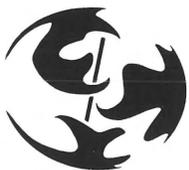# VARISCAN EVENTS IN THE ALPINE REGION

JÜRGEN F. VON RAUMER[1]

ABSTRACT

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Relics of the pre-Permian history are preserved in the five crystalline basement complexes of the External or Helvetic realm. Their evolution can be compared with the Variscan regional evolution in Central Europe. Precambrian to Palaeozoic sediments interlayered with acid and basic magmatic rocks suffered an early regional anatexis with contemporaneous formation of granitoid rocks. This event (5-6 kb/700 °C) supposed to be at least of Caledonian age is followed by the formation of blastomylonite zones probably contemporaneous to large scale B_3-folds. A second regional anatexis (of probably early Variscan age, 650-700 °C/4 kb) is characterized by the regional occurrence of cordierite-bearing granitoids, accompanied or followed by a regional growth of biotite and plagioclase. The later history is dominated by the intrusion of distinct granite bodies.

Although Variscan events are of importance for the structural evolution, the main metamorphic history is of pre-Variscan age. No considerable break could be seen in the rather continuous history of evolution from Caledonian until Variscan time.

INTRODUCTION

The Alpine domain, occupying the area bounded by the line Genoa-Geneva-Munich and limited on the south by the Po Valley, is laid out in a huge arcuate structure. Tectonic and metamorphic events since the Permian are well summarized in FREY ET AL. (1974) and have been treated also in the Metamorphic Map of the Alps (see the explanatory text compiled by NIGGLI, 1978). Relics of structures show that this region was also involved in Variscan and yet earlier events. DAL PIAZ ET AL. (1972), in the course of their discussion of the history of the Alpine Nappes, have already touched on the possibility of attempting to reconstruct the features of an old crystalline basement, and the southern boundary of the Alpides, the Ivrea zone, has also had a good deal of attention in recent years.

Several relics of older structures are preserved in the external parts of the Alpine domain, because Alpine metamorphism was weaker there than in the central parts. Such relics of pre-Alpine (indeed, pre-Permian) history are to be found in the five crystalline basement complexes of the External or Helvetic realm, i.e. the massifs of Argentera, Haut Dauphiné, Grandes Rousses-Belledonne, Mont Blanc-Aiguilles Rouges and Aar-Gotthard. The major literature sources on the five massifs have been reviewed by VON RAUMER (1976) discussing the possibility of making comparisons among the five. The purpose of this present paper is to examine what place the Variscan structures of the External Alpine domain have within a general European frame of events. A great amount of new data has been brought forward at meetings held at Bergamo 1974, Karl-Marx-Stadt 1974, Rennes 1974 and at the Geological Congress, Paris 1980.

The geological histories of the five massifs have a remarkable number of common features. The most striking of these are set out, for comparison, in Table I. In the region as a whole, age determinations are still rather few in number. It is therefore necessary to look to the particular cases of the Aar-Gotthard and Haut Dauphiné for guidance on the time scale of events. Nevertheless, even if one can establish only the relative sequence, one already has a valuable basis of discussion.

Within the region of the external massifs, taken as a whole, two main episodes should be distinguished. These are, first, establishment of a consolidated crystalline basement which around 400 Ma ago was already in existence over a large

[1] Institut für Mineralogie und Petrographie, Universität Freiburg, CH-1700 FREIBURG, Switzerland.

Table I Variscan and prè-Variscan history of the Alpine External Massifs.

Time scale	sedimentary history	metamorphic and tectonic events	magmatic rocks	products	ARGENTERA	HAUT DAUPHINÉ
Precambrian to Early Palaeozoic	early sedimentation of detrital series including some few carbonate layers		acidic and basic volcanics sometimes as bimodal volcanic series		Polymetamorphic. relics indicate detrital series with carbonates. basic and ultrabasic rocks (Val Colombo) bimodal series (St. Etienne).	Lavey-formation detrital sediments + carbonates. amphibolites and Olan amphibolic gneisses + ultrabasites
'Caledonian' event and/or older traces (?)		Early Palaeozoic metamorphic event (and/or traces of older events) High amphibolite-facies grade, Anatexis I, formation of migmatites containing 'resisters' as xenoliths.	formation of granites yielding Caledonian ages, biotite-granites, muscovite-granites, leucogranites, pegmatites with black K-feldspars, garnet and turmaline, turmalinite veins.	migmatites or gneisses with alumosilicates, calc-silicate rocks quartzites, amphibolites, 'leptynites', augengneisses.	migmatites. Augengneisses of Lago Valscura – Lago Claus, gneisses of Iglieres.	migmatites with relics of resisters Caledonian granites as Gneiss de Crupillouse et des Bans
Silurian?		early movements on major tectonic lines, blastomylonitization		granulation of all existing rocks, growth of quartz lenses, mineral assemblages of amphibolite-facies grade, low fH_2O	blastomylonite zones near St. Anna and Colle Sabbione	blastomylonite zones of Pilatte and Peyre-Arguet
Late Caledonian or early Variscan event		regional Anatexis II in the crystalline basement areas, or regional formation of biotite and growth of plagioclase. steeply dipping fold axes and strong lineation of biotite.	leucogranites, granites or granodiorites with cordierite, or two-mica-granites depending on rock composition.	granitoid rocks transformed to 'Streifen-gneiss', regional formation of K-feldspar, plagioclase, biotite, fibrolite. higher degrees of mobilization might yield Kf-rich amphibolic gneisses.	relics of kyanite, staurolite and garnet granito aplitico microgranolare d'anatessi 'granite de Valmasque' migmatites de Fenêstre granodiorites and granites with cordierite ((Mte. Pelago, Pagari, Lago Brocan). regional growth of biotite and plagioclase	Pigeonnier granitoid gneisses as products of Anatexis. II, regional growth of plagioclase. veins, mobilizates and granitoids with cordierite 'granite d'anatexie'
(Late Devonian to Early Carboniferous)	detrital sediments in intramontaneous troughs (graben-zones)		acidic and basic volcanics			sequence of granites, oldest in the south 'circonscrit'-type.
Early and Middle Carboniferous	detrital sediments		acidic volcanics granites			
Late Carboniferous	detrital sediments and coal seams		granites		granito fundamentale (Malinvern granite)	Westphalian and Stephanian (La Mure)
Permo-Carboniferous	detrital sediments	slight regional metamorphism of greenschist-facies grade?	rhyolites, microgranites		coarse detrital sediments in graben zones parallel to the central mylonite zone 'Mollie-résite'	grès de Champoléon
Permo-Triassic	coarse-grained clastic series				mainly southern part of Argentera, Dôme de Barrot	

Combeynot-Massif 'zone corticale' Vieux Chaillol	BELLEDONNE	Belledonne + Aig. Rouges West	AIGUILLES ROUGES	MONT BLANC	AAR MASSIF	Eastern part of Aar massif	GOTTHARD MASSIF
Vieux Chaillol detrital rocks and carbonates? (or Ordovician-Devonian?) Vieux Chaillol amphibolites?	detrital series amphibolites	detrital series	relics of quartzites and carbonates as boudins in migmatites. detrital rocks and carbonates / garnet-amphibolites with some few ultrabasic relics metarhyolites and 'leptynites'		detrital series highly transformed with some carbonate layers Erstfeld- and Central gneiss complexes. mainly basic rocks, some serpentinites, hornblendites, diorites, granodiorites		highly transformed Gurschen-, Giubine- and Cavanna-series, carbonate lenses with preserved ripplemarks / basic and ultrabasic interlayers
Vieux Chaillol amphibolite-facies grade with kyanite and staurotide (no migmatites)	granite of St. Columban		Metamorphose of high amphibolite-facies grade, formation of migmatites / Brevent augen-gneisses	leucogranites, muscovite-granites, turmalinite-veins	regional anatexis. migmatites / granitic and aplitic mobilizates		granulites facies grade (450 Ma) / regional anatexis migmatites Paradiesgneiss / 'Streifengneiss' – granitoid rocks (421 Ma)
	blastomylonites in the Beaufortin area		Chésérys gneiss / metapelitic rocks with kyanite, staurotide and garnet	blastomylonites from Trient area and Col de la Seigne / no alumosilicates preserved	older blastomylonites in the Gastern area		regional granulation 'Variscan' recrystallization / regional metamorphism of amphibolite-facies grade formation of regional biotite-lineation ('Streifengneis')
	granitoids with cordierite		granitoids with cordierite, regional growth of plagioclase and biotite, garnet replaced by plagioclase and biotite	leucogranites, granites and granodiorites with cordierite, two-mica-granites and mobilizates in rocks of granitoid composition. plagioclase-biotite rims around amphibolites, K-feldspar-rich amphibolites.	regional anatexis Lauterbrunnen and Innertkirchen (migmatites and granitoid rocks with cordierite)		
Vieux-Chaillol-series perhaps of this age. / Combeynot-series with detrital rocks and spilites + keratophyres.		detrital rocks, conglomerate / 'Serie verte' spilites, keratophyres, 'leptynites'				detrital sediments (Biferten, Gliems) / detrital sediments / (Westph. D-Steph) (Biferten,Lötschen) + acidic volcanics	
volcano-detrital rocks in Combeynot area / Combeynot-granite (330-310 Ma). Vieux-Chaillol-conglomerate	granite of Sept Laux	'Serie satinée' acidic volcanics	Vallorcine granite	Montenvers-granite (detrital rocks and acidic volcanics?)	Tödi-granite Punteglias-diories	deformations, contact-metamorphism (Biferten, Gliems)	Cristallina-granodiorite, Medelser granite
	grès d'Allevard		Salvan region: Westphalian B to Stephanian A	Carboniferous of Col de Miage Mont-Blanc granite	Gastern-granite Punteglias-granite Giuv-syenite Central Aare granite		(Tremola-series?) / Gamsboden-granite Fibbia-granite
	grès d'Allevard		local chloritisation	rhyolites, microgranites local chloritisation		local detrital sediments / locally sediments and volcanics	Rotondo-granite / Permian metamorphism

area, and secondly, development of a number of discrete troughs within which Late Palaeozoic sediments were deposited.

OCCURRENCES OF LATE PALAEOZOIC SEDIMENTS

We do not know at what time the sedimentary sequences began to accumulate in these areas known or supposed to contain the Late Palaeozoic sediments. LE FORT & EHRSTRØM (1969) compared lithologies from the western part of the Aiguilles Rouges (LAURENT, 1968) and from Belledonne with some from the Vosges. Their stratigraphic table is to be compared with the one published by LACOMBE (1970) who produced new data on similar sequences in the eastern part of the Pelvoux region (Massif du Combeynot). The work of these authors would suggest the succession listed from top to bottom in Table II.

It is noteworthy that already GIBERGY (1968) discussed the presence of fossil traces of possibly Viséan age, and newest palynological data (BELLIERE & STREEL, 1980) comfirm an age of late Viséan for the detrital series of the western part of Aiguilles Rouges. Continental detrital sediments of Early Carboniferous age have been described from the eastern part of the Aar massif by FRANKS (1966, 1968).

It seems that we might reasonably envisage a Variscan horst-graben system within which detrital material from an older basement was deposited during Devonian and Carboniferous time, and which also was the locus of occurrence of volcanic rocks of spilite-keratophyre type, whose distribution was influenced by major fault lines and which are affected only by greenschist-facies grade metamorphism.

OLDER CRYSTALLINE BASEMENT

After the discussion of the Late Palaeozoic series arises the question about the development during the preceding range of Palaeozoic time. Are there sediments of Variscan affiliation that are older than Devono-Carboniferous? The Carboniferous clastics obviously represent a time, when an older crystalline basement was already exposed to erosion and it is possible that there is a major break between the Devono-Carboniferous rocks and any of Early Palaeozoic age. The interesting interpretation of the Grauwackenzone in the Eastern Alps advanced by MOSTLER (1970) obliges us to raise some further questions concerning the evolution of the Western Alps region during the time from Cambrian to Devonian. Is there a kind of break between a Precambrian-Ordovician older cycle, followed by Silurian and Devonian? This kind of hiatus seems familiar to different localities of the Variscan chains.

The comparative table (Table I) of crystalline basement rocks and sedimentary trough-fillings should be taken as offering only a very general picture. It is certainly not to be regarded as an exact time table of events. We cannot be sure whether any particular type of event recognizable in all five massifs occurred at the same time in each, or whether instead such an event is better interpreted as having taken place at a certain grade of geological evolution, which might have been reached at different times in the five massifs. It would be useful, before proceeding to a wider discussion, to set down some information on the main rock types encountered in the crystalline basement.

Rock-types of the crystalline basement

In order to attempt interpretation of the pre-Variscan geology of the whole region it is necessary to have some information on sequences of rock types. One is therefore grateful for the fact that certain rock units are present, with only slight variations, throughout the five external massifs. The most noteworthy rocks in the older part of the crystalline complex besides metapelitic rock series are amphibolites and carbonates.

Amphibolites – These are common in all five massifs. Depending on the local grade of metamorphism they vary from eclogitic or symplectiuc garnet amphibolitis to massive amphibolites with a content, more or less well-developed, of plagioclase. Anatectic mobilization later led to diffuse rock types of granodioritic or quartz-dioritic composition.

Eclogites and symplectitic garnet amphibolites are abundant to the Argentera region, are well known in the Aiguilles Rouges (LIEGOIS, 1979), Mont Blanc and Gotthard areas, and are also reported from the Haut-Dauphiné (Peyre-Arguet).

Among the massive amphibolites, containing mainly hornblende and plagioclase, special interest attaches to relics which indicate the presence of ultrabasic rocks. Serpentinites have been reported from the Argentera and the Aiguilles Rouges and they are well known in the Gotthard and Aar massifs. Occurrences of nodules of fibrous actinolite and relics of clinopyroxene have been discovered in the Pelvoux area (LE FORT, 1973; GILLOT, 1970; PECHER, 1970) and in the Mont Blanc (VON RAUMER, 1974), and xenoliths with reaction rims of talc and actinolite are known from the Argentera (Lago Brocan).

In this same set of (variable) amphibolites there are coarse-grained vein-like bodies or layers of amphibolitic gneiss with large K-feldspars, which in their mineralogical and even chemical composition correspond to durbachites, as they were defined in the Black Forest, more recently described by MORCHE (1979). They are well known from the Argentera, Haut Dauphiné and Mont Blanc areas.

The character of this varying set of amphibolites is best understood in the Haut Dauphiné area, where the several types have been subjected to chemical analysis. LE FORT (1973) there established in a volcano-detrital sequence the

Table II
Variscan stratigraphic succession.

Rock types	*Probable stratigraphic assignation*
Flysch sediments with sandstones and shales	Dinantian (Tournaisian and Viséan)
Volcano-clastic rock types	Visćan according to LACOMBE (1970)
– spilites	Late Devonian according to LE FORT & EHRSTRØM (1969)
– tuffs	
– keratophyres	
– greywackes	
Volcanic rocks	Middle Devonian
– spilites	
– 'amphibolites'	

following features, listed from top to bottom:
– amphibolitic levels with frequent biotite interlayers;
– amphibolitic augengneisses of durbachite type (80-300 m);
– more or less fine-grained gneisses with biotite or chlorite (10 m);
– massive amphibolites, amphibolitic gneisses and amphibolitic agmatites (-100 m);
– detrital sequence with greywackes, quartzites, feldspathic sandstones and shales.

According to LE FORT (1973) this whole sequence was the product of what were originally volcanic and sedimentary accumulations, the volcanic rocks having spilitic character.

The main rock types of this association can be recognized again in the Argentera area, where amphibolites are much more important, whereas in the Mont Blanc area this series is of much lesser thickness, and where the different amphibolites might attain about 100 m. The available information on these rocks suggests trends which, accepting interpretations of the kind proposed by BEBIEN ET AL. (1977), would indicate circum-oceanic or intra-continental volcanism, a finding already established for Devono-Carboniferous rocks from the outer parts of the Haut Dauphiné.

This comparability led LE FORT (1973) to advance the idea that the two sets of rocks, one from the central area, the other from the outer parts of Haut Dauphiné, might be of the same age.

The chemical data from the Mont Blanc area (von Raumer, in prep.) confirm the general composition. A different set of amphibolites is known in the northwestern part of Argentera. They show thin interlayered units, some of which are hornblende-rich, others are more felsic (feldspars present include not only plagioclase). The felsic layers, sometimes irregular in shape, are locally the more important of the two. Both together could be interpreted as a sequence of basic and acid volcanics. Their general composition resembles that of a layered bimodal series, with acid and basic volcanics interbedded, an association which in the European literature is termed an amphibolo-leptinitic series.

Carbonate rocks – These are found in each of the massifs, but they are of small volume only. Two types should be distinguished. The first is represented by a unit of banded calc-silicate marbles or graphite-marbles. They can be traced over quite a distance in the Haut Dauphiné (LE FORT, 1973), and they are well known in the western part of Argentera, from Arpille in the Aiguilles Rouges (OULIANOFF, 1924; BLANC, 1976), from the Aiguilles Rouges in general and from the Aar massif. These well defined marble layers, of fairly constant thickness, are interbedded with fine calc-silicate layers and graphite-rich calcite marbles. It is difficult to decide whether this marble unit belongs to a relatively early series of metamorphic rocks which experienced the first anatectic event, or whether instead it is a sequence which was deposited after the first anatexis as a platform succession resting with an unconformity on older rocks. The same problem applies in the case of the associated metapelitic rocks, which show no clear evidence of any regional anatectic effect.

A second type of calc-silicate rocks is represented as boudins with anatectic rocks. They have survived at relatively high grades of metamorphism, in contrast to the metapelitic rocks around them, which have been transformed into migmatites. It is not yet clear whether these calc-silicate lenses first accumulated as homogeneous, continuous beds or instead represent what were originally small lenses of marly sediment. Locally, even small-scale ripplemarks can be found (ARNOLD, 1970-b), marked out by the layering of heavy-mineral concentrates. For purpose of regional interpretation, it is probably best at the present time to treat these rocks separately from the marbles mentioned above. They may well represent a distinct set of rocks and are quite possibly of a different age.

Coarse-grained augengneisses – These are noteworthy. They are present in all five massifs but are found in various different associations. Some augengneisses, with relatively strongly developed biotite lineations and abundant K-feldspar phenocrysts, are thought to represent earlier-established coarse-grained granitic rocks, possibly of Caledonian age, and will be excluded from this discussion. More important are those augengneisses which bear witness to the existence of an early

Fig. 1
Distribution of Variscan crystalline basement outcrops after the International Tectonic Map of Europe (1962) with the main occurrences of cordierite-bearing granitoids.

Palaeozoic, or even older, sequence of acid volcanics. The sequence would have included metarhyolites, locally with very coarse-grained K-feldspar crystals set in a fine-grained matrix, tuffs (leptynites), and the whole interbedded with metasedimentary units. Similar associations of rocks occur in southwestern France and are well known in northwestern Spain where they are given the collective name 'Ollo de Sapo'. Although anatexis has obliterated most of the older structures in this set of granitoids, the preserved relics are sufficient to indicate the earlier existence of a volcanic sequence of the kind described.

Metapelitic and detrital rocks – These rocks suffered in most cases high transformations by different stages of anatexis. But as already mentioned above, there seem to exist metapelitic layers which have not undergone regional anatexis. Quartzites of few centimetres up to one metre occur locally.

In summary, we can recognize quite a variety of old lithologies, including large quantities of highly transformed metapelitic and detrital rocks, which were present before the onset of the early, distinctly pre-Alpine, metamorphism. They are:

– detrital and metapelitic sequences (often highly transformed);
– a sequence of basic rocks and their tuffs with some ultrabasic rocks included;
– carbonate rocks;
– acidic metavolcanics.

Although these rock series suffered strong deformation, it would be interesting to try a kind of stratigraphy. Most of the rock units from the crystalline basement of the different massifs are not firmly dated and cannot yet be referred to particular positions in a stratigraphic sequence - 'coloured series' are not unique to one particular part of geological

time. But progress has been made by local occurrences of fossils (GIORGI, 1979; GIORGI ET AL., 1979), and the discussion of lithological sequences.

As already cited above, LE FORT (1973) established a kind of lithostratigraphy for the Pelvoux area, giving from top to bottom the following sequence for the Chaillol area:
– conglomerates and quartzites (700 m);
– 'dalles noires', garnetiferous micaschists with graphite (200-300 m);
– calc-silicate marble (few metres);
– series of micaschists, chlorite schists, leptynites, amphibolites and quartzites (-300 m);
– amphibolites with some quartzites ($\approx$ 400 m).

For the central part of Pelvoux, the Lavey Formation is composed by a volcano-sedimentary sequence already discussed. Both sequences could even be of the same age.

New comparative studies were made in the Grandes Rousses area, where GIORGI (1979) described the schists from Huez-Vaujany yielding fossils of Cambrian age:
Huez-Vaujany schists:
– gneisses with great K-feldspar phenocrysts;
– K-feldspar augengneisses;
– fine-grained amphibolites;
– marble unit (9 m);
– chlorite-sericite schists;
– fine-grained quartz-rich metapelites and metagreywackes (Cambrian age).
Bourg d'Oiseans series:
– metagreywackes and quartzites;
– amphibolites and amphibolitic gneisses.

New insight for Mont Blanc and Aiguilles Rouges reveals also a kind of lithostratigraphy, but without any sign of polarity due to the strong general deformation of all rocks.

For the Aiguilles Rouges two principal units of rocks should be distinguished, a more metapelitic and detritic rock series:
– biotite-rich metapelitic units (50-100 m);
– biotite-garnet schists;
– banded calc-silicate marble (about 10 m);
– quartz-rich detrital layers, quartzite until arcose (few metres);
– interlayers of metapelitic and metagreywacke bands - a kind of flyschoid series (about 50 m);
– thin interlayers of amphibolites (about 1 m)
and a more acidic complex, containing:
– mobilized leucocratic banded gneisses (probably 100-300 m)
which might correspond to a sequence of acidic volcanics.

For the Mont Blanc area most rocks correspond to highly mobilized migmatites with some relic boudins of amphibolites and calc-silicate rocks, probably a series of detrital rocks with some calcic and basic interlayers. Striking units are the amphibolites, corresponding in their general composition, but strongly reduced in size, to those of the central part of Pelvoux (LE FORT, 1973).

A second distinct series is represented by coarse-grained granitoid gneisses, sometimes augengneisses, with large K-feldspar phenocrysts, interlayered by fine-grained banded acidic gneisses, which could correspond to an acidic subvolcanic or volcanic series.

Besides these very few indications of stratigraphy for the crystalline basement of the Central and Western Alps MOSTLER (1970, 1978) has shown, for the Eastern Alps (Grauwackenzone), that Ordovician basic rocks are overlain by large volumes of acidic volcanic material; Silurian follows uncomformably above. Within the Ordovician there is strata-bound scheelite which is found over quite large distances (HÖLL, 1975). If the evidence of strata-bound scheelite in the Mont Blanc and Aiguilles Rouges areas could be interpreted in the same way, this would confirm the discussion of Cambro-Ordovician series in the External Massifs. Also to be considered in such context is the presence of the acidic metavolcanics. The age of the 'Ollo de Sapo', of northwest Spain (see above), which they sometimes resemble, is now taken to be within the range of late Precambrian to Ordovician (MARTINEZ GARCIA, 1973, 1975), and according to APALATEGUI (1977) one cannot exclude the possibility that a Cambro-Ordovician volcanic sequence is represented in the rocks, which after Martinez Garcia (pers. comm.) now should be interpreted as Late Cambrian.

Metamorphic events and deformations

The interpretation of the pre-Variscan geology of the five external massifs needs some information on metamorphic events.

Hypersthene-bearing garnet-biotite-feldspar schists from the Gotthard area indicate a pre-Variscan granulite facies event (ARNOLD 1970-b) of Caledonian age (450 Ma: GRAUERT & ARNOLD, 1968), and true eclogitic rocks are preserved in the Aiguilles Rouges (LIEGOIS, 1979). Besides these few relics of an oldest high-pressure metamorphic event all other rocks have been strongly affected by a regional anatectic event (Anatexis I), which probably also was of Caledonian age. In all massifs coarse-grained granites were formed, which in the Gotthard area were termed 'Streifengneiss' (NIGGLI, 1960), and which yielded an age of 420-450 Ma (ARNOLD, 1970-a). Corresponding bodies of orthogneiss, with the same production history, have been formed in the Aiguilles Rouges (Brevent and Emosson Kf-Augengneisses), Pelvoux (gneiss de Crupillouse), Argentera (Kf-Augengneisses from Lago Valscura-Lago Claus and Iglieres). They all carry the imprint of what is probably early Variscan metamorphism, i.e. a strong preferred orientation of biotite (Streifenlinear).

In the Argentera area their intrusive contacts survive and xenoliths also are preserved. In the general picture, these orthogneisses are akin to the Flüela gneiss (Silvretta region) which has been described and precisely dated (427 Ma: GRAUERT, 1966, 1969; GRAUERT & ARNOLD, 1968).

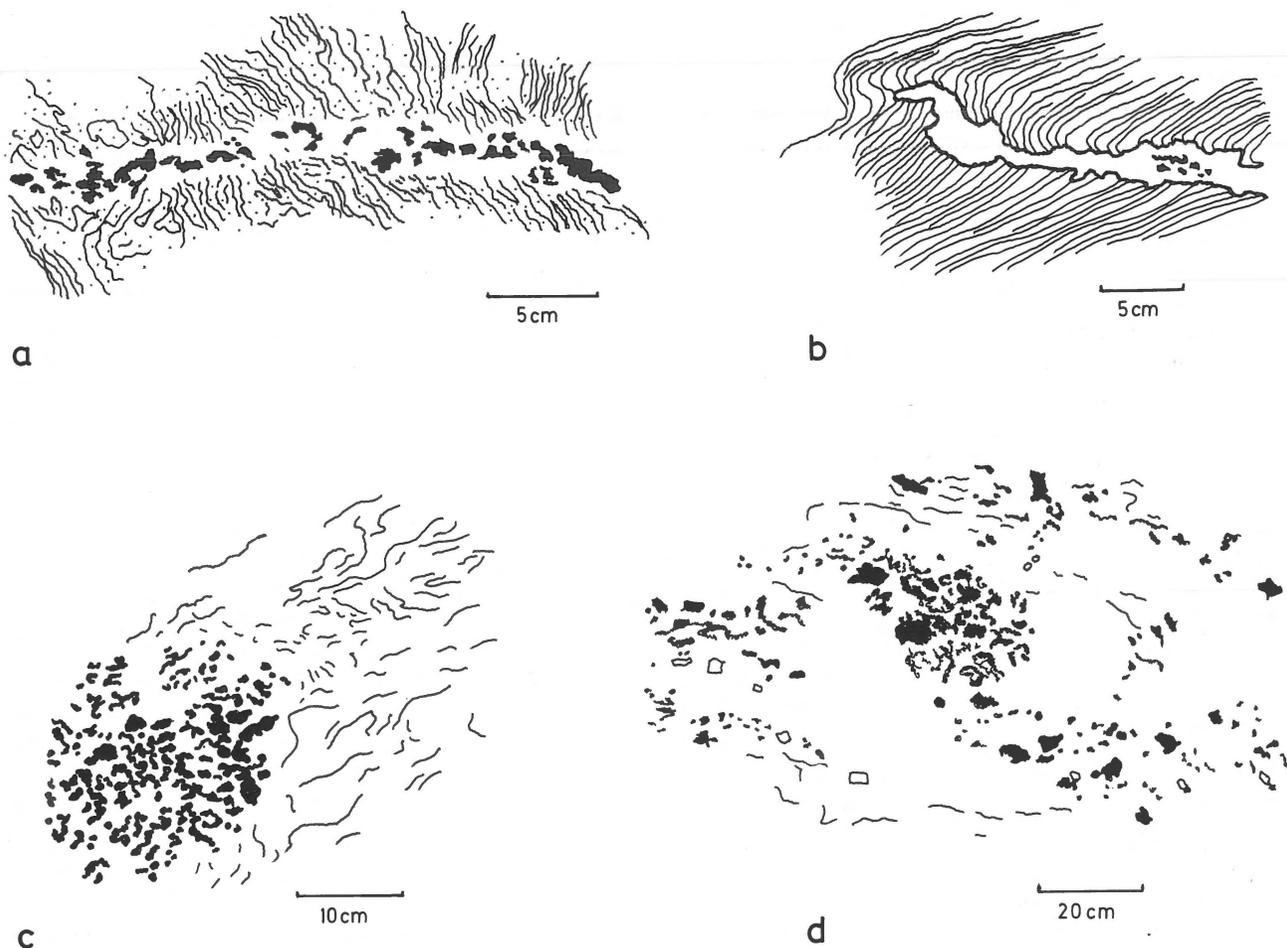After the first regional anatexis the existing structures in

Fig. 2
Mode of appearance of cordierite-bearing granitoids produced by anatexis II, of problably early Variscan age; black patches: cordierites, transformed to pinite.
(a) Vein-like occurrences of cordierite within older migmatites, with an equigranular growth of plagioclase. No sharp separation between the more leucocratic 'vein' and the migmatitic neighbourhood (Ville des Glaciers, SW end of Mont Blanc massif).
(b) Cross-cutting cordierite-bearing mobilizates following new structural features in older migmatites. (Pigeonnier area, Valgaudemar, Haut Dauphiné).
(c) Diatectic stage of mobilization with great patches of cordierite-aggregates (Colle Sabbione, Argentera massif).
(d) Already highly discordant granitoid with high concentration of cordierite patches. The patches are composed of a multitude of small prisms of former cordierite (Lauterbrunnen valley, Aar massif).

the massifs are cut by blastomylonite zones which (if one applies the evidence from the Gotthard area) may have come into existence about 420-400 Ma ago. These new cross-cutting fractures, which tend to produce a mosaic in the pre-Variscan crystalline basement, were important during the course of later developments, for together with north-south arranged structures they exerted an influence on most of the later tectonic trends. Blastomylonites were formed parallel to the newly formed lineaments. They are generally of high greenschist- to amphibolite-facies grade and in their textures they show some resemblance to the granulites of Saxony. Characteristic features of their mineral composition – new growth of garnet, kyanite, sillimanite and antiperthite, a granulation of K-feldspar, plagioclase and biotite – are seen at several places ('Gneiss de Chésérys': BELLIERE, 1958; blasto-

mylonites from the Mont Blanc and Argentera areas: VON RAUMER, 1976; 'Linéament de Pilatte', Pelvoux: PECHER & VIALON, 1970; Variscan mineral growth and granulation of older minerals in the Gotthard region: ARNOLD, 1970-b). The lensoid form of the disc quartzes in the blastomylonites is in accord with the regional schistosity and shows as well as the granulation of the different components the close relationship between temperature path and time of recrystallization. The stretching linear and the quartz lenses are sometimes related to small-scale folds. But they are not the oldest structural elements which may be recognized.

The new road cuts of Lake Emosson (Aiguilles Rouges) show for the different rock series two sets of isoclinal fold axes, before they are involved into a system of open style fold axes. The coarse-grained K-feldspar augengneisses in con-

trary display large-scale fold axes (3 km), but their relationship to the blastomylonites is not yet entirely understood, although it is supposed that they postdate the formation of blastomylonite zones.

The blastomylonite zones probably had an influence on the progress of a further anatectic event, called Anatexis II, which so far has received no dating. Since it postdates the establishment of the blastomylonites this regional event could be either late Caledonian or early Variscan. Several characteristic features distinguish this second regional anatexis. The most striking of these are mobilizates and granitoid rocks with abundant cordierite. This new-formed set of rocks – termed the 'migmatite of Innertkirchen and Lauterbrunnen' (RUTISHAUSER, 1973-a, b, c, 1974; RUTISHAUSER & HÜGI, 1978) or the 'granodiorite à pinite' in the Aiguilles Rouges and Mont Blanc (VON RAUMER, 1976), 'granodiorite à pinite' from the Belledonne (CARME, 1970) and Pelvoux (PECHER, 1970, 1971; LE FORT, 1973) or 'migmatites de Fenèstre' in the Argentera (FAURE-MURET, 1955; BLASI & SCHIAVINATO, 1968; VON RAUMER, 1976) – has been interpreted in different ways. KRUMMENACHER ET AL. (1965) discussed the regional distribution, but placing too much reliance on common lead data from zircon (800 Ma) took these to be the oldest rocks in the external massifs. The term 'serie de Fully' should be entirely dropped.

The genesis of these rocks is better interpreted in terms of a relationship with the NE-SW trending, deep-seated linear structures. In their initial stages they appear as fine veins of mobilizate set in older rocks which have cordierite growth parallel to a new set of planar structures. At the mesoscopic scale, these structures are seen to be axial planar to newly formed, steeply plunging folds. There is also a strong growth of plagioclase, but as mobilization proceeds these early details of fabric tend to be obliterated. All grades of mobilization are achieved, from *in situ* migmatites up to highly discordant magmatic rocks, and discordant granite bodies like the Gastern granite (HÜGI, 1956; RUTISHAUSER & HÜGI, 1978) or the Vallorcine granite should be interpreted as representing advanced stages of this process of evolution (Fig. 2).

Xenoliths show, that the whole lithologic sequence, excluded the Devono-Carboniferous sediments discussed above, is older than the cordierite-bearing granitoids.

The question arises: what were the ambient conditions during the different episodes of metamorphism? During Anatexis I P-T conditions of 5-6 Kb and 680-750 °C were attained and evidence from the cross-cutting blastomylonites suggests that broadly similar conditions were maintained to that stage. But their new-formed minerals indicate lower-water fugacities. One asks: had water pressure been subjected to a general lowering at the end of the first anatexis, or did the special circumstances in the blastomylonitic zones promote locally higher devolatilization? In the case of Anatexis II the mobilization of cordierite-bearing granitoids was possible. In addition, the new, regionally effective growth of plagioclase seems to indicate a heightened migration rate of Na, Ca and K. Had the water pressure been adjusted by a revival of movements parallel to the major lineaments? In the mobilizates, the abundance of cordierite cannot be explained as being due to the presence of older cordierite gneisses among the rocks mobilized. Most of these mobilizates must have been formed by anatexis of Al-rich sequences under conditions of the kind discussed by THOMPSON ET AL. (1977). After HOSCHEK (1974) Al-rich micas favour the presence of cordierite in the mobilizates.

It even seems that there are different generations of cordierite, and one particular generation forms patterns which are not influenced by the internal flow structures of the granitoids. These cordierites appear to have taken the role of mafic minerals and probably formed, within the granitoid melt, in place of normal mafic minerals such as hornblende or micas. All these cordierite-bearing rocks correspond to the S-type granitoids (CHAPPELL & WHITE, 1974), and their occurrence should have a palaeotectonic significance which will be discussed below.

After and parallel to the formation of blastomylonites we know, as already mentioned above, the occurrence of metapelites with the mineral paragenesis of Ky-Gar-Plag-Bi-Staur-Qu, where minerals seem to be undeformed. Not only these metapelites, but also metagranitic rocks show the formation of biotite and fibrolite, and fibrolite is even found as overgrowth on kyanite (oral comm. Stöckhert, 1980). A regional overgrowth of plagioclase (An 20-30) marks the axial planes of large-scale folds, and also the cordierite-bearing granitoids seem to favour similar axial planes. Alpine-type late-stage veins containing Kf-Qu-Andalusite seem to be the direct temporal consequence of this thermal evolution, and the occurrence of latest Andalusite-Muscovite filled joints are a final stage in the cooling history.

Thus the later history is characterized by a post-tectonic crystallization, which is in keeping with the general European picture as discussed by ZWART (1969). The emplacement of the late Variscan granites, their shapes influenced by the pre-existing structural pattern, marks what were the last events before revival of block tectonics and a general adjustment led to the disruption of the whole crystalline assemblage.

If placed in a P-T-diagram (Fig. 3), we can establish the following general stages of metamorphism for the External Massifs:
(1) Early formation of granulites (Gotthard) and eclogites (Aiguilles Rouges), at 450 Ma, as indicated above.
(2) Anatexis I, 650-750 °C/5-6 Kb (of probably Caledonian age) and formation of older granites, now present as orthogneisses in large-scale folds.
(3) Formation of blastomylonites, locally with Ky, Sill, Gar, granulation of older mineral components, amphibolite-facies grade, low H_2O fugacities.
(4) Mineral paragenesis of Ky-Staur-Gar in metapelitic rocks.
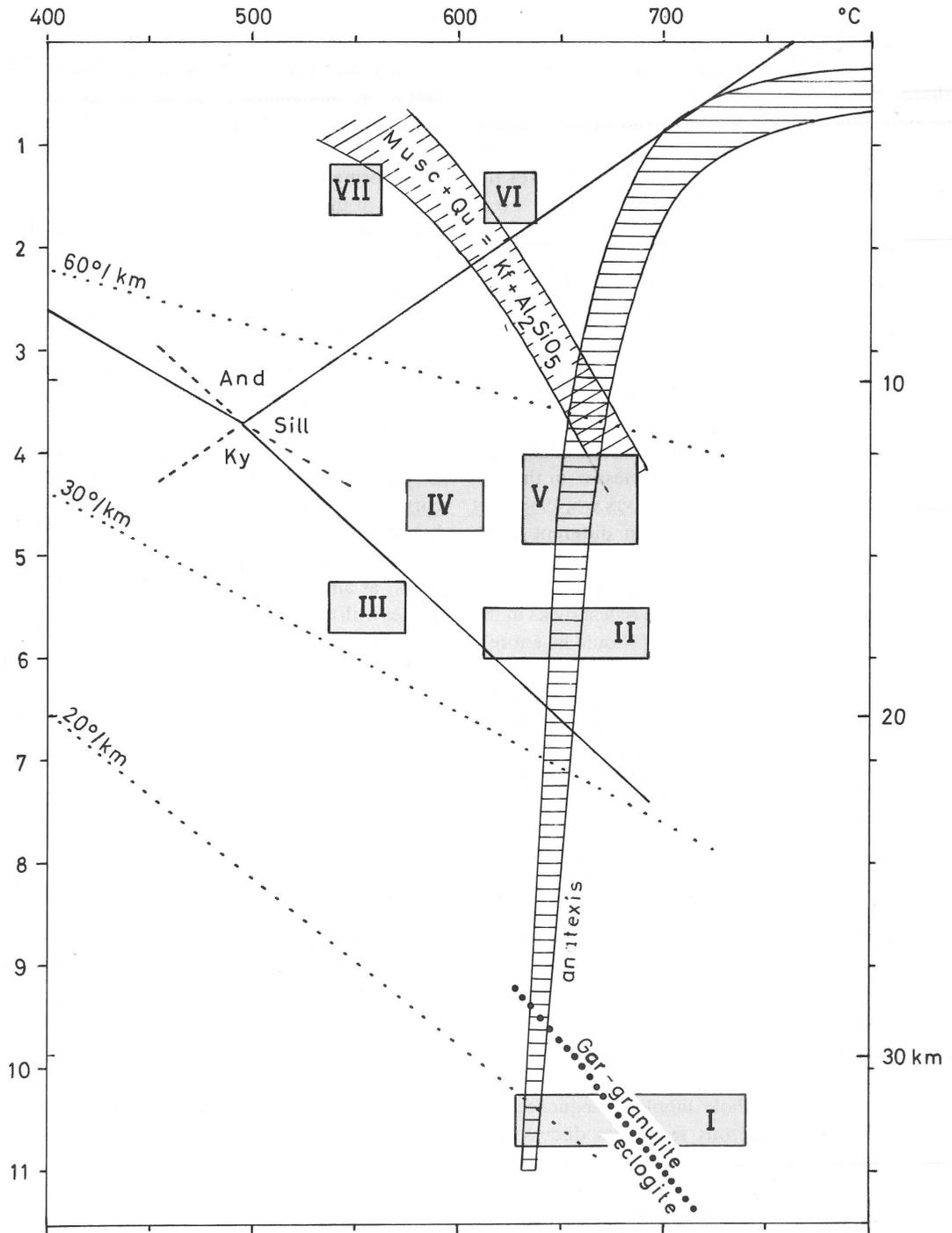(5) Widespread formation of fibrolite.

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Fig. 3
P-T evolution in time of the pre-Permian crystalline basement in the External Massifs of the Alps. Al_2SiO_5 – triple point after Holdaway (1971) and Helgeson et al. (1978). Explanation of the roman chiffers, references are given in the corresponding chapters.
(1) eclogites from Aiguilles Rouges, granulites from Gotthard massif (450 Ma).
(II) First anatexis and formation of granites, probably of Caledonian age (granites 450-420 Ma).
(III) Blastomylonite zones of probably late Caledonian age (or early Variscan age). Ky-Gar-Staur mineral assemblages (Argentera, Aiguilles Rouges).
(IV) Regional formation of fibrolite (Argentera, Aiguilles Rouges), biotite and plagioclase.
(V) Anatexis II with formation of cordierite-bearing granitoids (of probably early Variscan age).
(VI) New-formed late-stage andalusite-K-feldspar alpine-type veins and formation of andalusite in early Ky-Qu-veins.
(VII) Late stage growth of andalusite and muscovite on joints.

(6) Anatexis II with formation of cordierite-bearing granitoids.

(7) Regional formation of biotite-plagioclase, even with cordierite and late andalusite (plagioclase containing relics of Ky-Gar-Staur).

(8) Late-stage alpine-type veins with K-feldspar-quartz-andalusite.

(9) Latest cross-cutting joints with andalusite-muscovite.

The question arises, how to explain the anatexis and the large-scale formation of Al-rich granitoids containing cordierite. As a model could serve the idea of a general uplift since the formation of blastomylonites allowing the lowering of pressure and a rise of heatflow, as indicated by ENGLAND & RICHARDSON (1977). The low-pressure type of regional mobilization under higher heat-flow conditions would favour the formation of cordierite-bearing melts. The general uplift and updoming allows the formation of the late-stage alpine-type Kf-andalusite veins, whereas during the following cooling history the latest andalusite-muscovite veins were formed.

GENERAL EVOLUTION
OF THE EXTERNAL MASSIFS

It is now clear that the crystalline basement of the so-called 'Hercynian massifs' was mostly formed during an early, distinctly pre-Variscan episode. It is known that it contains relics of old detrital zircons (GEBAUER & GRÜNENFELDER, 1977), but according to JÄGER (1977) there is no indication of anything older than 700 Ma in the Alpine domain. VIDAL (1977), who dealt with this question in the course of discussing Rb/Sr initial ratios, came to similar conclusions. More recently ZWART & DORNSIEPEN (1978, 1980) discussed in contrary the existence of a much older continental crust similar to that of the Armorican massif, which underwent complete reworking during later events. Obviously since Caledonian time all five massifs show a continental evolution, and the production of anatectic rocks and granite bodies as well as the occurrences of granulites and eclogites refer to what is clearly a major Palaeozoic event, but what they signify in terms of the limit of the Variscan range of events is less clear.

This question of the transition from pre-Variscan to Variscan events deserves discussion in more detail. One might say that the task is to make a distinction between what is Caledonian (Taconic) and what is Variscan (Acadian). However, JÄGER (1971) has already discussed the possibility of a gradual transition from Caledonian to Variscan events and HUNZIKER (1974) has expressed the opinion that no real interruption separates the two cycles. SCHMIDT (1976) largely discusses the problem of the 'Caledonian event' and BEHR (1978) even advances the continuous creation of magma and appearance of zones of metamorphism as a property of secular deep-level events where no real time mark can be set.

In crystalline terrain, definition of Variscan effects and, indeed, of a Variscan 'cycle' is not easy. Events which took place at the surface, recorded in evidence such as unconformities or the presence of conglomerates in sedimentary successions, can be interpreted in terms of distinct Variscan tectonic phases. However, in crystalline terrain other criteria have to be sought. As WEGMANN (1953, 1956) has pointed out, a means of 'vertical synchronisation' is required in order to demonstrate contemporaneity of events at different levels. In older crystalline terrains, Variscan effects might be indicated by deformation, or magmatic activity, metamorphic overprint, geochemical exchange or isotopic evolution. In WATZNAUER's (1967) opinion it might be possible to recognize synchroneity at the point in time, when orogenic (s.l.) events give over to 'mosaic tectonics'; i.e. when major tectonic lineaments already in existence in the basement begin to have an effect on the cover. The blastomylonite zones recognized in the several different external massifs could be significant in this connection.

It is clear that two distinct sets of events took place in the regions discussed: first, production of the crystalline basement rocks and later, development of intramontaneous troughs which received sedimentary detritus starting perhaps already in Devonian time. But already in the first there has to be made a difference between areas where only anatexis II or its accompanying effects can be recognized, and areas, where anatexis II is superposed on anatexis I. They seem to be also those regions, where occurrences of granulite facies and of eclogites indicate the deeper localization during the first anatexis. The higher levels at the same time with identifiable stratigraphy seem to suffer more from a prograding metamorphism with its highest point in early Variscan time (Acadian?). Thus the discussion of obviously two different sets of metasedimentary series seems to be quite reasonable.

We should consider the palaeogeography up to the beginning of Variscan events. If the external massifs are to be taken as representing parts of a continental domain, where did this continent give over to an oceanic region? Different opinions have been put forward. LAURENT (1972) and NICOLAS (1972) postulated a Variscan subduction zone in the south of the Moldanubian zone, and BEBIEN ET AL. (1977) have recently again discussed that possibility, arguing that the chemical composition of the Devono-Carboniferous metavolcanics indicates an Andean-type plate boundary. The region under discussion has suffered so much during Alpine events that data bearing on the question of palaeotectonic situation are hardly thought to be accessible. But there are, nevertheless, some questions which deserve to be posed.

The occurrence of metabasics with tuffs and with ultrabasic rocks as well does not precisely indicate any particular palaeotectonic situation, for such rocks could have formed either in oceanic or in intracontinental circumstances. It is, however, the latter possibility that is favoured by the presence of the amphibolo-leptynitic series, which could be interpreted as a bimodal volcanic series such as CHRISTIANSEN ET AL. (1972) and LIPMAN ET AL. (1972) suggest to be typical of recent continental rift systems. Recently PIBOULE ET AL.

(1979) discuss the origin of the amphibolitic-leptynitic series from the Massif Central in the sense of affiniities to oceanic tholeiites. For the Alpine occurrences more chemical data are needed to try a more precise classification.

If there are differences in the sequence of metamorphic events for the metasediments, they may be explained as different erosion levels at a given time indicating level changes due to tectonic events. The occurrences of high-pressure rocks during a relatively early time may be the sign of relatively internal situated deep-level thrust planes. In the same direction point the local findings of flat-lying structures in the Argentera (BOGDANOFF, 1970; PRUNAC, 1976) and the Aiguilles Rouges (BLANC, 1976), which may be the sign of relatively early Pennide nappe systems already in development in time before the crystalline basement has been disrupted by active lineaments.

Where, if we apply a plate-tectonic model to Variscan tectonic evolution, is the high-pressure belt of Variscan age? Is it really hidden under the high-pressure belt of Alpine age, as NICOLAS (1972) has suggested? What is then the significance of granitoids with pinite? Known from the External Massifs, they are also present in the Massif de Maures (MAQUIL, 1976) and in the Black Forest. In the latter case they are present always as the earliest members of a sequence of Variscan granitic intrusions (EMMERMANN, 1973; EMMERMANN ET AL., 1975) yielding an age of 360 Ma (Klemmbach-Schlachtenhaus Granite, Rb/Sr: BREWER & LIPPOLT, 1974). What is apparently a similar event, involving closely comparable cordierite-bearing granitoid rocks, is dated at about 350 Ma in the Massif Central (AUTRAN & GILLOT, 1977; AUTRAN, 1978; CANTAGREL ET AL., 1979), and CHENEVOY & RAVIER (1977) refer to it as the later anatexis of the Massif Central.

This widespread occurrence of cordierite-bearing granitoids associated with a second anatexis could be evidence of 'Variscan' happenings within the older 'Caledonian?' crystalline basement; these phenomena should belong to the second stage of crustal evolution so clearly indicated by the different slope of general Rb/Sr-age relationship (DUTHOU, 1977) since early Variscan time. Could it be that this zone of cordierite-bearing granitoids represents a kind of low-pressure belt situated to the north of a former subduction zone? If we attempt comparisons with the much more complete N-S section available in Brittany, we might find that there are some things in common with the 'Anticlinal de Cornouailles' (COGNÉ, 1974, 1976, 1977). There again, after an earlier chapter of events, continental crust is disrupted by lineament-type structures along which Variscan mobilizates arise to affect transformations of earlier rocks. And to the north of the high-pressure belt (Ile de Groix) granitoid rocks with pinite are once more to be found (morbihanite: COGNÉ, 1961). Again one is left to ponder the possible palaeotectonic significance of these zones of cordierite-bearing granitoids present from the Alps until Brittany. It is interesting, that LE FORT ET AL. (1978) refer to a narrow zone of cordierite-bearing granites over 1600 km from the Himalaya. These rocks in the

Argentera region especially contain large quantities of xenoliths which show evidence of eclogitic origin. And although it is in the Argentera that they are particularly abundant, they occur in the Mont Blanc area also. If, in this latter case, there has been considerable subsequent translation to the north-west during the course of Alpine events, these remnants of old rocks could be the evidence of early tectonic activity, at sites farther to the south, involving a downgoing slab of oceanic crust, pieces of which were caught up in the subsequently evolved granitoid mobilizates and returned to the shallower levels where they now appear as xenoliths.

If referring again to Brittany, a situation in a zone comparable to the 'Ligérien' (AUTRAN & COGNÉ, 1980) seems to be the most adequate interpretation for the palaeogeographic situation of the External Massifs of the Alps between the Moldanubian zone in the north and the African shield in the south.

ACKNOWLEDGEMENTS

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