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*In memoriam P. Bearth*

## **The Briançon basement (Pennine Western Alps): Mineral composition and polymetamorphic evolution**

by *Jacqueline Desmons*<sup>1</sup>

### **Abstract**

Microprobe chemical analyses have been performed on Alpine and pre-Alpine minerals from the internal Briançonnais basement units, i.e. the ancient (pre-Alpine polymetamorphic) basement and the younger basement (where no pre-Alpine metamorphism is detected). The analyzed minerals are: garnet, muscovite, phengite, paragonite, Ca- and Na-pyroxene, chlorite, biotite, and others.

The P-T conditions of each metamorphic phase have been estimated from experimental mineral stability curves and element distributions.

On the basis of petrological observations and the available chronological data the facies succession appears to be the following: Proterozoic eclogite, Proterozoic (?–Early Cambrian) amphibolite I and II, (? late Variscan) H-T greenschist, Alpine glaucophane-epidote or glaucophane-lawsonite schists, greenschist I and II. The conditions are assumed to have evolved from Proterozoic cratonic deep-crust level to Proterozoic (?–Early Cambrian) orogenic middle-crust, through late Variscan extensional uplift to upper-crust level, to late eo-Alpine H-P, meso-Alpine M-P and neo-Alpine L-P orogenic regimes.

**Keywords :** Western Alps, Briançon zone, metamorphism, mineral chemistry, paleo-geothermal gradients.

### **Résumé**

Des analyses chimiques ont été effectuées à la microsonde sur des minéraux alpins et anté-alpins du socle briançonnais interne: le socle dit ancien (polymétamorphique anté-alpin) et le socle dit récent (où aucun métamorphisme anté-alpin n'est décelé). Les minéraux analysés sont: grenat, muscovite, phengite, paragonite, pyroxène calcique et sodique, chlorite, biotite, etc.

Les conditions thermobarométriques des métamorphismes successifs ont été évaluées grâce aux courbes expérimentales de stabilité des minéraux et aux coefficients de partage d'éléments.

La succession des faciès telle que l'indiquent les observations pétrologiques et les données chronologiques est la suivante: faciès éclogite protérozoïque, faciès amphibolite I et II protérozoïques (à Cambrien inférieur?), schiste vert de haute température (tardi-varisque?), schiste à glaucophane-épidote ou à glaucophane-lawsonite, alpin, puis faciès schiste vert I et II alpins. Au cours de leur évolution les roches ont pu se trouver dans des conditions d'abord de croûte profonde cratonique, au Protérozoïque (à Cambrien inférieur?), puis de croûte moyenne orogénique, puis être soumises à une extension et à un soulèvement jusqu'au niveau de la croûte supérieure, à la fin de l'orogénèse varisque, avant de connaître un régime orogénique, successivement de haute pression à l'éo-Alpin tardif, de pression moyenne au méso-Alpin et de basse pression au néo-Alpin.

**Mots clefs:** Alpes occidentales, zone briançonnaise, métamorphisme, chimisme des minéraux, paléo-gradients géothermiques.

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## Introduction

The Pennine Briançon basement (pre-Upper Carboniferous) has been metamorphosed and deformed several times during and before the Alpine orogeny, probably starting in the Proterozoic. Microprobe chemical analyses have been performed on minerals from various assemblages, Alpine or earlier in age, in order to display chemical differences between various mineral generations and constrain the P-T paths.

## The Briançon zone

The Briançon zone (equivalent to the Swiss Bernhard zone) (Fig. 1) is constituted of:

- 1) an external part consisting of a pile of Silesian to Scythian continental rocks exposed in the N (this is the "zone houillère"), supporting a cover of Mesozoic quartzite and carbonate rocks in the S (the latter is the so-called classical Briançonnais),

- 2) an internal part which is subdivided into basement massifs (massif being taken in a geographic meaning, each corresponding to a pile of sheets) and various cover series. In many cases the contacts between cover and basement are tectonic. On the basis of several lines of evidence, all these units are now considered as deriving from the northern margin of Gondwana rather than from the European margin (HUNZIKER and MARTINOTTI, 1984–86; DESMONS, 1986b; RADELLI and DESMONS, 1987, 1990; HUNZIKER et al., 1989).

The basement massifs belong to two types which differ in their metamorphic imprints and in lithological and chemical characteristics (DESMONS and FABRE, 1988; DESMONS and PLOQUIN, 1989; DESMONS and MERCIER, 1992; DESMONS, in press): 1) an ancient basement which records effects of pre-Alpine metamorphisms, and 2) a younger basement which is lithologically different from the Silesian–Permian sequence of the zone houillère and records no trace of a pre-Alpine metamorphic imprint. Slices of the ancient basement are associated with the younger basement within some massifs, e.g. in the Pourri-Bellecôte massif.

Ancient basement units consist of metasedimentary (pelite, greywacke, very rare carbonate rocks), metabasic rocks (mostly high-Ti tholeiitic, also spilitic, rarely alkaline rocks, commonly associated with leucocratic rocks) (DESMONS and HUNZIKER, 1988; DESMONS, in press), very rare ultrabasic rocks and a few subalkaline, anatectic, meta-granitoid rocks. The lithology is similar to the gneiss-amphibolite association typical of many Austro-Alpine and South-Alpine basement units.

Age determinations of the protoliths in the Western Alps are not yet available. The series can be considered as a Gondwana-type series characteristic of middle to deep crust, with staurolite-garnet-kyanite-sillimanite assemblages, relics of eclogite facies and intrusive granitoids. In the younger basement units metasedimentary rocks are found together with both cumulate and extrusive magmatic rocks of basic to intermediate composition (e.g. GUILLOT et al., in prep.). Major elements show these magmatic rocks to be, on an average, slightly more evolved than those from the ancient basement (DESMONS and PLOQUIN, 1989), but a proper distinction will be possible only on the basis of trace element data.

Available age data concerning the minerals and the parageneses will be summarized in the last section. The Alpine metamorphisms and deformations strongly overprinted the pre-Alpine primary and metamorphic features. The prevailing structural elements are related to late Alpine (Cainozoic) events. Many rocks are now tectonites and show a reduced grain size with respect to the pre-Alpine metamorphic or magmatic grain size. For decades these predominating Alpine effects prevented recognizing the pre-Alpine evolution (Bocquet [DESMONS], 1974 a, d).

Evidence supporting the Alpine metamorphic evolution in the Western Alps has been summarized elsewhere (e.g., FREY et al., 1974; DESMONS, 1977, 1989; HUNZIKER et al., 1989). The evolution includes early eo-Alpine eclogite facies (in units more internal, in their present location, than the Briançon zone), late eo-Alpine glaucophane  $\pm$  jadeite (in all Pennine units, including the Briançon zone), meso-Alpine greenschist facies (the grade increasing from WSW to ENE and from S to N, to reach amphibolite facies in the Monte Rosa massif) and neo-Alpine low-greenschist to very low-grade facies. Pendent questions include the exact timing of the eo-Alpine, especially the late eo-Alpine phase (the latter often connected either with the early eo-Alpine or with the meso-Alpine phase), the age and pressure conditions of some eclogite parageneses and the dynamic environment of the metamorphic phases.

## Sampling and technical procedures

Analyses have been performed on minerals from the Rutor-Pontis, Zona interna, Pourri-Bellecôte (also called northern Vanoise), Chasseforêt (also called southern Vanoise), Sapey and "4th slice" basement units. All valid analyses have been plotted in the diagrams, together with sixty-one unpublished analyses obtained by F. Guillot from

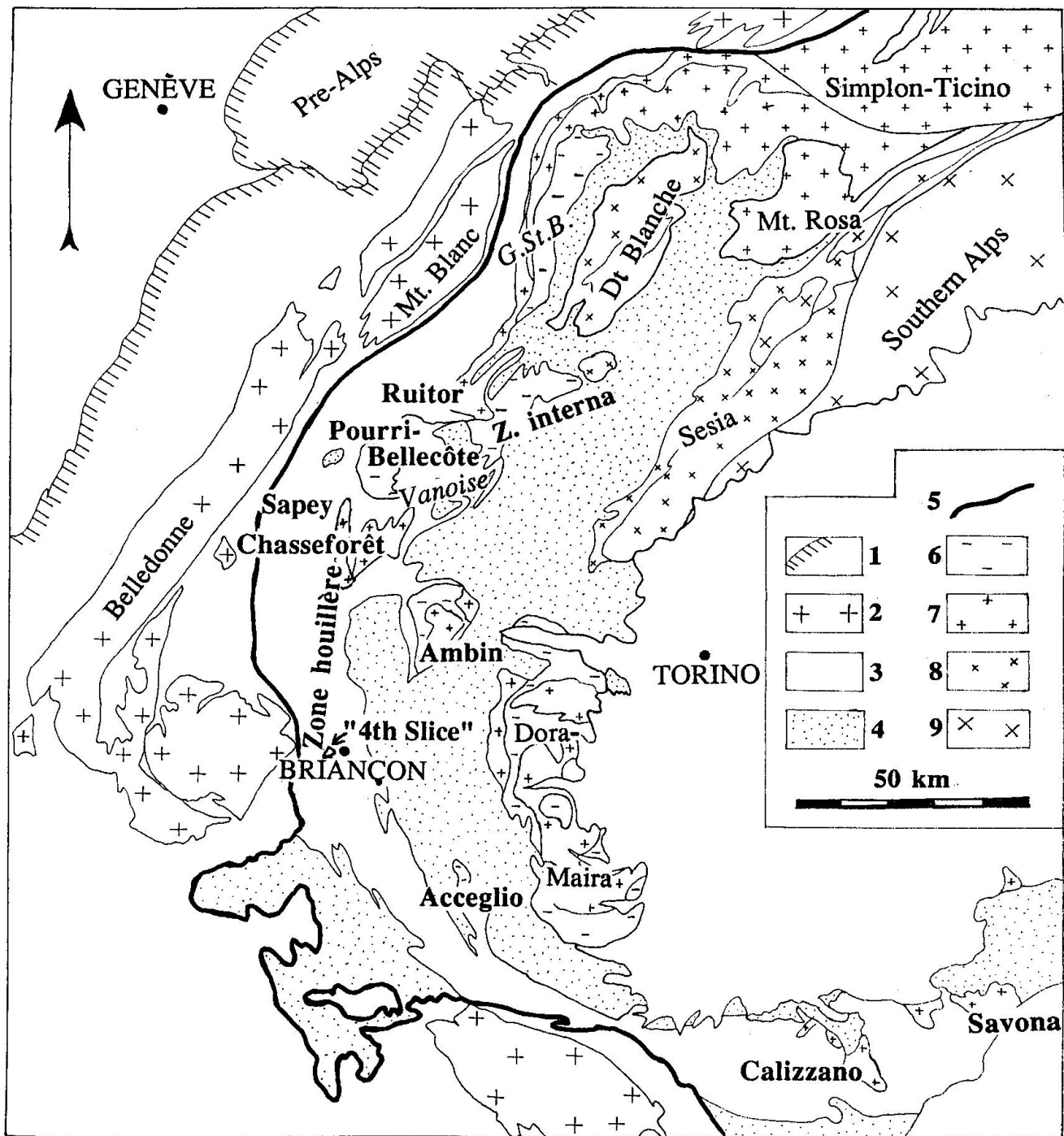


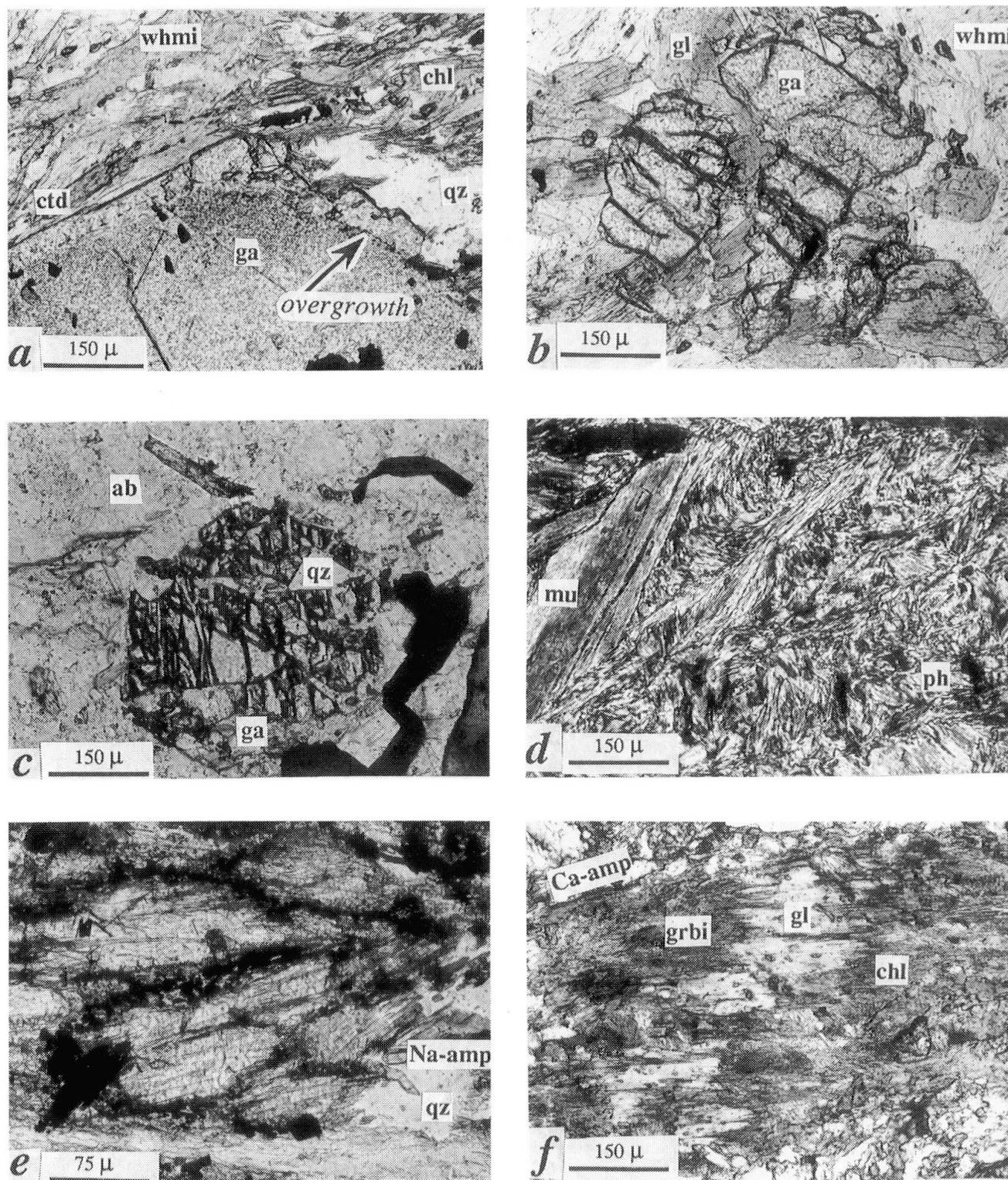
Fig. 1 Sketch map of the Briançon zone in the Western Alps. 1. Cover of the external zones, Pre-Alps; 2. External crystalline massifs; 3. Penninic cover, Valais zone; 4. Combin and Zermatt zones, undifferentiated; 5. Penninic front (boundary between Alpine Europe and Alpine Gondwana); 6. Penninic younger basement; 7. Penninic ancient basement, Simplon-Ticino nappes (Central Alps); 8. Sesia and Dent Blanche zones and related Klippen; 9. Southern Alps, "Second diorito-kinzigitic" zone.

minerals from the Mt. Pourri massif. A table of selected analyses is given in the appendix. More analytical data are available upon request.

Petrographical data on the same, or similar, samples can be found in BOCQUET (DESMONS) (1974c, with previous references), DESMONS et al.

(1977), ETERRADOSSI (1983), BAUDIN (1987), GUILLOT (1987), DESMONS and FABRE (1988). Stable mineral assemblages have been inferred from the textural relationships as observed in more than 650 thin sections from all Briançon basement units.





**Fig. 2** a) Mn-rich garnet overgrowth around almandine (chloritoid-bearing chlorite-garnet-white mica schist of the Ruitor massif). b) Garnet altered to, and overgrown by, Na-amphibole (garnet-white mica schist of the Chasseforêt massif). c) Idioblastic Mn-rich garnet in the younger basement (garnet-bearing albite gneiss of the Zona interna). d) Post-crystallization deformation in pre-Alpine muscovite and Alpine phengite (white mica schist of the Chasseforêt massif). e) Na-pyroxene altered to zoned Na-amphibole and surrounded by small Fe-oxide grains (green biotite-jadeite-Na-amphibole-white mica schist of the Chasseforêt massif). f) Na-amphibole (a pseudomorph of Ca-amphibole) altered to chlorite, Ca-amphibole and green biotite (metabasite of the Ruitor massif). Mineral abbreviations for all figures: ab, albite; aeg, aegirine; alm, almandine; amp, amphibole; and, andalusite; chl, chlorite; ctd, chloritoid; ep, epidote; ga, garnet; gl, glaucophane; grbi, green biotite; jd, jadeite; Ksp, K-feldspar; ky, kyanite; lw, lawsonite; mu, muscovite; ougr, uvarovite + grossular; ph, phengite; pum, pumpellyite; py, pyrope; pyph, pyrophyllite; qz, quartz; sill, sillimanite; sp, spessartine; whmi, white mica.

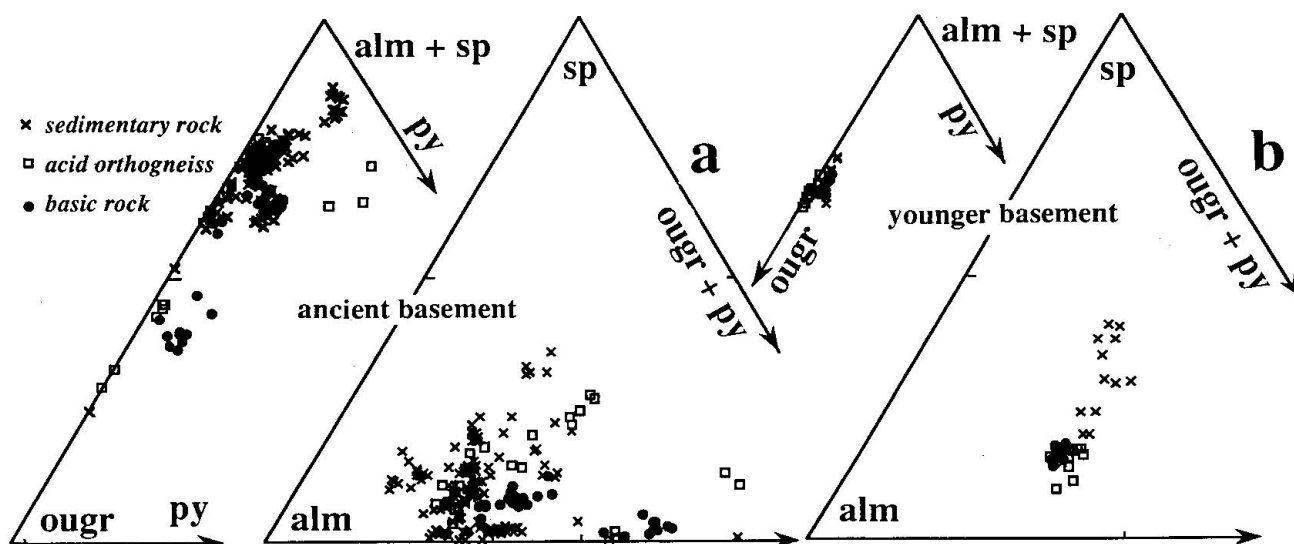


Fig. 3 Garnet composition in the ancient (a) and younger (b) basement (236 analyses from 24 samples).

Mineral compositions have been determined with the Cameca-Camebax microprobe of the University of Nancy I and with the ARL-SEMQ microprobe of the University of Bern.

Fe has been considered as entirely bivalent in white mica, Ca-amphibole, chlorite, Ca-clinopyroxene, pumpellyite, tourmaline, titanite and rutile, entirely trivalent in epidote, Na-pyroxene, stilpnomelane and kyanite, and half-bivalent, half-trivalent ( $\text{FeO \%} = \text{Fe}_2\text{O}_3 \%$ ) in Na-amphibole and biotite.  $\text{Fe}^{3+}$  can be regarded as being overestimated in Na-amphibole and biotite, and underestimated in Ca-amphibole. No effort has been made to refine the formulae by balance calculations or other methods as "no one recalculation scheme is even near to being reliable" (GRAHAM and POWELL, 1984). A conscious error, albeit of undetermined size, is better than the false security gained from figures.

## Discussion of analytical results

### GARNET

Garnet is of special interest as it has been stable during a great part of the pre-Alpine history of the ancient basement. It forms up to centimeter-sized porphyroblasts, which under the microscope appear as planed by Alpine foliation surfaces, or fragmented into smaller, commonly euhedral, grains swept along the fold limbs or the axial foliation plane. In the latter case, partial zoning patterns of each fragment can be integrated to make a consistent whole-grain pattern.

Occasional helicitic structure is marked by tiny titanite inclusions. The development of very small

epidote grains can be related to pre-Alpine alteration. Quartz inclusions are present in the garnets of metapelitic rocks, but generally they are not so abundant as to produce sieve structures. Atoll structures can locally be found. Alpine Na-amphibole and chloritoid may partially replace garnet or enclose garnet remnants (Fig. 2b). Conceivably, this might have been facilitated by a previous, thus pre-Alpine, greenschist alteration (to biotite or chlorite) of the garnet. Alpine deformation under the hydrous conditions of the greenschist facies produced chlorite veins, rim alteration or even a total replacement of the garnet grains by chlorite. Alpine garnet overgrowth is an uncommon feature, found in the Ruitor massif, but not in the Chasseforêt massif (Fig. 2a).

In the rocks of the younger basement Alpine garnet is present as small (0.05–0.30 mm) euhedral grains (Fig. 2c). It is more common in the Zona interna than in the Pourri-Bellecôte massif, due to the zoneography of the meso-Alpine metamorphism, the grade of which increased north-eastward (cf. ZWART and NIGGLI, 1973).

### Chemical composition (Appendix)

In the ancient basement the general composition (Fig. 3a) is almandine (average of  $\text{alm}_{59} \text{py}_7 \text{sp}_{12} \text{gr}_{22}$  in metapelites, with a maximum of 23% pyrope), consistent with amphibolite facies conditions. It is richer in grossular in basic rocks (average of  $\text{alm}_{49} \text{py}_6 \text{sp}_7 \text{gr}_{38}$ , with a maximum of 11% pyrope), especially in meta-clinopyroxenite. In most metagranitoidic rocks the garnet is grossular-rich (up to 67%), with either 20% or 43–45% almandine and 13 or 1% spessartine. Only garnets

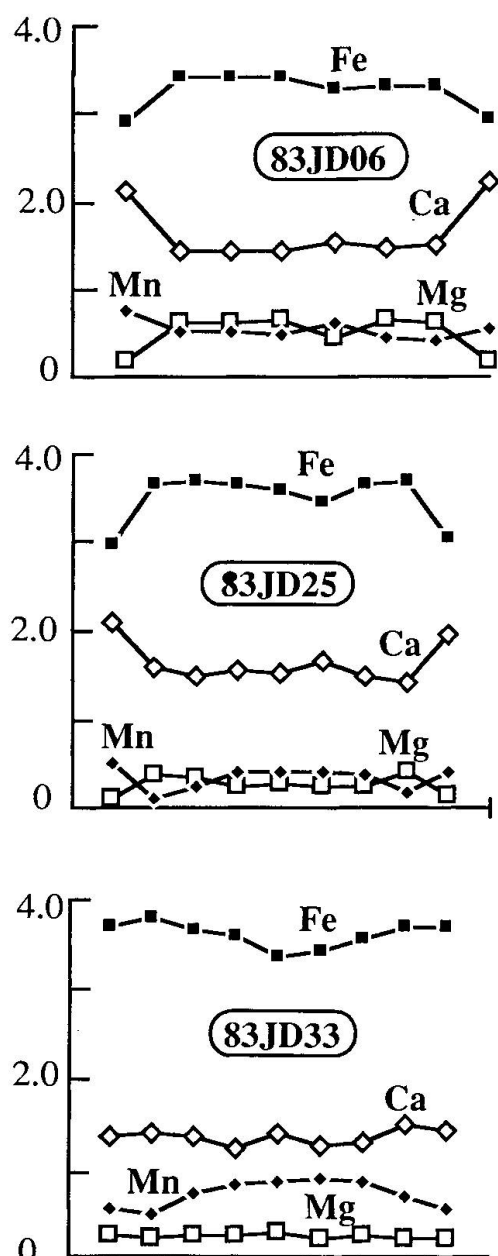


Fig. 4 Garnet zonation patterns in three samples. The distances between analytical points are arbitrarily shown as strictly equal.

from a meta-clinopyroxenite and an actinolitic hornblende-bearing amphibolite have compositions similar to those found in eclogites and associated amphibolites of the Siviez-Mischabel nappe in Switzerland (THÉLIN *et al.*, 1990). In the younger basement (Fig. 3b), garnets (which – and this must be emphasized – belong to Alpine assemblages), are characteristically spessartine-rich in all types of bulk compositions and are richer in grossular than in ancient basement rocks of comparable composition.

The overgrowths (Fig. 2b) are also spessartine-rich (25–27% spess in sample 87JD47;

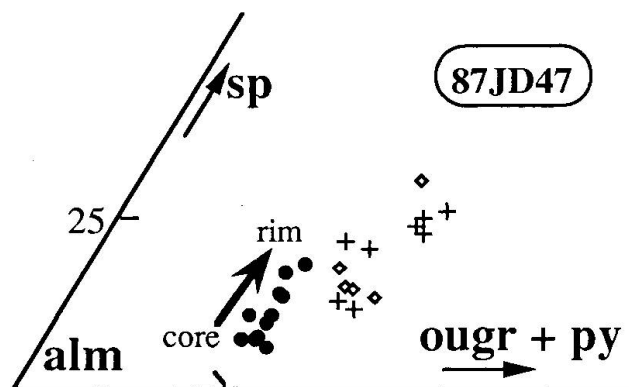


Fig. 5 Different compositions of garnet in an albite gneiss of the Rutor massif (sample No. 87JD47, see Fig. 2a). Dots correspond to center compositions (the arrow indicates the zonation), open diamonds correspond to overgrowth compositions and crosses to resorbed portions.

around 20% in the case analyzed by LADURON and DESMONS, 1981). This composition suggests greenschist facies conditions and, together with textural evidence, an Alpine age. It does not correspond to an eclogite garnet (*cf.* CABY and KIENAST, 1989).

The characteristic zonation patterns (Fig. 4) in the garnets from both the ancient and the younger basements are bell-shaped Mn- and Fe-patterns and bowl-shaped Mg- and Ca-patterns. Also characteristic are Mn- and Ca-enriched rims and crack walls, with depleted Fe- and Mg-contents (samples 83JD25 and 83JD06 in Fig. 4). Such a reverse zoning has been interpreted by DE BÉTHUNE *et al.* (1975) as resulting from a diffusion process which took place during resorption (here linked with chloritization), when garnet was preferably re-entered by the liberated Mn. This feature is likely to date from late Alpine (Cainozoic) times. Thus, various compositions can be found in a single grain (Fig. 5): (1) a zoned almandine garnet dating back from the amphibolite facies, (2) late Alpine spessartine- and grossular-rich overgrowths, and (3) resorbed portions as rich in spessartine as the overgrowths.

#### WHITE MICAS

In samples from the ancient basement, white mica grains belong to at least two generation groups (Fig. 2d). 1) One group consists of large relic grains preserved in microlithons and, locally, in old foliation planes; hand specimens may display crumpled flakes up to 8 cm in diameter; finely mashed grains may have preserved this same composition. 2) The second group is composed of

smaller grains parallel to Alpine foliation planes. Previous investigations (BOCQUET [DESMONS], 1974c; SALIOT, 1978; SALIOT and VELDE, 1982) have shown that micas of the first group are muscovite, and those of the second group phengite. It has been suggested (e.g., PLATT and LISTER, 1985; BAUDIN, 1987; PLATT et al., 1989) that the phengite content decreases in rocks of similar chemical composition from the glaucophane-bearing assemblages through the meso-Alpine greenschist to the neo-Alpine, biotite-bearing, greenschist assemblages. Moreover, there is evidence of increasing size and decreasing phengite content from SW to NE, that is, going towards the thermal culmination of the Central Alps.

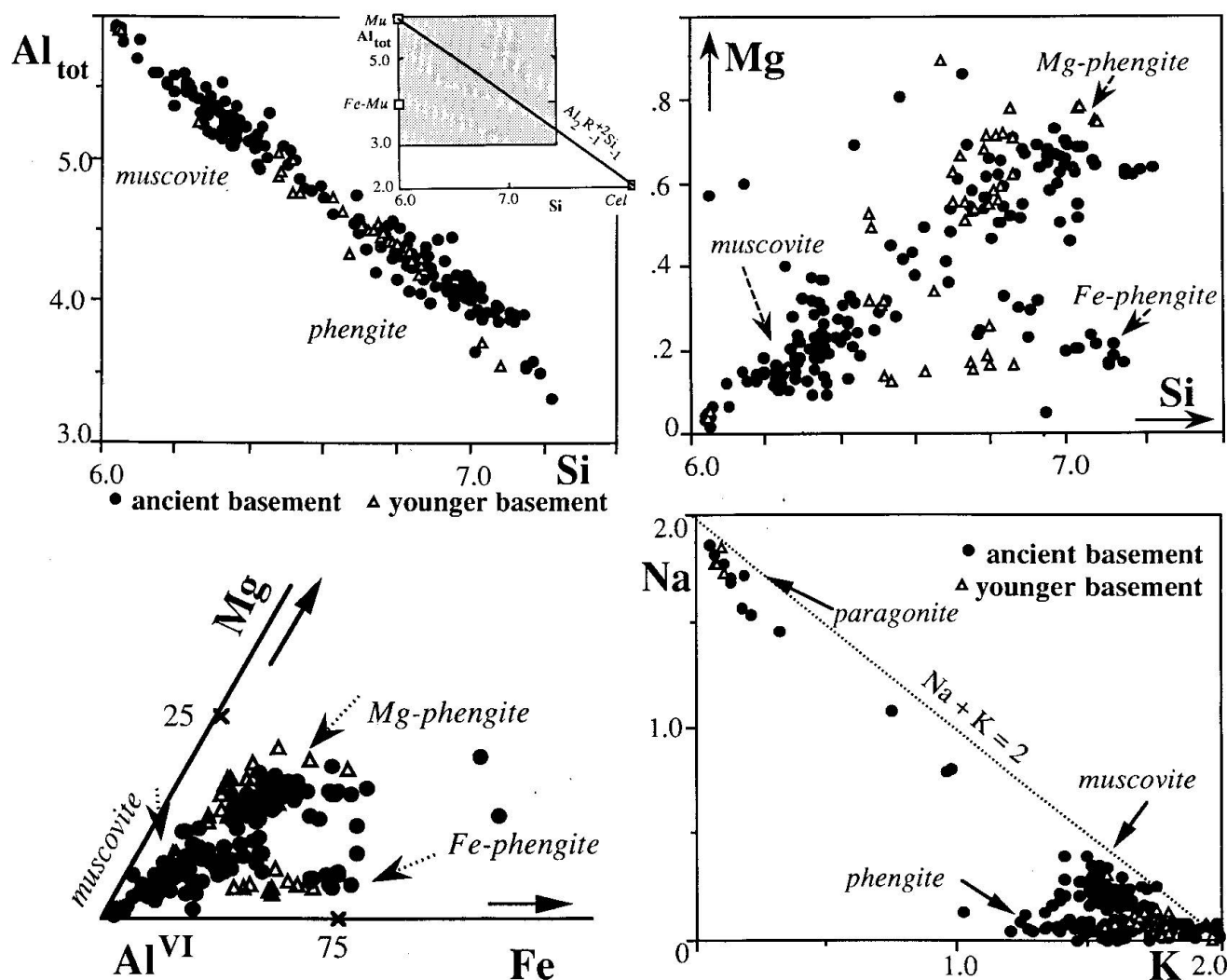
### Chemical composition

In many samples there is a chemical gap between both generations, although this is partly smoothed

out when all samples are plotted together (Appendix, Figs 6, 7, 8 and 9).

Most white micas from the younger basement are phengites. In the ancient basement the Si-content ranges from approximately 6.0 to 6.6 in the first generation group (muscovite), and from about 6.6 to 7.1 in the finer-grained Alpine generation group (phengite), with Mg contents of 0.1 to 0.4 in the first generation and up to 0.8 in the second.

The substitution of  $\text{Al}^{\text{IV}}$  by Si is accompanied in most cases by a higher Mg-content or, in meta-granitoidic rocks of either the ancient or the younger basement, by a higher Fe-content (Figs 7, 8). This suggests a local control by element availability, the Fe/Mg ratio being high in granitoids and the reaction domain where phengite grew including either quartz and muscovite (Fe-phengite) or quartz, muscovite and chlorite (Mg-phengite). Thus, a meta-granophyre of the Zona interna contains both muscovite and Fe-phengite;



Figs 6, 7, 8 and 9 White mica composition (some 210 analyses from 26 samples).



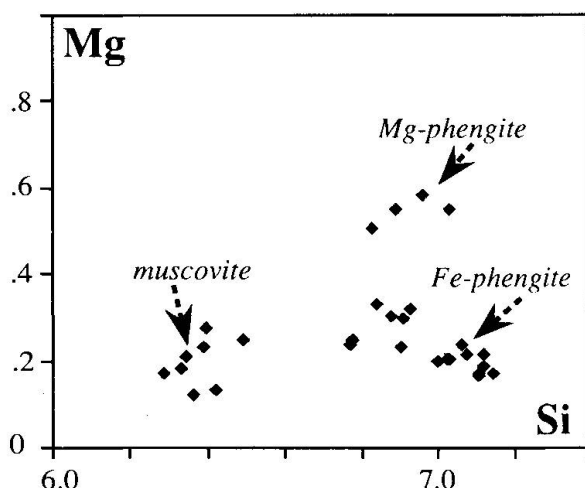


Fig. 10 White mica composition in a metagranitoid of the Ruitor massif (sample No. 83JD22).

a metagranitoid of the Ruitor massif contains both Fe-phengite and Mg-phengite, in addition to paragonitic muscovite (Fig. 10).

Paragonite contents in the range of 10–20% are common in muscovite samples from the ancient basement (Fig. 9), especially, but not only, in the Na-amphibole-bearing samples. Paragonite ( $\text{Na}/(\text{Na} + \text{K}) \geq 90\%$ ) has been found as small grains (0.1–0.3 mm) in samples containing relict jadeitic pyroxene in the Chasseforêt massif and as large grains (0.8–1 mm) at the bottom of the Pourri-Bellecôte massif (within a slice of undetermined structural relationship) (DESMONS, unpubl. report 1986). The latter case documents the stability of the left-hand member of the reaction: garnet + paragonite + glaucophane = chlorite + albite (+ quartz +  $\text{H}_2\text{O}$ ) (HOLLAND and POWELL, 1990).

#### Ca- AND Na-CLINOPYROXENE

Ca-clinopyroxene has been preserved only in the Ruitor massif. In a partly amphibolitized garnet clinopyroxenite (BAUDIN, 1987) augite is probably a magmatic relict, whereas diopside formed together with garnet.

Na-pyroxene (jadeite to aegirinic jadeite, Appendix, Fig. 11) uncommonly occurs in metagranitoid, schist and veins of the upper sheet of the Chasseforêt massif, where it clearly predates Na-amphibole. The pre-Alpine precursor mineral of this Na-clinopyroxene can be inferred to have been rich in Fe, possibly an aegirinic augite, as the Na-clinopyroxene is rimmed by, and includes, numerous tiny Fe-oxide grains (Fig. 2e). In the Ruitor massif no analysis has so far been pub-

lished of the green pyroxene reported as omphacite by CABY and KIENAST (1989).

#### Ca-AMPHIBOLE

Microscopic observations show that Ca-amphibole occurs in two generations. i) An early generation of large, pre-Alpine, hornblende s.l. grains within amphibolite facies assemblages is preserved in the Ruitor and the Ambin massifs but very rare in the Chasseforêt massif. The grains are more or less altered to Na-amphibole, or to actinolite and/or chlorite, or a succession thereof. Hornblende s.l. is also found as magmatic to post-magmatic product in younger basement sequences. ii) Later actinolite needles belong to an Alpine greenschist facies.

#### Chemical composition

In samples of the ancient basement the composition of the coarse-grained Ca-amphibole is that of hornblende, either Mg-, tschermakitic, ferro-tschermakitic, pargasitic or, rarely, actinolitic hornblende (Appendix, Fig. 12). The A-site is vacant except in one sample of the Ruitor massif in which the hornblende is pargasitic, with  $\text{Na} \approx 0.8$  in the structural formula. Ca-amphibole of the second generation, mostly fine-grained, is actinolite.

Younger basement samples contain actinolitic hornblende or actinolite. The actinolitic hornblende forms millimeter-sized grains, often clouded by tiny (titanite?) inclusions. It has been interpreted by DESMONS and FABRE (1988) as the remnant of a magmatic to post-magmatic stage.

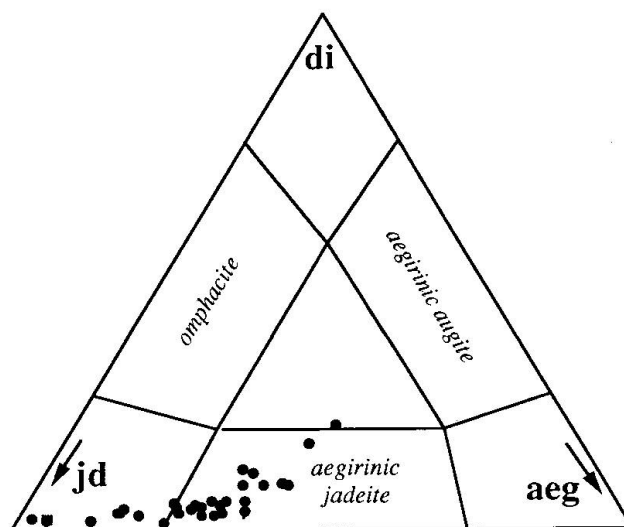


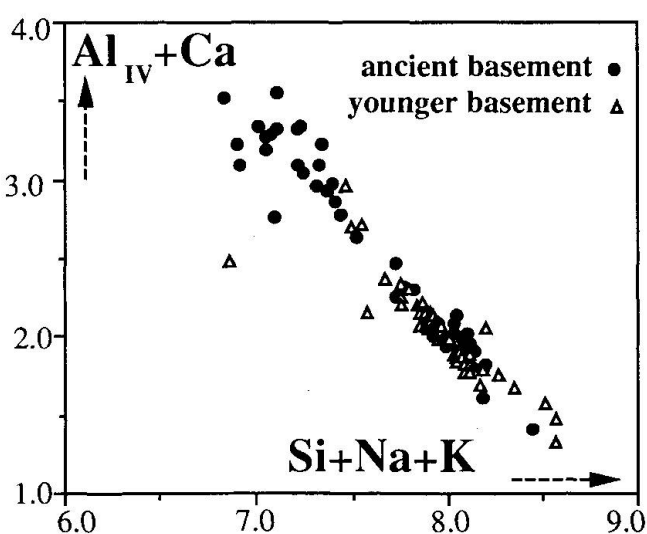
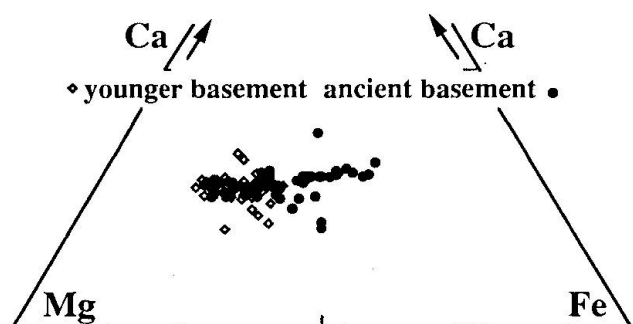
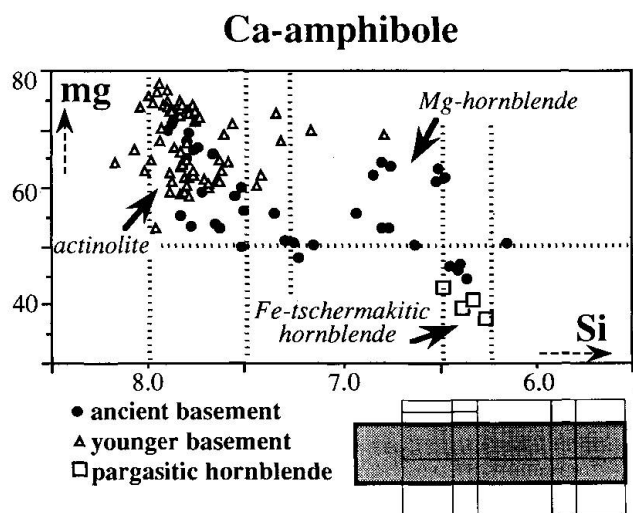
Fig. 11 Na-pyroxene composition (some 30 analyses from 4 samples from the Chasseforêt massif).

Figures 13 and 14 show the bipartition of the Ca-amphiboles into: i)  $Al^{IV}$ , Fe and Ca-rich hornblende s.l. of the early generation(s) of the ancient basement, and ii) Si and Mg-rich, actin-

olitic, amphiboles of the younger basement and, as the Alpine generation, of the ancient basement.

### Na-AMPHIBOLE

Na-amphibole grew during early stages of the Alpine metamorphic evolution. It predates the foliation planes identified as  $S_1$  by PLATT and LISTER (1985) in the Chasseforêt massif and by BAUDIN (1987) in the Rutor massif. In the ancient basement, Na-amphibole is derived from Ca-amphibole, Na-clinopyroxene, biotite or garnet. It has been altered to a fine-grained symplectite of chlorite and albite, or to Ca-amphibole, or to green biotite (Fig. 2f). It is not frequent in the younger basement. In the northern part of the Pourri massif, in the Isère valley, Na-amphibole-bearing rocks are exposed in an undetermined structural position. In this case the Na-amphibole is associated with paragonite and garnet.



Figs 12, 13 and 14 Ca-amphibole composition (108 analyses from 7 samples). In figure 12 the pargasitic hornblende has been projected from the plane  $(Na + K \geq 0.50)$ .

### Chemical composition (Appendix)

According to wet chemical analyses published by BOCQUET (DESMONS) (1974 b and c), ferroglauco-phane is common in the Briançon basement rocks. Many of the new analyses, calculated with an equal amount of  $Fe^{3+}$  and  $Fe^{2+}$ , a process that overestimates the  $Fe^{3+}$  content, plot in the crossite field (Fig. 15). Glaucophane s.str. and Mg-rie-

### Na-amphibole

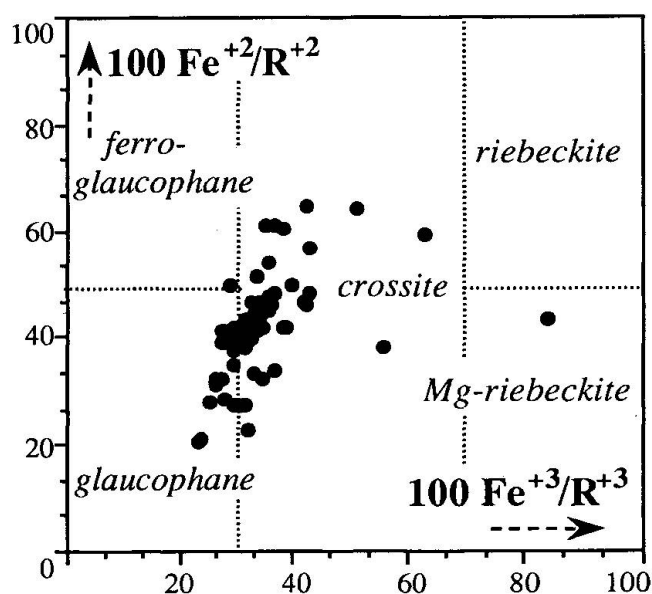


Fig. 15 Na-amphibole composition (68 analyses from 7 samples).



beckite compositions are also present. Microscopic observations and preliminary bulk rock chemical investigations indicate that this wide compositional variation is controlled by the chemistry of the microdomain or the bulk rock.

In jadeitic pyroxene-bearing samples of the Chasseforêt massif, Na-amphibole shows zoned compositions ranging from glaucophane s.str. through crossite to Mg-riebeckite. In one case, the zoning corresponds to an increase of  $Al^{VI}$  and Mg and a drop of Fe toward the rim and also at the contact with quartz inclusions. In another case, Mg-riebeckite abruptly rims the glaucophane grains. In most cases, however, the within-sample compositional variation remains low, even if the zonation is optically strong:  $\approx 10\%$  in both  $Mg/R^{2+}$  and  $Al^{VI}/R^{3+}$ .

### CHLORITE

Chlorite in the Briançon basement derives from the alteration of either brown biotite, garnet or amphibole (Ca or Na), and seems to be mostly or entirely of Alpine age. During the latest Alpine metamorphic events, part of the chlorite has been converted to green or brownish-green biotite.

#### Chemical composition

The chemical composition (Appendix, Fig. 16) is that of ripidolite, with some brunsvigite-pycnochlorite and diabantite compositions; the Fe-richest composition is found in a metagranitoid.

There is a clear correlation between the chlorite composition and the nature of the precursor mineral (Fig. 16). Chlorite derived from garnet (where  $FeO = 23\text{--}27\%$ ) is Fe-richer than chlorite derived from amphibole ( $FeO \approx 12\%$ ) or biotite ( $FeO = 19\text{--}20\%$ ). Distinct compositions can co-exist in a same section containing both garnet- and biotite-derived chlorite. This is another evidence of an equilibrium restricted to microdomain scale.

### BIOTITE

Biotite occurs as: i) uncommon pre-Alpine brown or greenish-brown grains in the Ruitor, Ambin massifs, the Sapey zone and in the "4th slice", and ii) as Alpine grains. Alpine biotite is of microscopic size and shows a green pleochroism in the Ambin, Chasseforêt and Pourri-Bellecôte massifs. It increases in size and becomes khaki to brown in the Ruitor massif and the Zona interna.

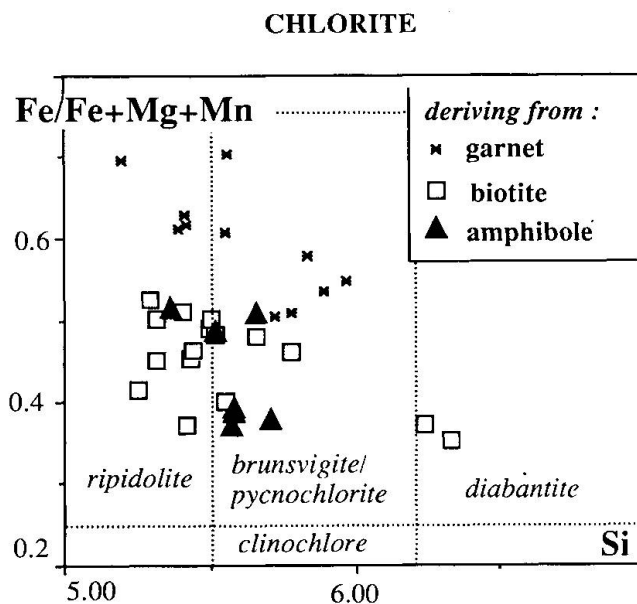


Fig. 16 Chlorite compositions grouped according to replacement relationships (58 analyses from 20 samples).

It is a late crystallization product in the Alpine evolution, growing from phengite + chlorite, according to the reaction:  $ph_I + chl_I = \text{green bi} + ph_{II} + chl_{II}$ .

Although the transformation of biotite into ferroglaucophane + phengite is very rarely visible, it must have been a common process. In the Sapey zone there is a complete transition between the brown biotite through biotite with faded colour to chlorite.

Structural relationships point to at least two pre-Alpine biotite generations (BOCQUET [DESMONS], 1974d): one coeval with, and one younger than, the garnet-kyanite-staurolite assemblage.

#### Chemical composition (Appendix)

The compositions of both pre-Alpine brown and Alpine green to brownish biotite in general range from Mg- to Fe-biotite with  $Mg/Fe \approx 1$ . Alpine green biotite from a metagranitoid of the Ruitor massif is close to siderophyllite, and another Alpine green biotite from a jadeite-bearing schist of Chasseforêt is close to phlogopite (a mineral also found epitaxial on Na-amphibole in the Mesozoic cover: BOCQUET [DESMONS], 1969).

Both pre-Alpine and Alpine biotites have rather low Ti-contents (max 1.9%  $TiO_2$ ), pointing to a metamorphic origin. The fading colour is transitional and involves decreasing  $K_2O$  and  $SiO_2$  contents, together with increasing  $H_2O$  and  $(Mg + Fe_{tot})$ , as prelude to complete chloritization.

### CHLORITOID

Chloritoid probably formed entirely in Alpine times. It is associated with white mica (muscovite  $\text{Si}_{5.85}$ ) in pseudomorphs after staurolite or kyanite in the Rutor and Ambin massifs. One occurrence has been reported from the Chasseforêt massif. To the author's knowledge it has not been described from the Pourri-Bellecôte massif and the Zona interna. X-ray investigations of BOCQUET (DESMONS) (1974c) have shown the coexistence of both monoclinic and triclinic polymorphs.

#### Chemical composition

The analyses show Fe-chloritoid compositions ( $\text{Fe}/(\text{Fe} + \text{Mg} + \text{Mn} + \text{Al}^{\text{VI}} + \text{Ti}) = 75\text{--}83\%$ ). Mn remains low ( $\leq 1.3\%$  MnO, corresponding to  $\leq 0.09$  Mn). Grain portions adjacent to chlorite are Mg-richer, cores are Fe-richer.

### EPIDOTE s.l.

Epidote s.str. and clinozoisite are mostly derived from magmatic or metamorphic plagioclase, also from garnet, or have grown around allanite grains. Optically zoned grains are common, with highly birefringent, pleochroic, pistacite rims. Epidote s.str. (pistacite) is also found in veins. Allanite is a relict mineral, particularly common in actinolite-chlorite metabasites of both ancient and younger basement types. It is generally overgrown by pistacite.

#### Chemical composition

The analyzed grains subdivide into a clinozoisite group (0–20%  $\text{Fe}^{3+}$ ) and an epidote s.str. (pistacite) group (28 to 35%  $\text{Fe}^{3+}$ ), represented in both the ancient and younger basement, with a pistacite peak at  $\text{Fe}^{3+} = 47\%$  in a aegirinic jadeite-Na-amphibole schist of the Chasseforêt massif. Mn-epidote ( $\text{Mn} = 0.12$ ) was found in tiny grains associated with white mica in a metagranitoid from the Rutor massif.

### OTHER MINERALS

#### Stilpnomelane

A mineral of sporadic occurrence in rocks of metagranitoid and albite-gneiss compositions of the internal basement massifs, stilpnomelane has been analyzed from a sample of the Sapey zone

where it grew during Alpine times as microscopic brown platelets from K-feldspar. The proportions of  $\text{Al}^{\text{VI}}$ , Fe and Mg are similar to those found in other gneisses and schists from the Western Alps (cf. BOCQUET [DESMONS], 1974c).

#### Kyanite

Analyzed in a grain partially pseudomorphed by chloritoid and muscovite, kyanite is almost pure:  $\text{Si}_4 \text{Al}_{7.93}^{\text{VI}} \text{Fe}_{0.2}^{3+}$ .

#### Pumpellyite

Minute pleochroic grains of pumpellyite from the groundmass of a Sapey leucocratic gneiss correspond to the formula:  $\text{Ca}_{3.0-3.4}(\text{Mg}_0 \text{Mn}_{0.0-0.1})_{0.0-0.1}(\text{Al}_{4.0-4.4} \text{Fe}_{1.3-1.5}^{2+} \text{Ti}_0)_{5.7} \text{Si}_{6.0-6.1}$ . Compared with rock-forming pumpellyite from acidic gneisses in Liguria (LUCCHETTI et al., 1990), it is richer in Al and poorer in Mg, Fe and Ca.

#### Albite and plagioclase

Plagioclase from the amphibolite facies paragenesis has been replaced by Alpine albite  $\text{An}_{0-3}$ . Oligoclase  $\text{An}_{15}$  is preserved in a banded amphibolite sample of the Rutor massif.  $\text{K}_2\text{O}$  is almost absent, only one sample from the Chasseforêt massif contains albite with 0.54  $\text{K}_2\text{O}$ , corresponding to 3% orthoclase.

#### Tourmaline

Tourmaline, a common accessory mineral in ancient basement schists and gneisses, is optically zoned, with either a blue core surrounded by a greenish-brown shell and a dark brown rim, or just the reverse. Analyses of a homogeneous greenish grain from the Chasseforêt basement indicate a composition intermediate between dravite (67–69%) and shorl (31–33%).

#### Ti-minerals

Many samples show titanite derived from rutile, itself likely to be a relict from an eclogite or another high-grade facies. Titanite occurs as idiomorphic crystals in metabasites containing well-developed hornblende or actinolite. The Al-content is low. Titanite remained stable up to the very last Alpine recrystallizations, which again produced Ti-oxide: titanite grains are bristling with small needles considered to be rutile from optical characters.

### P-T conditions

The P-T ranges shown in figures 17a and 17b are derived mainly from experimental stability curves and a few geothermo- and barometers. No fluid inclusion nor stable isotope data are so far available. Chronological data and tectonic settings will be discussed in the next section.

1) The eclogite conditions shown (Pre-Alpine<sub>I</sub>, in figure 17a:  $P \geq 15$  kbar,  $T \geq 650^\circ$ ) are those proposed for the Siviez-Mischabel occurrences by THÉLIN et al. (1990).

2) For the amphibolite facies assemblages (Pre-Alpine<sub>II</sub>) the minimum pressure is given by the presence of kyanite. The temperature assumed (cf. BAUDIN, 1987) is supported by geothermometric calculations on garnet-hornblende and garnet-biotite pairs.

3) The following assemblage (Pre-Alpine<sub>III</sub>), which has been recognized in some relictual samples of the Rutor massif (BOCQUET [DESMONS], 1974d) and is also reported from the Ligurian Alps (CORTESOGNO, 1984–86), includes biotite and muscovite and a new foliation. There is no final

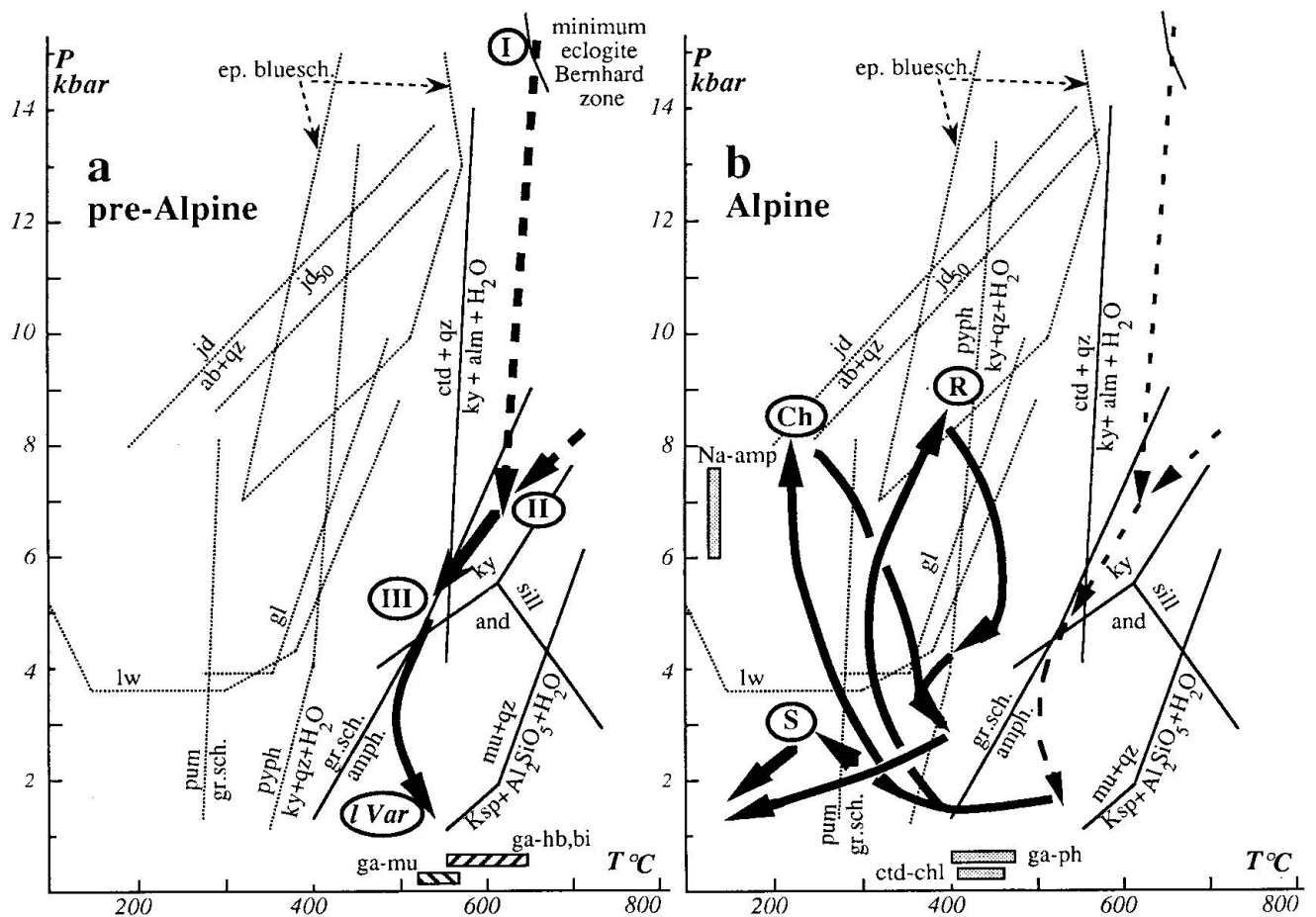


Fig. 17 P and T values inferred for the various pre-Alpine (a) and Alpine (b) assemblages in Briançon basement units. The pre-Alpine paths shown correspond to ancient basement units. The three Alpine paths correspond to three different structural units: the Rutor massif (R) with glaucophane-epidote associations, the Chasseforêt massif (Ch) with glaucophane-lawsonite and the Sapey zone (S) with pumpellyite-crossite.

The small rectangles (bottom and left-hand sides of the figures) represent the values obtained from element distribution: garnet-biotite geothermometer according to INDARES and MARTIGNOLE (1985), garnet-muscovite according to HYNES and FOREST (1988), corrected for the pressure, garnet-hornblende according to GRAHAM and POWELL (1984), chloritoid-chlorite by comparison with GHENT et al. (1987), Na-amphibole geobarometer extrapolated from MARUYAMA et al. (1986).

Al-silicate triple point according to RICHARDSON et al. (1969). Minimum values for the Siviez-Mischabel zone eclogites from THÉLIN et al. (1990). Epidote blueschist field from EVANS (1990). Jadeite curves from LIOU et al. (1987). Lawsonite curve and boundary between pumpellyite-bearing associations and greenschists from FREY et al. (1991). Glaucophane curve according to MARESCH (1976). Pyrophyllite curve according to FREY (1987). Boundary between greenschist and amphibolite facies according to MARUYAMA et al. (1983). Chloritoid-out curve according to GHENT et al. (1987). Muscovite-out curve taken from TURNER (1981). Mineral abbreviations: see figure 2.

evidence of garnet having still been growing. The possible field of this metamorphic stage has been tentatively placed near to the boundary between the amphibolite facies and the high-grade portion of the greenschist facies.

4) From radiometric measurements (BOCQUET [DESMONS] et al., 1974; DESMONS and HUNZIKER, in prep.) there is evidence of a widespread thermal event in Permian times, of a grade higher than the Alpine ones, as inferred from the persistence of Permian isotopic ratios. The temperature indicated in the figure is based on the minimum opening temperature of the isotopic systems and include possible spatial variations. Andalusite-bearing veins near the Gt. St. Bernhard pass (OULIANOFF and TRÜMPY, 1958) may represent another effect of the same event. With respect to the previous phase, the pressure is suggested to have decreased owing to crustal attenuation.

The next assemblages are the result of Alpine events. Three paths are shown in figure 17b, corresponding to three different Briançon basement units.

5) For the glaucophane-epidote assemblage found in the Rutor massif (R in Fig. 17b) the temperature is constrained by the absence of lawsonite and of jadeite-rich Na-clinopyroxene. The temperature and pressure values shown for this field are taken from EVANS (1990). In the Chasseforêt and Ambin massifs and in the Ac-

ceglio zone (Ch in Fig. 17b), lawsonite and Na-amphibole have been stable instead of glaucophane-epidote. In the Sapey zone (S in Fig. 17b) the pumpellyite-crossite (+ stilpnomelane?) assemblage has been assigned conditions similar to those of the pumpellyite-actinolite facies (LIOU et al., 1987; FREY et al., 1991).

6) For the greenschist associations the minimum temperature of  $\sim 350^\circ\text{C} \pm 50$  taken from FREY et al. (1991) is extrapolated to systems other than basaltic. This temperature is substantiated by the fact that Alpine opening of the mica K-Ar isotopic system was not attained, as shown by the coexistence of both pre-Alpine relics and Alpine new grains. A minimum pressure value of 3 kbar and a maximum value of 6 kbar are indicated on the basis of regional consistency and on EVANS' data (1990), although much higher pressures are often mentioned owing to a confusion between late eo-Alpine and meso-Alpine events and on the basis of the Si-content of white mica considered alone. A small temperature peak is revealed by the late growth of biotite and porphyroblastic albite. Higher temperature values are valid for the N and NE part of the Briançon zone (where spessartine-rich garnet was stable), lower values west- and southwards, in frame with the zonation around the thermal culmination of the Lepontine Alps. In the zone houillère it is not clear whether the chlorite-albite assemblages belonged to a lawsonite-chlorite-albite, or to a low-grade greenschist facies, or to a succession of the two.

The P-T conditions indicated in figure 17 are to be taken with caution. Very limited results can be expected from the use of element distribution coefficients in polymetamorphic rocks such as the Briançon basement samples. These are often poor in measurable relicts, post-crystallization diffusion may have altered the original compositions, the relictual minerals did not retain their original shape and size and, therefore, the choice of grain portions in mutual equilibrium may often be erroneous. Moreover, the author is fully conscious of: i) The unquantified discrepancy between the P-T values derived from experiments, that is, what can be called simulated values, and the work of the free and unaided nature, and ii) The fact that taking these simulated values at face value one will infer crustal positions and palaeotectonic processes that may never have existed. For instance, it is still unclear whether the so-called high P/T assemblages formed in a deeply subducted crust or in high-stress environments such as thrust planes or other settings.

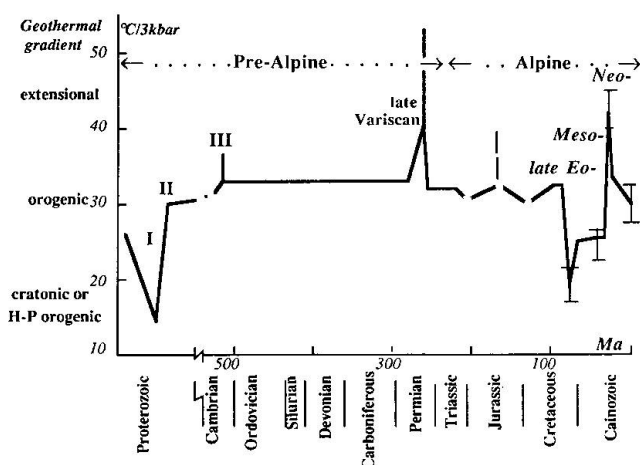


Fig. 18 Variation with time of the geothermal gradient and tectonic setting in the ancient basement. Chronological data as mentioned in the text. Bars for the three Alpine phases correspond to various parts of the Briançon zone. Present geothermal gradient is valid for the northern Briançon zone (RYBACH, 1979). Steady-state linear geothermal gradients calculated from the P and T values given in figure 17, uncertainty estimated at  $\sim 10^\circ\text{C}/3\text{ kbar}$ .



### Discussion: timing and tectonic regimes

*"The basement of the Alps is Precambrian, its metamorphism too." (R. STAUB, 1948)*

A possible time table for the metamorphic events corresponding to the above assemblages (Fig. 18) is discussed in terms of tectonic settings, starting with the youngest events. The values mentioned for the geothermal gradient have been derived from the P-T diagrams of figure 17.

1) Alpine. The meso-Alpine crystallization phase is radiometrically well dated from  $38 \pm 2$  Ma, i.e. Late Eocene (BOCQUET [DESMONS] et al., 1974; DESMONS et al., 1982; HUNZIKER et al., 1989). The age of the neo-Alpine phase, to which the biotite and porphyroblastic albite are somewhat arbitrarily ascribed, is poorly defined in the Western Alps, but can be considered as Oligo-Miocene by comparison with data from the Central Alps. The meso- to neo-Alpine metamorphic isograds cut the nappe boundaries (ZWART and NIGGLI, 1973), indicating that the deformation associated with the thrusting was not the cause of such metamorphism. An increased heat flow must be assumed for this neo-Alpine event, whereas the meso-Alpine gradient must have had a normal orogenic value (about  $25 \pm 2^\circ/\text{km}$ ).

The age of the high-pressure phase in the Briançon zone is not yet precisely known. A few radiometric data point to a latest Cretaceous-Paleocene age, i.e. the time proposed for the late eo-Alpine phase defined by DESMONS (1989) and coeval with the Provence tectonic phase of the European margin. An age  $\geq 54$  Ma is mentioned by MONIÉ (1990). This phase has been given an Eocene age by various authors owing to an assumed Lutetian age of the uppermost stratigraphical term of the cover in the internal Briançon zone. However, this cover is unconformable and its contact upon the basement is in many places demonstrably tectonic. Moreover, it is difficult to ascribe to only one phase glaucophane and greenschist rocks, whose assemblages lie in successive foliation planes and denote such different P-T gradients, thus such different tectonic settings (normal orogenic against H-P orogenic). It must be noted here that at least part of the Na-clinopyroxene found in the Chasseforêt and Ambin massifs, including jadeite in metagranitoids, may well be pre-Alpine as in the Rutor massif and the Bernhard zone: the jadeite-aegirine jadeite which is currently found in both of these massifs and so far considered as Alpine, actually are only dated as earlier than Na-amphibole (BOCQUET [DESMONS], 1974b; PLATT and LISTER, 1985).

No early eo-Alpine ages (coeval with the Austrian tectonic phase of the Eastern Alps) have been obtained from the Briançon zone, the history of which thus appears to be unlike that of both the Zermatt zone and the internal Penninic massifs.

The Jurassic extensional phase and the Middle Cretaceous magmatic phase are best recorded in the ophiolite, Piemont, zones. At those times the Briançon basement was concealed by a sedimentary cover of probably a few kilometers (2 km is the thickness of the Mesozoic sequence now overlying the ancient basement and 4 km that of the Permian and Mesozoic sequence lying upon the younger basement).

2) Variscan. The Permian K-Ar and Rb-Sr mica radiometric ages obtained in ancient basement massifs have been mentioned above and the lack of any associated foliation as well. Permian ages have been found also in the Monte Rosa (HUNZIKER, 1970) and the Ligurian Alps (DEL MORO et al., 1982). Owing to the recurrence of these age findings, a thermal phase is assumed, linked with crustal attenuation and mantle upwelling, with the widespread magmatism and high heat flow of that late Variscan age. K-Ar muscovite ages of 241–231 Ma obtained from the tectonic basement of the Ligurian Carboniferous zone have been interpreted by DEL MORO et al. (1982) either as partly Alpine-rejuvenated ages of a Permian intrusion ( $\geq 250$  Ma), or as deriving from a mechanical mixture of both magmatic and Alpine metamorphic micas. From the Permian extension until the Alpine phases both Briançon basement types were at an uppermost-crustal level.

No petrographic-mineralogical trace of a Variscan metamorphism has been detected in the rocks of the younger basement. Therefore, they should not have attained a grade higher than very low to low before the Alpine metamorphic phases (DESMONS and FABRE, 1988; GUILLOT et al., 1991; GUILLOT et al., in prep.). However, a few Variscan K-Ar, Rb-Sr and  $^{40}\text{Ar}/^{39}\text{Ar}$  apparent ages ( $\sim 360$ – $340$  Ma) have been found in the Briançon ancient massifs, and also in the Ligurian and the Southern Alps. These apparently Variscan ages have been interpreted either as ages partly reset by the later phases (K-Ar mica from the Ambin massif, because the corresponding Rb-Sr biotite age is Permian: BOCQUET [DESMONS] et al., 1974), or as minimum (cooling) ages of pre-Alpine metamorphism (DEL MORO et al., 1982, from Rb-Sr data from the Ligurian Alps; MONIÉ, 1990, from discordant  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra from the Ambin massif and Acceglio unit). If only the Western and Ligurian Alps are taken into account, there are,

thus, some data that seem to point to high heat flow and magmatism of possibly Variscan age, but no associated deformation and regional orogenic metamorphism are so far ascertained. The absence of detectable recrystallizations in the younger basement argues against a regional Variscan metamorphism in the Briançon zone. In contrast, the external crystalline massifs, the Simplon-Ticino crystalline thrust sheets and the Tauern crystalline rocks in the Austrian Alps have been involved in the orogenic accretion of Gondwanan fragments and in the magmatic activity which were to build up Variscan Europe. The crustal level at which the Briançon basement was lying during Variscan times can be regarded as high enough to have prevented any recrystallization.

3) Pre-Alpine<sub>III</sub>. No age data are available of the two-mica bearing foliation, younger than the amphibolite facies, found in the ancient basement: the Rutor massif and the Ligurian Alps. If this foliation was Variscan, it should be found in the younger basement, which is not the case. A timing earlier than Variscan thus seems to be a logical inference.

4) Pre-Alpine<sub>II</sub>. The amphibolite facies mineral assemblages and the associated foliation are the most considerable and widespread re-organization recorded in the ancient basement rocks. This extends widely beyond the Briançon basement massifs and is found with similar characteristics in the internal Penninic massifs, the Southern Alps, the Apuane basement in the Apennines, the Austro-Alpine, etc. It appears to be a Gondwanan feature. Partly concealed by Variscan events, it is also detected in the external massifs, i.e. in Alpine Europe, which migrated away from Gondwana one orogenesis before the internal Alpine units (DESMONS, in press). These large-scale petrographic-metamorphic homogeneous characteristics point to a common deep (lower to intermediate) position in the crust during the Upper Proterozoic.

The minimum age proposed earlier (DESMONS and PLOQUIN, 1989) for this Gondwana-wide feature was Cambrian–Early Ordovician. The basis was: i) that it must be earlier than the minimum age of the sedimentary deposition and magmatism of the younger basement, a minimum age that was considered as Upper Ordovician–Devonian, and ii) a few ~500–550 Ma whole-rock Rb–Sr ages from the Berisal complex, a unit compared to the Briançon zone (STILLE, 1980), and similar ages from internal, Austro-Alpine and South-Alpine basement units. The proposed period coincides with the late Pan-African events. Now an older minimum age has to be considered

for the younger basement: a granophyre subvolcanic body in the Pourri massif has recently been dated as  $507 \pm 9$  Ma (Late Cambrian) by GUILLOT et al. (1991). According to these authors and to GUILLOT et al. (in prep.) the granophyre constitutes a sill intrusion, coeval with the deposition of the host series, and it does not belong to a slice of ancient basement. This shifts the age of the amphibolite facies of the ancient basement into the lowermost Cambrian or, more probably, into the Proterozoic. It cannot be excluded that the Berisal 550–500 Ma ages are not those of the amphibolite facies imprint, but are rejuvenated ages due to late Pan-African intrusions and high heat flow (perhaps related to the pre-Alpine<sub>III</sub> period above?). A prolonged middle-crustal residence can be contemplated for these widespread amphibolite-facies assemblages.

The hypothesis that the ancient and younger basement protoliths were coeval, but situated one deeper and the other shallower at the time of the amphibolite facies event, seems less likely owing to several facts: i) The lithologies show differences; ii) No basement units consisting of transitional metamorphic types is found; iii) The present superposition is tectonic with the younger basement higher in the nappe pile (more internal in origin); iv) Comparable ancient and younger basement pairs are found in the Apuane Alps, in Calabria and in other areas where the younger basement is fossiliferous and not, or poorly, metamorphosed and lies directly upon an amphibolite facies basement.

5) Pre-Alpine<sub>I</sub>. Finally, the eclogite assemblages document the oldest bench-mark in the Briançon zone, so far dated from an undetermined Proterozoic period only by reference to the following amphibolite assemblages. The wide scattering of such relics and their greater abundance in areas of low to absent Alpine metamorphic overprint (e.g., Austro-Alpine) indicate widespread rather than localized eclogitic conditions. Granulite facies relicts, known from the Sesia zone (COMPAGNONI et al., 1977, p. 296) and from the external massifs (e.g. in the Gotthard massif where they are reported to post-date the eclogite facies by ABRECHT et al., 1991), have not so far been found in the Penninic units. However, granulite associations may well have existed here prior to their destruction by the following hydrous phases. Cratonic and orogenic gradients are calculated for these assemblages from the assumed P and T values.

The metamorphic succession in the Briançon ancient basement thus shows the history of pieces of deep, eclogitic (to granulitic?) crust, which were involved in orogenic processes, metamor-



phosed and uplifted probably in late Proterozoic times up to middle-crust level, not affected by Variscan events or only to a limited extent, attenuated during the Permian and finally involved in the Alpine great stir including (early eo-Alpine effects being absent in the Briançon zone): (late eo-Alpine?) P-dominated metamorphism, thrust-related deformation and meso- to neo-Alpine heating, deformation, re-heating and uplift.

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**Appendix** Selected mineral analyses and formulae. Abbreviations: anc, ancient basement; Chass, Chasseforêt massif; éc. int., "écaillés intermédiaires" at Serre-Chevalier; GSBd, Rutor zone at the Gd. St. Bernhard pass; m.bas, metabasite; orthog, orthogneiss or schist; Pourr, Pourri-Bellecôte massif; Rui, Rutor massif; Sap, Sapey zone; sch, pelitic schist or gneiss; you, younger basement; Zint, Zona interna, Abbreviations of minerals: see figure 2.

<b>GARNET</b>													
sample analysis	83JD03	263	263	82-001	88JD80	Rut 82	83JD22	87JD47	A74-7A	84JD15	86JD15	81-074	
basement	33 core	142	148	G.3 core	42	10	Bern 124	7 core	38	121 rim	40 core	G.2 core	
rock type	anc/Rui	anc/Chass	anc/Chass	anc/Pourr	anc/Rui	anc/Rui	anc/Rui	anc/Rui	anc/Sap	you/Pourr	you/Pourr	you/Pourr	
	sch	sch	sch	sch	m.bas	m.bas	orthog	orthog	orthog	sch	m.bas	m.bas	
SiO <sub>2</sub>	37.03	37.77	38.36	36.33	38.44	39.37	39.85	38.85	38.97	38.68	38.42	36.02	
Al <sub>2</sub> O <sub>3</sub>	21.75	21.19	21.42	19.08	21.21	22.07	20.44	21.71	21.75	21.59	21.18	20.96	
TiO <sub>2</sub>	0.00	0.05	0.18	0.18	0.00	0.30	0.00	0.07	0.12	0.04	0.08	0.21	
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
FeO	30.29	30.57	21.38	17.63	18.58	20.69	9.49	14.87	27.88	14.33	22.87	24.82	
MgO	2.75	0.25	0.04	0.24	2.09	1.55	0.00	0.15	4.71	0.33	0.38	0.50	
MnO	5.12	0.56	1.73	13.01	0.78	0.83	6.00	12.09	1.02	16.79	7.78	6.25	
NiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.01	0.00	0.00	0.00	
CaO	2.59	7.95	16.46	8.75	18.83	16.57	24.49	12.53	6.02	10.04	9.86	10.50	
Na <sub>2</sub> O	0.00	0.06	0.00	0.02	0.00	0.06	0.04	0.00	0.00	0.02	0.21	0.00	
K <sub>2</sub> O	0.00	0.03	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.02	0.02	
total	99.53	98.43	99.61	95.24	99.93	101.50	100.38	100.27	100.48	101.82	100.80	99.28	
24 oxygens													
Si	5.963	6.122	6.060	6.133	5.997	6.045	6.164	6.115	6.065	6.066	6.089	5.863	
Al IV	0.037	0.000	0.000	0.000	0.003	0.000	1.836	0.000	0.000	0.000	1.911	0.137	
Al VI	4.127	4.047	3.987	3.796	3.896	3.993	1.890	4.026	3.989	3.990	2.044	3.883	
Ti	0.000	0.006	0.021	0.023	0.000	0.035	0.000	0.008	0.014	0.005	0.010	0.026	
Cr	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Fe <sup>2+</sup>	4.078	4.143	2.824	2.489	2.423	2.656	1.227	1.957	3.627	1.879	3.030	3.378	
Mg	0.660	0.060	0.009	0.060	0.486	0.354	0.000	0.035	1.092	0.077	0.090	0.121	
Mn	0.698	0.077	0.231	1.860	0.103	0.108	0.786	1.611	0.134	2.230	1.044	0.861	
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	
Ca	0.447	1.380	2.785	1.582	3.146	2.725	4.057	2.112	1.003	1.686	1.673	1.830	
Na	0.000	0.019	0.000	0.007	0.000	0.018	0.012	0.000	0.000	0.006	0.064	0.000	
K	0.000	0.006	0.000	0.000	0.000	0.000	0.014	0.000	0.000	0.000	0.004	0.004	
total	16.010	15.861	15.923	15.949	16.054	15.933	15.986	15.864	15.926	15.938	15.959	16.104	
alm	69.3	73.2	48.3	41.5	39.4	45.5	20.2	34.2	61.9	32.0	51.9	54.6	
py	11.2	1.1	.2	1.0	7.9	6.1	.0	.6	18.6	1.3	1.5	2.0	
sp	11.9	1.4	4.0	31.0	1.7	1.8	12.9	28.2	2.3	38.0	17.9	13.9	
ougr	7.6	24.4	47.6	26.4	51.1	46.6	66.8	37.0	17.1	28.7	28.7	29.6	

<b>WHITE MICA</b>										<b>Na-PYROXENE</b>			
sample analysis	83JD12	83JD34	83JD34	263	263	83JD22	83JD22	87JD57		263	263	303	346
basement	Bern 39	Bern 2	Bern 7	128	131	Bern114	Bern117	80		140	163	230	186
rock type	anc/Rui	anc/GSBd	anc/GSBd	anc/Chass	anc/Chass	anc/Rui	anc/Rui	you/Zint		anc/Chass	anc/Chass	anc/Chass	anc/Chass
	sch	sch	sch	sch	sch	orthog	orthog	sch		sch	sch	sch	sch+vein
SiO <sub>2</sub>	45.13	50.45	47.18	52.17	48.03	51.44	46.73	51.18		57.59	58.83	58.17	56.80
Al <sub>2</sub> O <sub>3</sub>	34.22	26.46	35.03	24.61	39.61	28.08	32.41	29.03		16.01	17.59	15.84	13.13
TiO <sub>2</sub>	0.73	0.33	0.68	0.13	0.00	0.22	0.48	0.13		0.05	0.00	0.08	0.10
Cr <sub>2</sub> O <sub>3</sub>				0.00	0.00			0.03		0.00	0.00	0.00	0.97
FeO	1.14	4.05	0.00	5.64	0.77	4.82	2.99	1.90		10.38	8.01	10.93	11.93
MgO	0.71	2.70	0.47	2.56	0.20	1.48	0.60	3.40		0.39	0.77	0.54	1.20
MnO	0.00	0.04	0.00	0.00	0.00	0.07	0.00	0.08		0.00	0.06	0.01	0.07
NiO <sub>2</sub>				0.00	0.03			0.00		0.04	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00		0.80	1.34	0.89	2.29
Na <sub>2</sub> O	0.75	0.26	0.82	0.13	7.03	0.19	0.36	0.26		14.19	13.49	14.57	13.00
K <sub>2</sub> O	9.44	10.16	8.26	10.24	1.17	7.12	9.87	10.32		0.01	0.04	0.07	0.00
total	96.62	98.95	96.94	95.48	96.89	97.92	97.94	96.33		99.46	100.13	101.10	99.49
12 oxygens										6 oxygens			
Si	6.182	6.837	6.327	7.032	6.050	6.906	6.366	6.724		2.064	2.063	2.060	2.067
Al IV	1.818	1.163	1.673	.968	1.950	1.094	1.634	1.276		.000	.000	.000	.000
Al VI	3.706	3.062	3.862	2.941	3.930	3.349	3.568	3.218		.676	.727	.661	.563
Ti	.075	.034	.069	.013	.000	.022	.049	.013		.001	.000	.002	.003
Cr				.000	.000			.003		.000	.000	.000	.028
Fe <sup>2+</sup>	.131	.459	.000	.636	.081	.541	.341	.209		.000	.000	.000	.000
Fe <sup>3+</sup>										.308	.232	.320	.359
Mg	.145	.545	.094	.514	.038	.296	.122	.665		.021	.040	.028	.065
Mn	.000	.005	.000	.000	.000	.008	.000	.009		.000	.002	.000	.002
Ni				.000	.003			.000		.001	.000	.000	.000
Ca	.000	.000	.000	.000	.007	.000	.000	.000		.031	.050	.034	.089
Na	.199	.068	.213	.034	1.716	.049	.095	.066		.986	.917	1.000	.917
K	1.649	1.756	1.412	1.760	.188	1.219	1.714	1.729		.000	.002	.003	.000
total	13.905	13.929	13.650	13.897	13.962	13.484	13.889	13.912		4.088	4.033	4.109	4.093
100 Na/(Na+K)	10.8	3.7	13.1	1.9	90.1	3.9	5.3	* 3.7					
jd%										66.6	71.8	65.2	55.6
aeg%										30.3	23.0	31.6	35.5
di%										3.0	5.2	3.3	8.9

Ca-AMPHIBOLE								Na-AMPHIBOLE				
sample	83JD06	83JD25	88JD80	86JD72	86JD20	82-131	87JD57	83JD06	263	263	303	346
analysis	68	59	45	63	113	G.25	70	76	114	152	211	183
basement	anc/Rui	anc/Rui	anc/Rui	éc.int.	you/Pourr	you/Pourr	you/Zint	anc/Rui	anc/Chass	anc/Chass	anc/Chass	anc/Chass
rock type	m.bas	m.bas	m.bas	m.bas	m.bas	m.bas	sch	m.bas	sch	sch	sch	sch+vein
SiO <sub>2</sub>	46.42	42.53	55.06	43.36	55.38	53.24	55.72	56.03	57.50	54.51	57.54	59.27
Al <sub>2</sub> O <sub>3</sub>	12.39	14.79	1.84	15.49	1.13	1.56	2.67	11.14	10.11	7.51	12.65	10.13
TiO <sub>2</sub>	0.58	0.63	0.00	0.67	0.02	0.00	0.01	0.00	0.12	0.06	0.08	0.00
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.08	0.03	0.00	0.03	0.00
FeO	11.94	19.29	11.71	16.81	12.73	16.33	10.33	12.22	17.38	23.45	14.09	10.00
MgO	12.18	7.08	15.64	8.23	15.70	13.87	16.42	9.01	5.44	3.70	6.18	10.53
MnO	0.42	0.00	0.27	0.26	0.36	0.47	0.39	0.00	0.12	0.06	0.00	0.01
NiO <sub>2</sub>	0.00	0.00	0.00	0.04	0.09	0.00	0.05	0.00	0.00	0.00	0.09	0.00
CaO	11.50	10.74	12.24	10.75	11.88	11.89	11.59	1.56	0.29	0.49	0.00	0.13
Na <sub>2</sub> O	1.66	2.59	0.55	1.80	0.57	0.22	0.62	6.53	7.34	6.77	7.40	7.87
K <sub>2</sub> O	0.13	0.51	0.07	0.83	0.08	0.07	0.12	0.05	0.00	0.01	0.01	0.03
total	97.21	98.15	97.38	98.35	97.94	97.65	97.92	96.62	98.33	96.56	98.07	97.97
23 oxygens								23 oxygens				
Si	6.753	6.387	7.896	6.410	7.935	7.803	7.875	7.764	7.977	7.932	7.879	8.031
Al IV	1.247	1.613	.104	1.590	.065	.197	.125	.236	.023	.068	.121	.000
Al VI	.877	1.004	.207	1.108	.126	.072	.320	1.583	1.630	1.219	1.920	1.617
Ti	.063	.071	.000	.074	.002	.000	.001	.000	.013	.007	.008	.000
Cr	.000	.000	.000	.013	.000	.000	.000	.009	.003	.000	.003	.000
Fe <sup>3+</sup>								.700	.907	1.283	.726	.510
Fe <sup>2+</sup>	1.452	2.422	1.404	2.077	1.525	2.000	1.221	.708	1.008	1.426	.806	.566
Mg	2.639	1.584	3.341	1.812	3.351	3.028	3.457	1.860	1.124	.802	1.261	2.125
Mn	.052	.000	.033	.033	.044	.058	.047	.000	.014	.007	.000	.001
Ni	.000	.000	.000	.005	.010	.000	.006	.000	.000	.000	.010	.000
Ca	1.792	1.727	1.880	1.702	1.823	1.866	1.754	.232	.043	.076	.000	.019
Na	.468	.754	.153	.516	.158	.062	.170	1.753	1.973	1.909	1.963	2.066
K	.024	.098	.013	.156	.015	.013	.022	.009	.000	.002	.002	.005
total	15.368	15.659	15.031	15.496	15.054	15.100	14.997	14.853	14.715	14.732	14.700	14.941
	Mg-hb	parag-hb	act	Fe-tsch-hb	act	act	act					
100Mg/R <sub>2</sub> +	63.7	39.5	69.9	46.1	68.0	59.5	73.1	72.4	52.4	35.9	60.7	78.9
100Al/VI/R <sub>3</sub> +								69.1	63.9	48.6	72.3	76.0

CHLORITE									BIOTITE			
sample	83JD03	83JD34	83JD06	87JD47	V.615	86JD20	82-131	87JD55	83JD03	86JD72	82-001	87JD60
analysis	44	Bern 3	84	13	Bern171	112	G.41	62	40	64	G. grBt	74
basement	<i>anc/Rui</i>	<i>GSBd</i>	<i>anc/Rui</i>	<i>anc/Rui</i>	<i>anc/Chass</i>	<i>you/Pourr</i>	<i>you/Pourr</i>	<i>you/Zint</i>	<i>anc/Rui</i>	<i>and/éc.int.</i>	<i>anc/Pourr</i>	<i>you/Zint</i>
rock type	<i>sch</i>	<i>sch</i>	<i>m.bas</i>	<i>orthog</i>	<i>sch</i>	<i>m.bas</i>	<i>m.bas</i>	<i>m.bas</i>	<i>sch</i>	<i>sch</i>	<i>sch</i>	<i>orthog</i>
SiO2	25.03	24.41	26.48	24.35	25.43	27.15	26.41	25.83	35.70	35.96	37.27	37.25
Al2O3	23.43	19.20	19.59	21.07	19.39	20.01	19.16	20.84	18.36	17.81	14.86	17.37
TiO2	0.00	0.09	0.00	0.00	0.13	0.00	0.07	0.00	1.89	1.62	1.82	0.93
Cr2O3	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	23.55	29.01	22.02	33.85	30.74	21.69	26.52	22.95	19.81	22.40	24.79	19.18
MgO	14.79	11.41	17.92	7.63	11.31	18.25	14.39	16.06	10.61	8.38	7.08	11.51
MnO	0.14	0.21	0.07	0.30	0.48	0.37	0.37	0.32	0.07	0.05	0.20	0.10
NiO2	0.00		0.00	0.00	0.00	0.04	0.00	0.08	0.00	0.00	0.00	0.09
CaO	0.03	0.00	0.03	0.08	0.00	0.05	0.06	0.01	0.05	0.11	0.01	0.00
Na2O	0.00	0.00	0.05	0.08	0.00	0.00	0.01	0.00	0.05	0.06	0.09	0.07
K2O	0.06	0.06	0.00	0.02	0.00	0.02	0.00	0.05	8.68	8.72	9.54	9.11
total	87.03	84.39	86.21	87.38	87.48	87.58	86.99	86.14	95.22	95.11	95.66	95.61
28 oxygens									12 oxygens			
Si	5.254	5.494	5.582	5.410	5.510	5.614	5.655	5.477	5.321	5.419	5.663	5.511
Al IV	2.746	2.506	2.418	2.590	2.449	2.386	2.345	2.523	2.679	2.581	2.337	2.489
Al VI	3.050	2.587	2.448	2.926	2.538	2.489	2.489	2.685	.546	.581	.324	.540
Ti	.000	.015	.000	.000	.021	.000	.011	.000	.212	.184	.208	.103
Cr	.000		.000	.000		.000		.000	.000	.000	.000	.000
Fe2+	4.133	5.459	3.881	6.288	5.609	3.749	4.747	4.069	1.234	1.411	1.575	1.186
Mg	4.625	3.826	5.627	2.525	3.667	5.621	4.590	5.073	2.356	1.881	1.603	2.537
Mn	.025	.040	.012	.054	.089	.062	.064	.055	.009	.006	.026	.013
Ni	.000		.000	.000		.007		.014	.000	.000	.000	.011
Ca	.007	.000	.007	.019	.000	.011	.014	.002	.001	.002	.000	.000
Na	.000	.000	.020	.034	.000	.000	.004	.000	.014	.018	.026	.020
K	.016	.017	.000	.006	.000	.005	.000	.014	1.650	1.676	1.849	1.719
total	19.856	19.944	19.995	19.852	19.934	19.944	19.919	19.911	15.132	15.028	15.027	15.196
100Fe/Fe+Mg	47.2	58.8	40.8	71.3	60.4	40.0	50.8	44.5				
100Ti/Ti+Fe									8.3	6.4	6.5	4.4