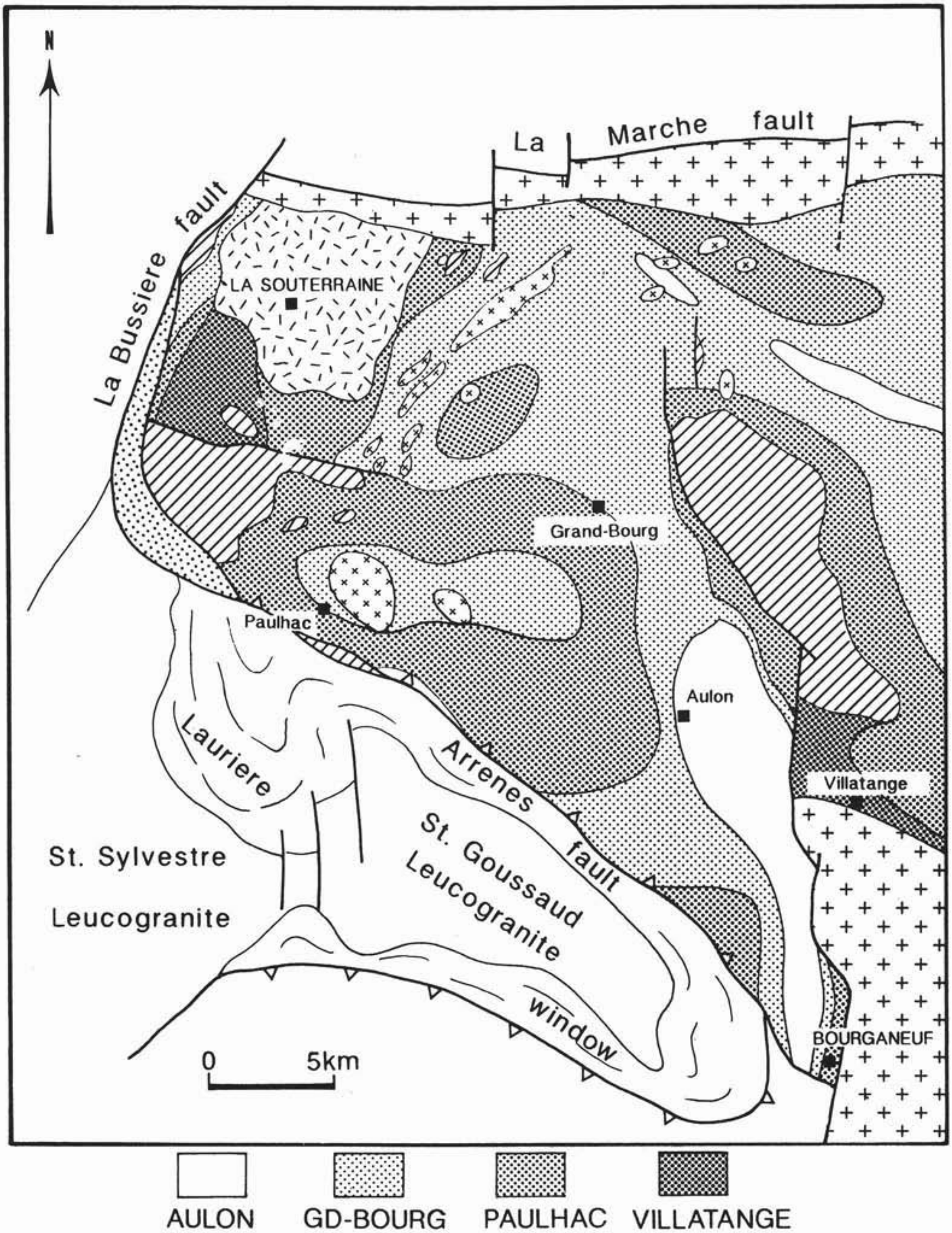

Fig. 4. — An example of peraluminous complex: distribution of compositions in the western part of the Gueret massif. **Heavy grey**: Villatange tonalitic facies SiO_2 < 64%, Al_2O_3 > 17%, Fe_2O_3 tot + MgO + MnO = 8%; CaO > 3%; $Na_2O + K_2O$ < 7%. **Medium grey**: granodioritic facies: SiO_2: 67,5-64%, Al_2O_3: 17-16%; Fe_2O_3 + MnO + MgO: 8-5%; CaO: 3-2%; $Na_2O + K_2O$: 7,5-7%. **Light grey**: Grandbourg monzogranitic facies. SiO_2: 70-67,5%; Al_2O_3: 16-15%; Fe_2O_3 + MgO + MnO: 5-3,5%; CaO 1-2%; $Na_2O + K_20$: 7,5-8%. **White**: Aulon granitic facies. SiO_2 > 70%; Al_2O_3 < 15%, Fe_2O_3 + MgO + MnO < 3,5%, CaO <1%, $Na_2O + K_2O$ > 8%. **Oblique lines**: Cordierite gneisses forming the sole of the laccolith **Horizontal lines**: defomed granites from Montjourde. **Stippled area**: nearcontemporaneous intrusion of La Souterraine. **Crosses**: Late Carboniferous leucogranites (after VAUCHELLE, 1988).

with restite-like cores. They also contain scattered enclaves or swarms of basic inclusions which belong to the high-K series, also rich in Mg, known in France as vaugnerites (Sabatier, 1980). Another example is provided by the Velay dome, a large intrusion of late Carboniferous, cordierite-bearing granodiorites, emplaced in an intermediate position between the late Carboniferous to Permian calc-alkaline volcanic and plutonic units, largely developed in Sardinia, Corsica, Spain and Southern France, and the K-Mg rich intrusions scattered in the northern part of the country.

Among other structural studies on modern active margins, Bally and Snelson (1980), Uyeda (1982), Aubouin (1984), have highlighted the back-arc compressive systems acting in the Andean type. The history of this margin is well documented in Peru by Bourgois and Janjou (1981) who stressed a major change from a *back-arc extensional* regime prevailing during the Mesozoic, with the development of Andean and Subandean

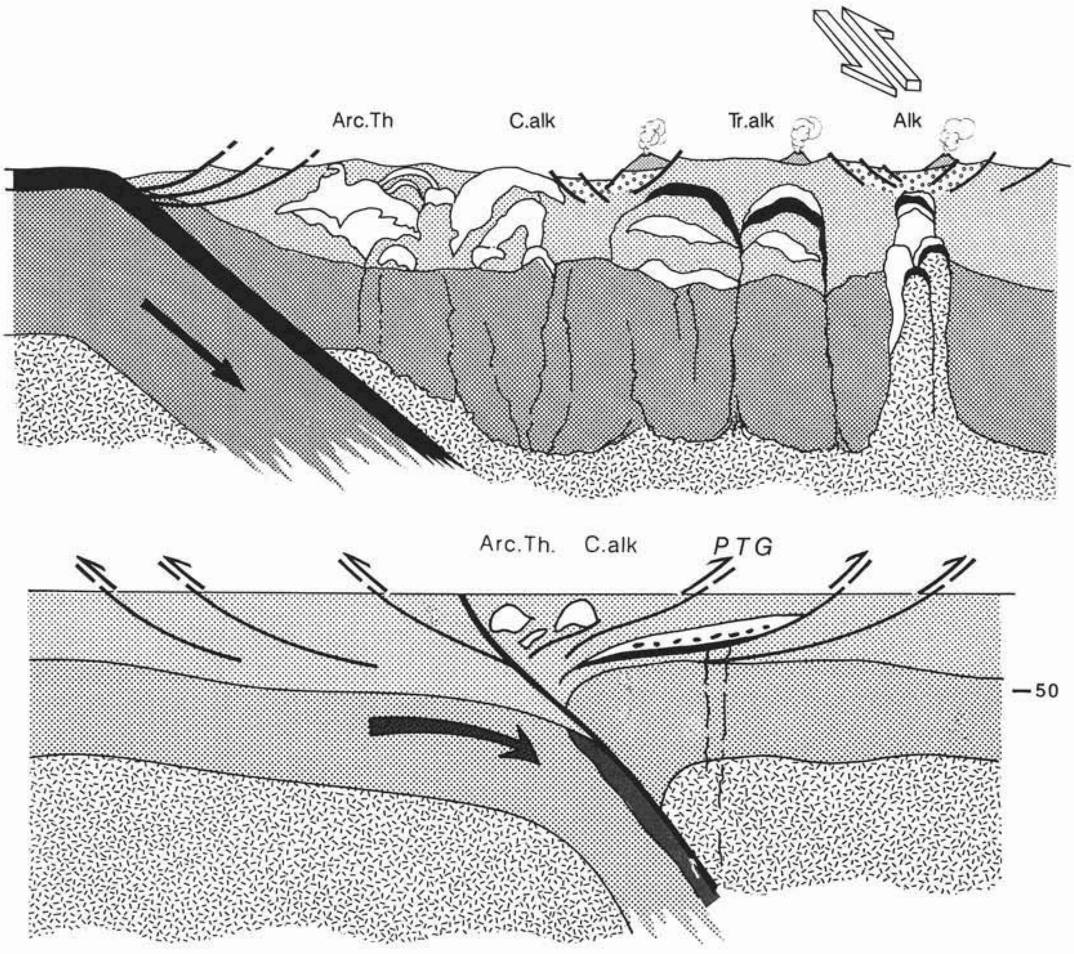

Fig. 5. — Evolution of an active margin
5a: back-arc extensive regime with development of sedimentary basins. A complete sequence of arc-tholeiite, calc-alkaline, transalkaline, and alkaline series is supposed to have been emplaced. **In black**: active magma chambers; **in white**: intrusions. Arrows record the importance of shear systems.
5b: back-arc compressive regime with continental subduction. Peraluminous granitoids may be generated and mingled or mixed with mantle derived magmas which belong to the calc-alkaline or transalkaline series according to their situation; dots represent basic enclaves in peraluminous tonalites and granodiorites (PTG).

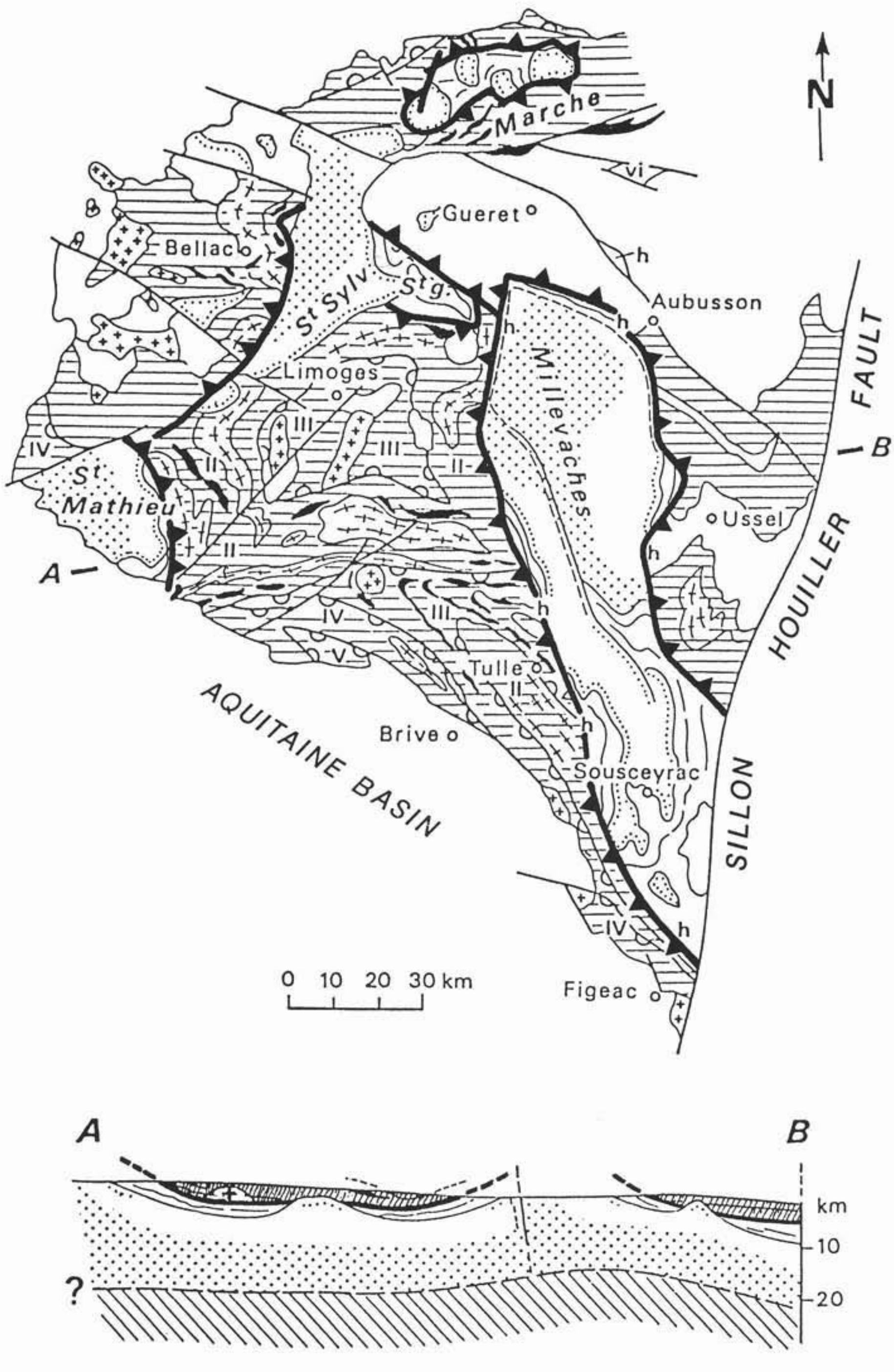

Fig. 6. — Diapiric windows in the western part of the French Massif Central opened in overlying allochtonous units by leucogranitic domes. Their discontinuous belt of metapelites is indicated by structural lines. Leucogranites contacts are either magmatic (**little dots**) or tectonic (**interrupted lines**). Migmatitic formations appearing in the core are indicated by heavy dots. Roman numerals indicate different tectonic units (after LAMEYRE, (1982-1984); FLOCH, 1983). The question mark on the section locates a possible equivalent of the MCT, beneath the migmatitic roots of leucogranites.

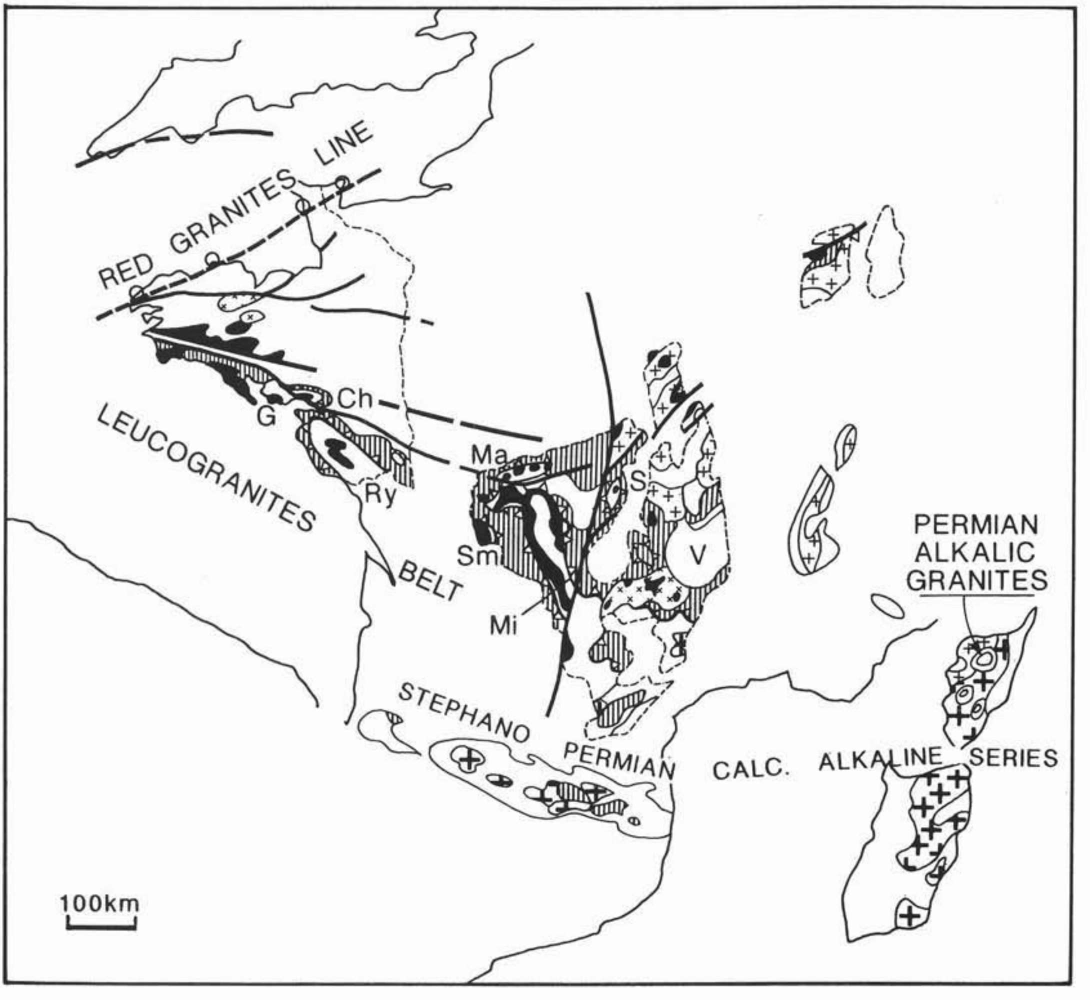

Fig. 7. — The diapiric windows around leucogranitic domes (**in black**) in the Massif Central (**Ma**: Marche, **SM**: Saint Mathieu; **Mi**: Millevaches, **S**: Sioule) and in south Brittany and Vendée (**G**: Guerande, **Ch**: Champtoceaux, **Ry**: Lo Roche sur Yon). **Shaded areas** correspond to metamorphic units including orthogneisses with eclogites and granulites as relicts. Visean high-K granitoïds are indicated with **small crosses** and the cordierite-bearing granitoïds of Huelgoat (in Brittany) and Margeride with **small diagonal crosses**. Late Carboniferous and Permian granites are very varied with the calc-alkaline series in the southern part (**heavy crosses**), the high-K series of the Red granite line (**RGL**) in Brittany (**circles**), the large dome of Velay (**V**) and the alkalic granites of the Permian ring complexes in Corsica.

basins filled by marine volcano-detritic sediments, to the present *back-arc compressional* regime acting since the Oligocene, with the large thrust-faults of Maranon and Eastern Cordillera and the presently active foot-hills. They described a continental subduction towards the west working at the same time as the oceanic subduction. Peraluminous granites of Cordillera Blanca (ATHERTON and SANDERSON, 1987) and andalusite-bearing rhyolites known as macusanites (PICHAVANT et al., 1987) may have been generated in this environment, *without collision*. In Northern America, the western Cordillera is more complex and considered as resulting from the accretion of allochtonous terranes (UYEDA, 1982). The back-arc thrust belt is also characterized by peraluminous granites and related Sn and W deposits, which form an eastern belt, parallel

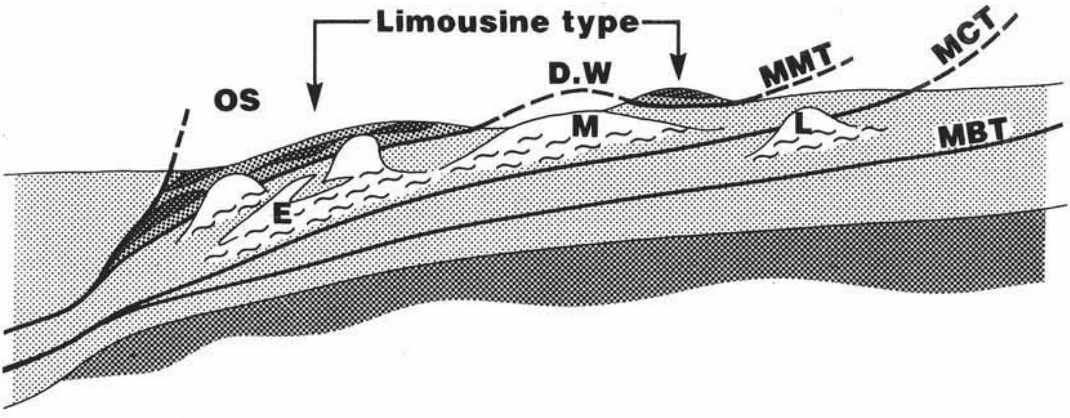

Fig. 8. — The Limousine type structure modelled by reference to the Himalayan structures. **Os**: ophiolitic suture (not yet recognized in the Massif Central); **MMT**: Main Mantle Thrust; **MCT**: Main Central Thrust; **MBT**: Main Boundary Thrust; **D W**: diapiric window; **E**: early (335 m.a.) generation of leucogranites; **M**: main (325-315 m.a.) generation; **L**: late generation (300 m.a.).

at 200-300 km, to that of the Cu-Mo porphyries aligned along the coast (SILLITOE, 1981). The classic relationship between peraluminous granites generated from a crustal melt and collision processes may be invoked.

Such a complex evolution may have occurred in the case of the Gueret type, generated during the late Devonian - early Carboniferous «Acadian events» of the geological history of France. Volcanic series with tholeiitic affinities associated with typical plagiogranites are known in Devono - Dinantian basins of la Brevenne. They suggest back-arc openings (PIBOULE et al., 1982; SIDER and OHNENSTETTER, 1986) between a south-western belt with early calc-alkaline tonalites followed by peraluminous Gueret-type granodiorites, and the north-eastern area with late, high-K intrusions (Fig. 2).

Whether or not back-arc openings with a tholeiitic floor occur, the back-arc compressional regime that follows offers conditions for crustal thickening. The metasediments filling the back-arc basins, subducted during the compressive phase, constitute a possible source of the crustal contribution together with water for peraluminous melts, the heat and mantle component being provided by calc-alkaline, high-K calc-alkaline, or shoshonitic magmas, according to the situation. The classic model of active margins, illustrating the evolution of magmas from arc-tholeiites to alkaline series, through all the spectrum of more or less K-rich orogenic magmas, should be complemented by the interposition of these tectonic opportunities for mingling or mixing with crustal magmas (Fig. 5).

II - The leucogranites of collisional ranges; their generation and tectonic role in the Hercynian French segment

The generation of granites related to the overthrusting of the Higher Himalaya after the Indo-Eurasian collision, has been described by LE FORT (1975) and well documented in petrological and geochemical studies (VIDAL et al., 1982, LE FORT, 1986). After the collisional interpretation of Sudetides by LAURENT (1972) and the classic comparison of the Himalayan and Variscan fold belts as products of continental collisions by DEWEY and BURKE (1973), many articles have developed the tectonic and magmatic consequences of the Palaeozoic collision between Laurasia and Gondwana in the West-European segment of the Hercynian belt (RIDING, 1974; MATTAUER & ETCHECOPAR, 1976; COGNÉ et al., 1980; BARD et al., 1980; LAMEYRE, 1982, 1984; ZIEGLER, 1984; MATTE, 1986, etc.).

One of the most striking features, stressed by ZWART (1967), PITCHER (1979), and others, is the presence of light-coloured, peraluminous, white and pink granites, often muscovite-bearing, sometimes with cordierite and garnet. They lend themselves to hewing and have been used as ashlars in stately old cities such as Quimper in Brittany, Limoges in Limousin, Santiago de Compostella in Galicia, Viana do Castello in the Minho, even Boston with the Quincy Market, giving in some measure a common appearence to these places despite the difference in age and style. Their composition is always close to the experimental minima. In consideration of their leucocratic characteristics and the presence of two feldspars, K-feldspars and oligoclase (or albite), I have called them leucogranites (LAMEYRE, 1966) after the definition by JOHANNSEN (1938) slightly enlarged to alaskites and leucogranodiorites. Moreover their connection with migmatites and the restitic nature of the enclaves, generally metapelitic, are indications of a crustal origin (LAMEYRE, 1966; DIDIER et al., 1982). In the French segment of the Hercynian chain, the main period of leucogranite production is Namuro-Westphalian with a shift of ages towards the south (BERNARD-GRIFFITHS et al., 1985). This period is notably younger than the collision with an Iberian microcontinent, which took place after the lower Visean according to ZIEGLER (1984), still earlier, during the Devonian, according to MATTE (1986). They correspond more precisely, as in the Himalayas, to *hypercollision processes* after the collision itself.

In the northern part of Massif Central and southern Brittany, such granites generally intrude metapelites overlain by metamorphic series in which orthogneisses, serpentinites, amphibolites and leptynites are particularly abundant. Relicts of eclogites, garnet peridotites and sapphirine granulites, are also known (FORESTIER and LASNIER, 1963; KORNPROBST et al., 1980). Thus the metapelites are of lower grade than overlying series. This inversion has been largely discussed during the seventies and different answers proposed, on the basis of tectonic mechanisms or puzzling intersections of foliations and isograds (GROLIER, 1971). More recently they have been interpreted as the result of the downward shift of isograds (KORNPROBST et al., 1980) by intralithospheric overthrustings or lithospheric slab subduction according to classic models of plate tectonics.

However the main difference between metapelites and the overlying series is less the intensity of metamorphism than the gradient. Metapelites associated with leucogranites evolve from sericitoschists (quartz-muscovite-albite-chlorite +/—andalusite +/—staurolite) to kinzigites (quartz - andesine - orthoclase - garnet - sillimanite - cordierite - biotite) associated. Garnet-biotite-cordierite equilibria indicate pressure lower than 4 Kb and temperatures higher than 700°C (VAUCHELLE, 1988). In contrast pressures higher than 10 Kb have been reached in the eclogitic and granulitic relicts of the overlying series. The difference in age also has been underlined: Devonian for the mobilizates related to the metamorphism of the overlying series (DUTHOU et al., 1984), late Carboniferous for the leucogranites associated with the metapelites.

The «Himalayan model of a hot series overthrust on a cold one» (KORNPROBST et al., 1980) cannot be accepted directly in this case which is closer, with its ultrabasic masses and high pressure relicts, to Alpine or Californian situation where ophiolites or melanges, including high pressure, basic and ultrabasic, metamorphic rocks, are overthrust on sediments.

Thus it has been proposed, in the case of the Limousin and adjacent provinces, to consider these structures as the result of a large overthrust, late Carboniferous leucogranites having locally forced up the overlying nappes, opening tectonic windows of a particular type, *diapiric windows*. *Buchan type* metapelites appear in these windows around the leucogranites and are surrounded by *Barrovian-type* metamorphic formations with high-pressure, high-temperature relicts (LAMEYRE, 1982, 1984) (Fig. 6). The northern part of the Massif Central, formerly considered as an old basement, the Lemovico-Arvern Core (ROQUES, 1971), is mainly

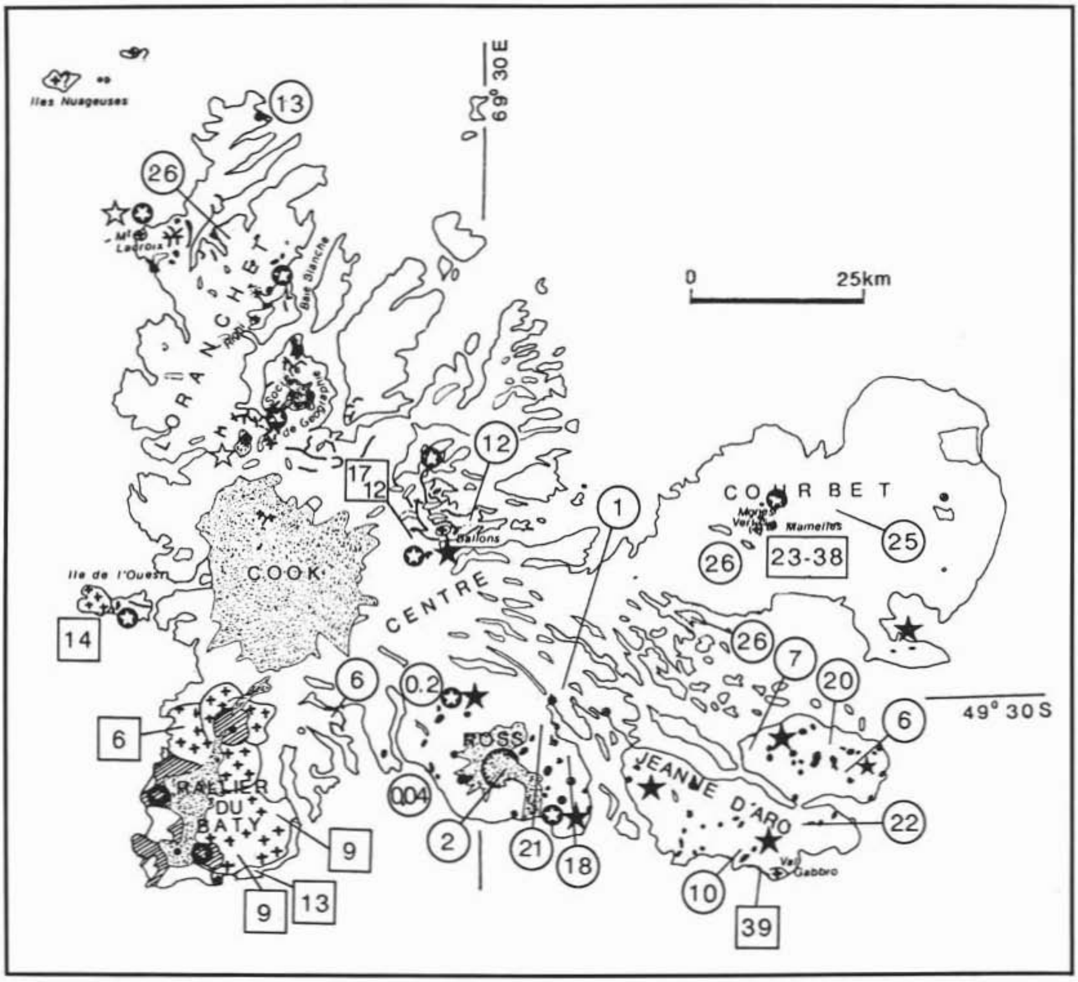

Fig. 9. — In Kerguelen the magmatic activity lasted at least from the emplacement of the 39 m.y. tholeiitic gabbros in the Jeanne d'Arc peninsula. Very recent lavas have been dated on the western flank of the Ross Mountain and fumaroles are still active in the Rallier du Baty peninsula near the Mio-Pliocene nordmarkite-granite ring complexes. Lava ages are inscribed in circles, plutons in squares. Trachytes are represented by white circled star, rhyolites by white stars, phonolites by black stars (after GIRET et al., 1981).

composed of an allochtonous series pierced by the windows of Millevaches, St. Mathieu, Marche, Sioule. Some klippes with metabasic formations (BARD et al., 1980) are scattered in the southern part, overlying the metapelitic series. This structure is also present in southern Brittany with the windows of la Roche-sur-Yon, Guerande, Champtoceaux (Fig. 7).

However, the Himalayan model elaborated by LE FORT is satisfactory for the generation of late Carboniferous French leucogranites. The overthrust of Marjevols, discovered by BURG (1977) and BRIAND (1978) where the metapelitic series of St-Genies d'Olt, with inverted metamorphic grades reaching the sillimanite zone, underlies the kyanite - sillimanite Marjevols series, is also consistent with a Himalayan system. The Marjevols series contains basic rocks with high pressure relicts. This suggests, using the Himalayan terminology, a superimposition of the Main Mantle Thrust and of the Main Central Thrust, the different units in the Hercynides being less thick than in the Himalayas, possibly as a result of differences in the age and nature of the crust (Fig. 8).

As a consequence the leucogranites produced on the MCT extrados have generated an original tectonic system. The diapiric windows are the most conspicuous. In other cases leucogranites intrude directly the allochtonous units such as in the St-Yrieix area where gold deposits have been related to the leaching of basic rocks and metagreywackes by fluid systems induced by the leucogranites (FLOCH' et al., 1984). Such a situation has also been found recently in the 2 b.y. series of the Sao Francisco craton in Brazil, where the leucogranites of Campo Formoso intrude ultrabasic allochtonous units, the interaction of Be rich fluids and chromite having generated emerald-bearing phlogopite-pegmatites (RUDOWSKI et al., 1987), beautiful products of the encounter of mantle formations and highly differentiated crustal leucogranites.

Finally the structure of the Hercynian chain combines several of the types defined by PITCHER and ZWART. Considering only the Devonian to Westphalian interval, the Andinotype was realized before the collision, then the Alpinotype and finally the Hercynotype.

III - Granites in within-plate anorogenic provinces and in divergent plate boundaries

The attention of structural geologist, drawn by within-plate situations, has largely been focused on major faults consequent on collisions (MOLNAR and TAPPONNIER, 1975; TAPPONNIER et al., 1986; KLOOTWIJK et al., 1985). Anorogenic granitoids as compared to those of the active margins, have been somewhat neglected in geodynamic reconstitutions for a number of reasons (BONIN, 1986). They are not located in impressive mountains nor are they related to spectacular fold belts, with their intense regional metamorphism and wealth of mineral deposits with few exceptions such as Nigeria. Moreover the popular Morgan plume model (1972) gave an explanation which does not imply any local tectonic and lithospheric control.

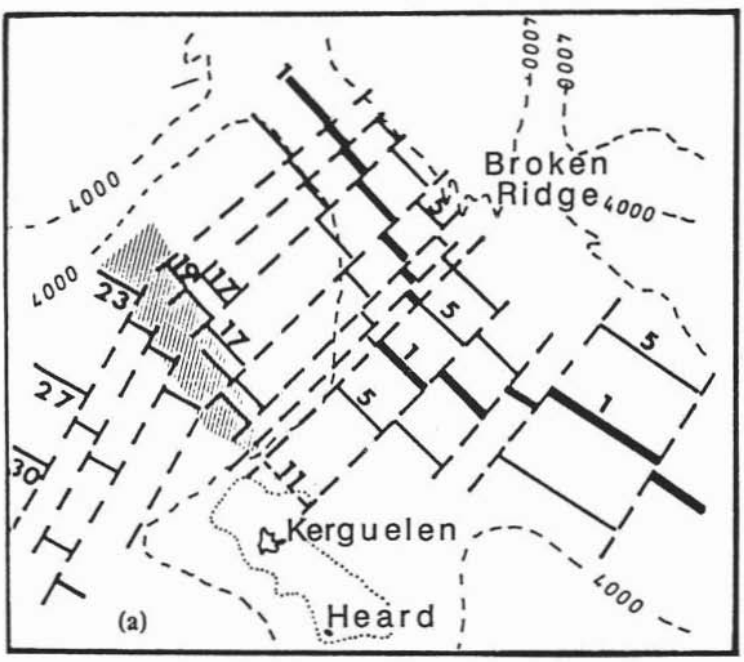

Fig. 10 — Structure of the South Indian Ocean floor (after SCHLICH, 1975). The shaded area indicates the change in direction of the magnetic anomalies. According to Giret the Kerguelen Heard plateau and Broken Ridge have been generated together by the East Indian Ridge and then separated.

However the structures of within-plate provinces, as well as the chronology of their activity and the nature and evolution of the magmatic series, strongly suggest that the nature, age and structure of the lithosphere play a role also in this case, and that tectonic events more local than the motion of plates over deep-seated mantle plumes, are to be considered.

In the Kerguelen Islands where typical alkalic granites associated with nordmarkites, in large Mio-Pliocene ring complexes, have

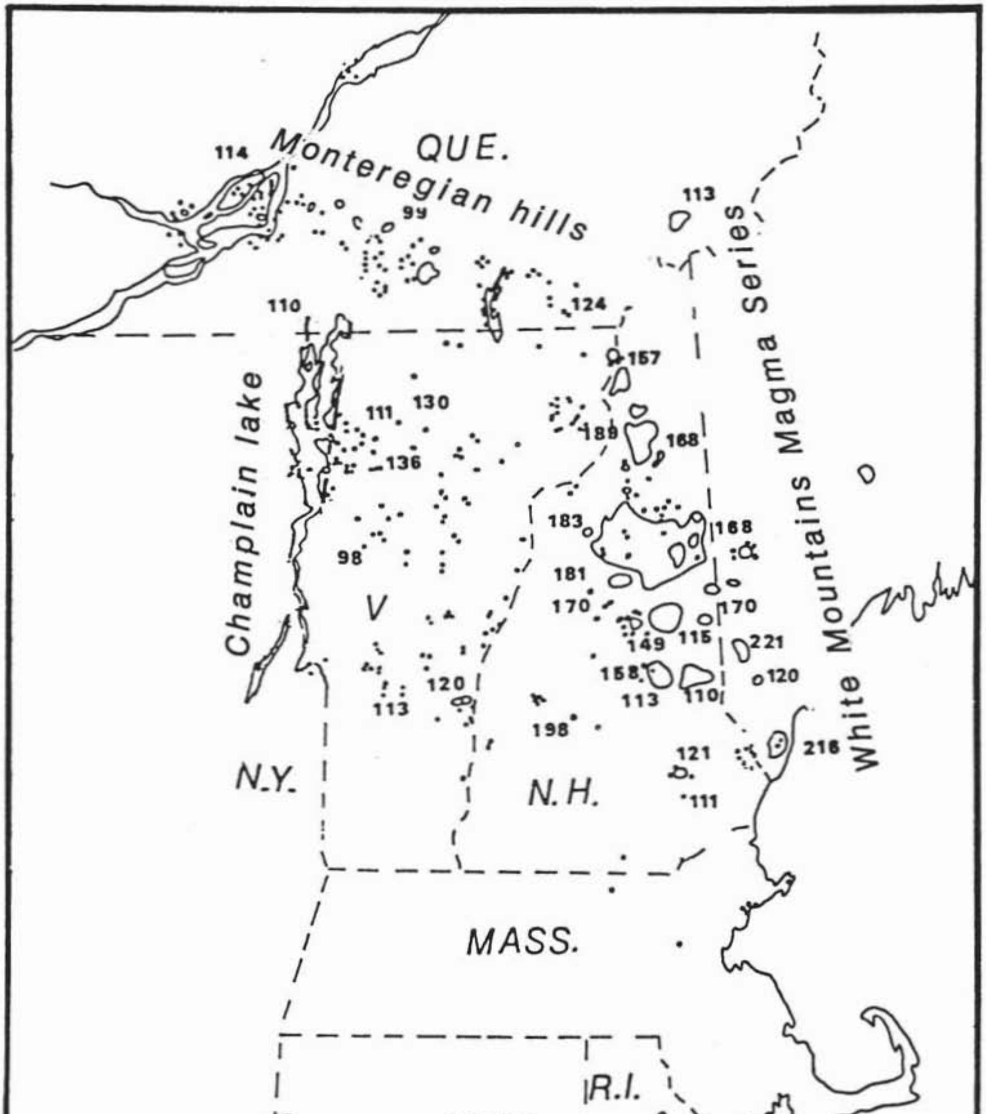

Fig. 11. — The Mesozoic georhomb of North-East America. In this sketch map of the Quebec - New-England province, complexes of the White Mountains Magma Series in Maine (M) and New-Hampshire (N H) and of the Monteregian Hills in Quebec have been delineated, dykes in Vermont (V) east of the Champlain Lake, are indicated with points. Age after FOLAND (1971, 1977) and MCHOME (1975, 1976) in SYKES (1976). From LAMEYRE et al., 1984; and BROUSTET, 1986.

been recognized (LAMEYRE et al., 1976), the first dated activity has produced 39 m.y. transitional gabbros intruding more ancient basalts (GIRET et al., 1981). In this area the age of oceanic floor is 48-52 m.y. (19^{th} to 21^{th} magnetic anomaly, SCHLICH, 1975). Thus the magmatic activity has persisted GIRET and LAMEYRE, 1985), with an evolution from tholeiitic to transitional and alkaline series, classic in Oceanic Islands. It may be related to the lithospheric thickness and thus fit with the experimental data on the PT conditions of magma generation (GREEN, 1971). Moreover, in the late alkaline series

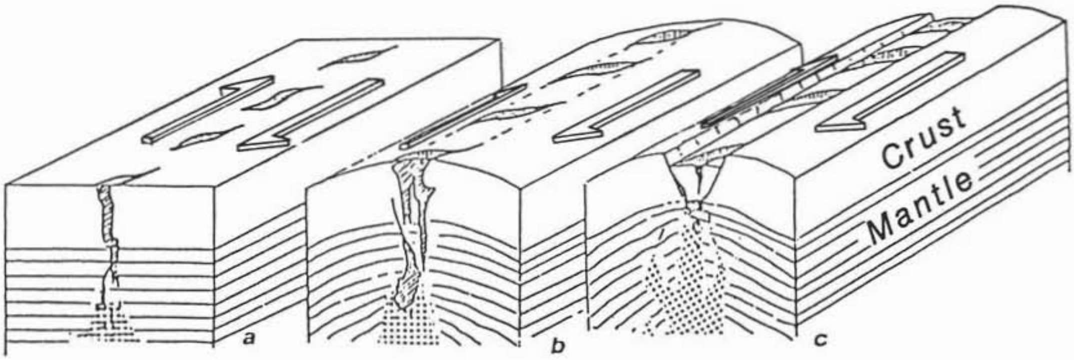

Fig. 12. — Evolution of a within-plate magmatic province. Deep gashes are induced by shear; pressure release and channelling of fluids trigger the melting process (a). Doming results from the volume increase as result of melting and collection of the magmas (b). The rift remains active as long as the shear acts, without necessary change of width (after LAMEYRE et al., 1984).

almost since the creation and during the migration of the Kerguelen Islands (Fig. 9).

Moreover, in a detailed study of the Rallier du Baty complexes, different ages for individual ring dykes, indicate that pulses of magma, separated by an interval of about 1 m.y., have been emplaced between 12 and 6 m.y. These data are not consistent with the hypothesis of a lasting mantle plume rising beneath the moving lithosphere which is supposed (DUNCAN, 1983) to have given rise to, successively, the Radjmahal trapps of India, the Ninety East Ridge (60 to 31 m.y.) and the Kerguelen plateau (27 m.y. to present). Besides, the Kerguelen hot spot is «the least fixed» in the frame of reference according to Morgan himself, as recently recalled by MOLNAR and STOCK (1987).

The setting of the province is very particular; it lies at the apex of an angle formed by magnetic anomalies of the Indian Ocean floor which displays a dislocated pattern noticed by SCHLICH (1975) since the first surveys in this area (Fig. 10). The change in the nature of the magmatic products with time is another striking feature (GIRET, 1983, the distribution of different types is remarkable. The silica-oversaturated series of Rallier du Baty, Iles Nuageuses, Mont Lacroix are located in the western part. On the contrary the central and eastern part are intruded by undersaturated or mixed complexes. The limit seems rather sharp and has been related to local fracturation (GIRET, 1983) which may be responsible for hydration of the magma and its subsequent evolution towards silica oversaturated compositions (HELZ, 1976; WYLLIE, 1979).

Finally data obtained through the seismic tomography method (DZIEWONSKI, 1984), indicate that hot bodies, very apparent at shallow levels under the Kerguelen plateau, vanish at depths of over 500 km, a feature which does not seem to support a simple expression of the mantle plume model.

In continental anorogenic provinces the distribution of ages is not always consistent with the model as underlined, for example, by WRIGHT (1973), and SYKES (1978) with regard to Niger-Nigeria and New England. The anorogenic provinces of West Africa offer striking examples of a Quaternary reactivation

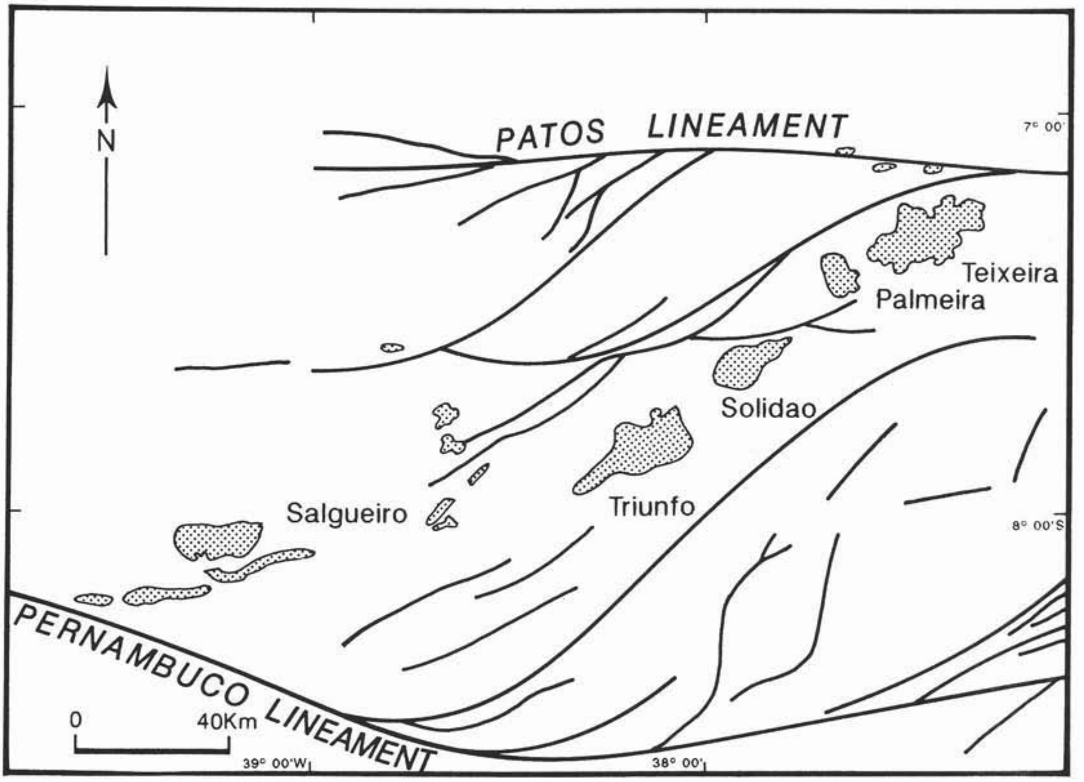

Fig. 13. — The alkalic syenites of North East Brazil (after SIAL et al., 1987).

after a long, and variable, period of inactivity. Recent alkaline volcanoes are superimposed on late Proterozoic (Hoggar), Paleozoic (Niger), Mesozoic (Nigeria) alkaline complexes, features which are rather unlikely with a model ignoring local conditions. These provinces are set in the Panafrican fold belt along the West African craton. Moreover the recently discovered Ahnet-Adrar des Iforas Cambrian provinces are aligned on the very edge of the craton, not far from the Permian Tadhak province, which is located on the craton itself. They not only differ in age but also in composition. The Ahnet -Adrar des Iforas intrusions are silica-oversaturated, with dominant granites, whilst in the Tadhak they are undersaturated with abundant carbonatites (BLACK et al., 1985). The Mesozoic province of Quebec-New England provides similar features. The mainly undersaturated complexes of the Monteregian Hills are deeply rooted in the Precambrian Grenville domain, partly overthrust by Appalachian nappes. On the contrary the White Mountains magma series of New England, which is located in the Palaeozoic Appalachian belt, is mainly granitic. Thus we have proposed to relate the silica saturation to the age, nature and water content of the crust, the wet materials of orogenic belts favouring evolutions towards silica oversaturated types (HELZ, 1976).

Moreover the shape of this latter province is remarkable (Fig. 11). The Monteregian Hills, the White Mountains Magma series and the Vermont dyke field are located within a rhombus with sides of 250 km. The Nigerian province has a similar shape which we have proposed to term «*Georhomb*» and suggested that it might be generated by shear systems along transcurrent faults (LAMEYRE et al., 1983).

SYKES (1978), BONIN and LAMEYRE (1978) have highlighted geological features favouring

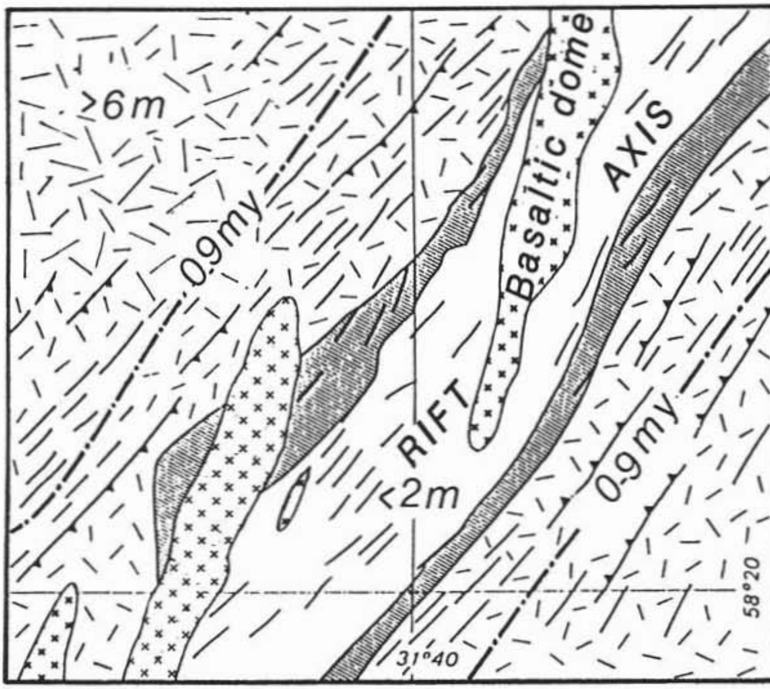

Fig. 14. — An interesting structure in the Reykjanes Ridge. Basalitic domes 3 km wide and 30 km long form an en echelon system in the rift. Thickness of sediments and the 0,9 m.y. anomaly are indicated (after BOGDANOV and SAGALEVITCH, 1984).

a structural control for within - plate magmatism. More recently we have stressed chronological, structural and petrological arguments leading us to propose a complement to the mantle-plume model (LAMEYRE et al., 1983). We believe that shear systems, which generate pull apart basins or tension gashes, may trigger pressure release at deep lithospheric levels, allowing the channelling of fluids along tectonic discontinuities and thus favouring the melting process (WYLLIE, 1979) and the collection of magmas trapped beneath the lithosphere (BONIN and LAMEYRE, 1978). The partially melted material rising along the fractures is a translithospheric variety of the classic diapir model of Green & Ringwood. In this connection the episodic and recurrent magmatic activity, well expressed in ring complexes, could be the expression of a *self sealing system* where the magma, filling the fractures, generates a pressure which inhibits further melting (LAMEYRE et al., 1985) (Fig. 12).

In the within-plate provinces evidence of extensional systems are provided mainly by the dykes. Careful studies on the Adrar des Iforas dykes system (BOULLIER et al., 1986; LIÉGEOIS and BLACK, 1987) have documented the «harpoon-effect» proposed by BLACK et al. (1985) which relates the opening to sharp reversals of the motions along transcurrent faults. The shape of the Sierra de Itiuba, an elongated intrusion of Precambrian nordmarkites mapped by Sabate (VERMER INDA et al., 1978) suggests a tension gash filled by alkaline magma at an intermediate level between the chamber and the upper ring complexes and volcanoes. The alkaline intrusions described by SIAL et al. (1987) in the north-east Brazil have also a remarkable distribution with regard to the Pernambuco and Patos lineaments (Fig. 13).

The continental rifts are also preferential settings for alkaline magmatism, and their long history (BAKER et al., 1972) is not always consistent with a simple distensive model. For instance the Limagne Rift in France, filled by 2000 m thick Oligocene sediments, has not enlarged notably since this period, although Miocene, Pliocene and Quaternary magmatic episodes have occurred. In East-Africa, recent structural data (CHOROWICZ, 1983) demonstrate the importance of shear systems which we have considered as responsible for the recurrent magmatic activity: the rift remains active as long as shears operate and does not necessarily widen.

Little data are available on Oceanic Ridges and related granites. Plagiogranites represent only a small part, perhaps 1% according to COLEMAN and PETERMAN (1975) of the ophiolitic complexes and the huge activity of the Mid Oceanic Ridges (75% of the magma production of the planet according to CRISP, 1985), has been ignored until the recent developments in Marine geology. Moreover they are generally studied in obducted ophiolites more than in the divergent context of their birth-place. However an en echelon system has been described in the western Reykjanes Peninsula by JACOBSON et al.(1978) and survey of the Reykjanes Ridge by BOGDANOV and SAGALEVITCH (1984) has revealed basaltic domes, 30 km long, 3 km wide, and 500 m high. They are located on the axial zone of the Rift, delimited by the 0.9 m.y. anomaly (Fig. 14). They are clearly in the position of en echelon gashes and suggest also the existence of shear systems controlling locally the emplacement of magma chambers.

Thus attention should be given to shear systems which operate the adjustments between divergent and convergent systems and to magmatic rocks, especially granites, which are emplaced along them. Furthermore their importance is also well recognized in orogenic environments, for instance in Peru (PITCHER and BUSSEL, 1977). The leucogranites of south Britanny provide another good example of emplacement controlled by a major shear (COGNÉ, 1960). In the same province, high-K granodiorites and granites of the 300 m.y. Red Granite Line (Fig. 7) also have been related to a shear which has operated along the edge of the 2 b.y. Icartian block i.e. along the Channel (BARRIERE et al., 1980), giving an additional example of lithospheric memory.

Conclusions

To each tectonic situation, each stage of the Wilson cycle, corresponds its proper type of granite. This statement, founded on many observations and analyses, has been progressively accepted after the distinction introduced by MARTIN and PIWINSKI (1972) between orogenic and anorogenic granites. It has been proven by many studies on different areas of different ages. In active margins the wide range of mantle derived orogenic types which belong to the arc-tholeiitic, calc-alkaline and shoshonitic (or transalkaline) series is closely related to subduction processes. The hypercollisional situations, related pressure and temperature changes and subsequent dehydrations, generate crustal derived peraluminous granites. In within-plate settings, which may evolve to divergent plate boundaries, granites are generally allied with differentiated tholeiitic or alkaline series. Finally plagiogranites characterize the Mid Oceanic Ridges.

However many distorsions affect this classic scheme. In the Rodriguez Ridge alkalic granites have been found as dykelets crossing tholeiitic gabbros (ENGELS and FISHER, 1975) and such occurences are not exceptions in orogenic areas. Peraluminous granites, widespread in active margins, are not related, systematically, to collisional processes. Back-arc compressive regimes and subsequent continental underthrusting offer adequate conditions for subduction of hydrous materials, dehydration and generation of crustal melts. It also provides opportunities of mingling and mixing with rising mantle magmas, and finally pathways and room for large forceful syntectonic intrusions. The situation is rather similar in post-collisional regimes except that there the source is only crustal, and thermal conditions more moderate, on account of the lack of mantle magmas interaction. Consequently the compositions of leucogranites generated in these settings, considered on the whole, are closer to the experimental minima, reaching in some cases «especially low solidus» compositions due to flux elements (F, Li, B), (PICHAVANT et al., 1987).

Moreover the tectonic conditions in our restricted west-Mediterranean area illustrate short distance changes, through shear systems, from a collisional situation in the Alps to an active volcanic arc in Sicily not far removed from the alkaline provinces of Pantelleria and Comende. Vertical changes are also to be considered in association with the extensional regimes, related to subduction, as described even in Tibet where a North-South graben system has been generated since the Pliocene (MOLNAR and TAPPONNIER, 1975; KLOOTWIJK et al., 1985) above the still active underthrust. Reconstitutions of past geodynamic conditions also stress the importance of evolutions in time (BIJU-DUVAL, DERCOURT and LE PICHON, 1977).

Thus one should be cautious when dealing with the tectonic significance of granite types. Although they are generally reliable, subsequent geodynamic reconstitutions are more subject to extrapolations and thus more difficult to assert. Moreover, as with other geological objects, granites have been subdivided into many types. They are defined according to their setting, the nature of their enclaves, their mineralogical and geochemical compositions. It is not yet possible to superpose these different modes of classification which are probably still insufficient for representing the great variety of granites. Other types are likely to be defined as refinements are introduced into our analytical systems and the modelling of geodynamic processes. Thus it is important to keep one's attention on the granites, major components of continental crust which preserve the Earth memory.

Aknowledgements. — I am grateful to Professor A. Boriani for his invitation to attend the Verbania meeting which acted as a stimulus for writing the paper. I thank my colleagues J. Aubouin, R. Black, B. Bonin, J. Bourgois, J. Didier, A. Giret and W.S. Pitcher for helpful discussions.

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