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Alpine metamorphism of the Western Alps: II. High-P/T and related pre-greenschist metamorphism

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Über allen Gipfeln ist Ruh (Goethe)
(On all summits there is peace)

Abstract

The Internal zones of the Western Alps contain assemblages indicative of one or more H-P/T imprints, which have been more or less overprinted in Eocene and Oligocene by the greenschist facies events described in the companion paper. In most eclogite-free zones there is a grade increase from S to N and from W to E (from higher to deeper units in the nappe pile). A lawsonite-albite-chlorite ± carpholite facies is present in the Houillère zone S of the Aosta valley, and in the Briançon cover where Al-rich rocks contain minerals such as Mg–Fe-carpholite, Fe-chloritoid, cookeite and aragonite. In the basal thrust and shear zones of the Dent Blanche nappe and Second Diorito-Kinzigitic zone there are some indications of a H-P/T trend (phengite, Fe-Na- amphibole and greenish pyroxene). In the Briançon basement rocks and in the Combin zone a glaucophane-schist ± jadeite facies is found from approximately the Isère-Arc valleys southwards, and epidote-blueschist associations northwards. These imprints may not have been coeval in all zones, but most if not all of them may be related to the Eocene thrusting phases.

An eclogite facies predates glaucophane-schist and other imprints in five zones: the Zermatt zone and the Voltri Group in the Ligurian Alps, the Internal Penninic massifs including the Ligurian Torrente Visone massif, the Sesia Eclogitic Micaschist complex and its cover, the Lanzo massif, and the small Clapey slice of the Valais zone. The assemblages characteristically include omphacite + garnet in the basic rocks and, in schists of appropriate composition, talc + phengite + chloritoid or kyanite. In addition, one sheet in each Zermatt zone and Dora-Maira massif contains UH-P assemblages, with coesite, pyrope, etc. The external part of the Sesia zone – the Gneiss Minuti complex – seems not to have overstepped the conditions of albite breakdown. Recent zircon dating of the eclogite facies yielded in the Sesia zone latest Cretaceous, in the Zermatt zone Middle Eocene and, for the UH-P metamorphism of the Internal Penninic massifs, latest Eocene ages. A distinction is made between "mineral" (i.e. the crystallization of the eclogitic mineral association) and "radiometric" eclogitization (i.e. the isotopic closure or mineral growth that will be radiometrically dated), and the consistency of the radiometric ages with geological data is closely examined. Interpretation of the metamorphic imprints is briefly given within the frame of a tectonic-lithospheric evolution model.

Keywords: Western Alps, Alpine metamorphism, glaucophane-schist, eclogite.

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1. Introduction

In the Western Alps, the polyphase Alpine metamorphic evolution first included H-P/T facies which are the topic of this paper, and it terminated with the greenschist facies which have been detailed in the companion paper (DESMONS et al., 1999b, this volume). The H-P/T metamorphic facies produced UH-P metamorphic rocks, eclogites and whiteschists, glaucophane schist including epidote blueschist rocks, and lawsonite-albite-chlorite facies rocks. These H-P/T metamorphic facies are grouped in this paper because they reflect geothermal gradients lower than Barrovian, and/or high pressure conditions uncommon in the crust, and because they all predate a greenschist facies. Such H-P/T facies have not been coeval, most eclogites having experienced retrogression in glaucophane-schist assemblages and, as will be explained below, only some of the H-P/T facies being related to events which are largely older than the main thrusting.

The H-P/T facies are strictly related to the structural subdivision into tectonic zones. Therefore, the facies will be described in each zone taken separately, from those devoid of eclogites to those bearing eclogite facies assemblages, the oldest of the Alpine orogeny.

The H-P/T metamorphisms overprinted pre-Alpine basement rocks of the Internal zones (see DESMONS et al., 1999a, this volume), Briançon and other cover rocks, as well as the sedimentary and ophiolitic rocks derived from the Valais, Combin, Zermatt and similar basins of the Ligurian Alps (for the structural divisions, see the first chapter of the companion paper). This diversity in the pre-H-P/T mineral composition is the cause of a variety of resulting H-P/T Alpine assemblages. Therefore, appraising whether they indicate similar or different P and T values is often not straightforward.

In order to shorten the paper, many references already included in the explanatory notes to the first edition of the map (BOCQUET [DESMONS] et al., 1978) or in comprehensive papers mentioned below are not repeated here.

2. Lawsonite-chlorite-albite and glaucophane-schist facies in the eclogite-free zones

2.1. METAMORPHIC ASSEMBLAGES AND THEIR DISTRIBUTION

2.1.1. Houillère zone

South of the Isère valley, and north of the Ligurian Alps, volcanic rocks included in the Houillère zone contain assemblages characteristic of the lawsonite-chlorite-albite facies: Lws + Ab + Chl ± Act + Ttn ± Pmp (abbreviations according to BUCHER and FREY, 1994; in addition, Aeg stands for aegirine and Wm for white mica). Lawsonite appears to post-date a sericitization stage of the feldspar which has possibly been a late magmatic process. In the host siliciclastic rocks, which are devoid of, or very poor in CaO, such a lawsonite association is only rarely found. Hence, the question arises whether the Chl-Wm-Ab assemblage of the clastic rocks results from greenschist conditions post-dating and obliterating a lawsonite-chlorite-albite facies (as it has been shown on the map), or *is* a lawsonite-chlorite-albite facies with no lawsonite having crystallized owing to the absence of CaO. The possible occurrence of carpholite may be locally envisaged (cf. the mineral shown by FABRE, 1961, p. 210). North of the Aosta valley any trace of H-P/T metamorphism is now lacking in the Houillère zone, likely due to a stronger greenschist overprint.

2.1.2. Briançon basement

There are glaucophane-schist facies assemblages (Fe–Gln and/or Fe-richer Na–Am + Phe ± Pg ± Cld ± Jd) in the Chasseforêt and Ambin massifs as well as in the Acceglio zone (e.g. BOCQUET [DESMONS], 1974). The conditions have been estimated at about 350 °C and 10 kbar (DESMONS, 1977) or between 7 and 8.5 kbar (GAY, 1972). In some areas at least (Chasseforêt) Na-amphibole post-dates Na-clinopyroxene (Jd_{97} in metagranitoid according to SALIOT, 1979, Jd_{56-72} Aeg_{35-23} Di_{9-3} in schist, DESMONS, 1992). It seems that the H-P/T mineral assemblages are more widespread near the major thrust planes. This can be explained by an easier nucleation of new assemblages in deformed rocks, and by the higher fluid flow through these rocks. It has been suggested (in DEBELMAS and DESMONS, 1997) that some pre-Alpine alteration under greenschist or lower-grade conditions may have participated in hydrating the basement, a process which later facilitated the low-grade Alpine neoformations. Deerite has been found in Fe-rich rocks from the Ambin massif.

Northwards, an epidote blueschist facies is indicated in the Pourri-Bellecôte massif by epidote associated with uncommon glaucophane (locally, Gln + Pg + Czo + Qtz, DESMONS and FABRE, 1988) and in the Ruitor massif where the facies is irregularly but widely spread (BAUDIN, 1987). The temperature is assumed to have been in the range of 350 to 400 °C for a pressure of 4 to 6 kbar. On the map a northern limit of glaucophane-schist facies has been drawn across the Ruitor-Pontis zone, on the southern slope of the Gd St-Bernard pass, meaning that H-P/T relics gradually disappear in that direction, again owing probably to a stronger greenschist overprint. Chloritoid can be locally found associated with the Na-amphibole.

In the Mont Fort nappe glaucophane-bearing rocks are common. A typical assemblage is Gln + Ep + Grt + Act + Chl + Wm + Ab + Ttn (WUST and BAEHNI, 1986; CHESSEX, 1995), an assemblage including both glaucophane-schist and greenschist facies minerals. For the first assemblage a temperature of 360 to 470 °C and a pressure higher than 8 kbar are proposed. In metapelites, the assemblage Cld + Ms + Pg + Chl + Qtz ± Grt is widespread (SCHAER, 1960; BEARTH, 1960–63). The coexistence of chloritoid + glaucophane is reported from the assemblage Cld + Gln + Wm + Chl + Grt + Rt + Gr (TSCHOPP, 1923, p. 124). Paragonite is present (SCHAER, 1960; THÉLIN et al., 1994). X-ray diffraction data on K-white micas indicate high phengite contents and the presence of the 3T polytype (THÉLIN et al., 1994). Detailed geothermobarometric data are, however, missing.

No fresh lawsonite has ever been found in these regions, but lozenge-shaped epidote-paragonite pseudomorphs suggest its former presence (Siviez-Mischabel: RAHN, 1991; Mont Fort: ALLIMANN, 1987; Vanoise: PLATT and LISTER, 1985; Ambin: BORGHI et al., 1997).

In the Sapey zone, jadeite has never been reported and Na-amphibole is Fe-rich. Although no lawsonite has been mentioned from these calc-silicate-poor rocks, a lawsonite-chlorite-albite facies has tentatively been assumed for the map on the basis of the zoneography.

In all these rocks, garnet is either a relic from pre-Alpine assemblages or a product of the later, greenschist facies, conditions; in the latter case it is spessartine-rich.

In the Briançon units of the Ligurian Alps the metamorphism attained higher conditions in the geometrically uppermost internal units and it decreased westerly towards the more external, geometrically lower, units. The highest pressure is recorded in the Bagnaschino unit of the internal Briançon zone, which includes sheared slices of basement amphibolite and gneiss. The assemblage is Jd_{95-100} + Qtz + Na–Am + Phe and locally Czo and Pmp. Metamorphic conditions were estimated at 300 °C for P of at least 13 kbar (CABELLA et al., 1991a). The basement units and the Permo-Carboniferous sequences of inner units are characterized by Lws, Ab, Chl assemblages; Na–Am is widespread, sometimes coexisting with Act, Na-Ca-clinopyroxene ($Jd_{\leq 30}$) and Pmp. The inferred temperature is 300–350 °C and the pressure about 9 kbar (CABELLA et al., 1991b). Minor variations in metamorphic grade have also been observed within the same unit (CABELLA et al., 1991b). Metasedimentary rocks of suitable composition contain carpholite and chloritoid (L.C. and L.G., unpubl. data). Stilpnomelane is a widespread occurrence. Some major Briançon tectonic units are separated by mylonitic zones showing a polyphase evolution, where relics of Na-amphibole are related to the older deformation event.

2.1.3. Briançon cover

Ab + Qtz ± Wm pseudomorphs after probable jadeite have been found in a mica-schist from the southern slope of the Chasseforêt massif. Carbonate layers contain Fe-rich Na-amphibole (crossite to riebeckite) and pseudomorphs after probable lawsonite (Chasseforêt, Ambin covers), indicating a lawsonite-albite-chlorite facies. Aegirine and deerite are rarely found. Remarkable are foraminifers included in Na-amphibole grains and ammonites studded with Na-amphibole needles (BOCQUET [DESMONS], 1974, and references therein).

The Jurassic Al-rich rocks supply detailed information which in the Vanoise massifs has been extensively studied (e.g. GOFFÉ, 1982; GILLET and GOFFÉ, 1988, and ref. therein; BROUDOUX, 1985). Two main assemblages are found: an earlier assemblage of Prl + Dsp + Fe–Mg–Cp ± Fe–Cld ± Arg ± cookeite + Pg + Chl + Ms, for which up to 350 °C and 8 kbar have been assumed; and a later assemblage of Fe–Cld + Ms + Pg ± Chl ± Czo, pointing to a lower pressure. In chloritoid the mg number (100 Mg/Fe + Mg) ranges from 2 to 21, and in carpholite from 48 to 79 (BOCQUET [DESMONS], 1974; GOFFÉ, 1979; GOFFÉ and VELDE, 1984). In the Barrhorn series the assemblage in metabauxites is Cld + Ky + St (Zn-rich) + Ms + Mrg + Chl + Cok + Dsp + Ank + Cal + Rt, for which a temperature of 400 to 450 °C and a pressure of 4 to 6 kbar have been proposed (SARTORI, 1990). Kyanite marks a stretching lineation which is related to the major Tertiary regional deformation, associated with the overthrusting of the upper Penninic and Austroalpine nappes on the Barrhorn unit.

In the Ligurian external Briançon cover, carpholite and lawsonite have been very locally found in similar Al-rich layers (GOFFÉ, 1984–86). This whole external Briançon cover, mainly carbonate in composition, has so far not yielded any indication of a grade higher than anchizone, but the whole area perhaps should be labelled as affected by high-P/T and very low-grade metamorphic conditions.

To the north, H-P/T minerals become very rare, most likely because they have been obliterated by the later greenschist facies overprint. From Briançon southwards the cover rocks are less and less metamorphic in appearance. Lawsonite is found in Upper Palaeozoic metavolcanic rocks from the Preit (Val Maira, ZERBATO, 1984–87) and the Guil valleys. Carpholite is found near the present-day boundary with the Combin zone (GOFFÉ and CHOPIN, 1986), but no compositional data have been published.

2.1.4. Valais zone (Roignais-Versoyen unit)

Sedimentary rocks contain Na–Am + Cld + Sps-rich Grt ± Fe–Cp ± Lws (OBERHÄNSLI et al., 1995; CANNIC et al., 1996). Na-amphibole occurs in basic sills thicker than 10 m (LASSERRE and LAVERNE, 1976), and jadeite in the gneiss of Pte Rousse (GOFFÉ and BOUSQUET, 1997). The Clapey occurrence, which contains eclogite assemblages, will be dealt with in section 3.1.6.

2.1.5. Combin zone

There is a distinct staggered decrease in the degree of metamorphic transformation from east to west, i.e., from the lower to the upper slices of the zone. In basic rocks the mineral assemblages include (e.g. DESMONS, 1977, 1989 and ref. therein): Na–Am + Ep in the Aosta valley, the two minerals being more widespread in the easternmost (deeper) part; Na–Am ± Jd ± Lws in the Fréjus area, the Chisone valley and in the deeper slices of the Queyras area, for which temperatures ranging from 200 to 400 °C and pressures from 7 to 11 kbar have been proposed; rare Rbk + Aeg ± Lws ± Pmp ± Stp in the lower part of the Montgenèvre unit (e.g. BERTRAND et al., 1984). It is noteworthy that the upper part of the Montgenèvre ophiolite body hardly displays any Alpine transformation but only oceanic metamorphism (not distinguished on the map). This part of the Combin zone bears many similarities with the Montenotte-Cravasco-Voltaggio units of the Ligurian Alps (see below).

As shown on the map, there is a gap in the present-day metamorphic assemblages between the ophiolitic rocks and the sedimentary rocks. This gap is generally interpreted as resulting from differences in the chemical composition, fluid content and post-H-P/T evolution of the rocks. In meta-sedimentary rocks the Fe-rich Na-amphibole correlates with the high Fe/Mg ratio of the rock itself, jadeite is absent and the greenschist facies overprint is more pronounced. This seems to be a combined result of the higher sheet silicate content, the greater fissility, therefore an easiest access to fluids and an easiest reaction to the later greenschist conditions.

In the ophiolitic rocks the Ca-silicate is pumpellyite in the Mt Jovet klippe between the Isère and Arc valleys, lawsonite ± pumpellyite associated with glaucophane-crossite from the Sana klippe, Vanoise, to Queyras, and epidote-clinozoisite (a greenschist facies replacement product of lawsonite ?) in the Aosta valley where glaucophane and garnet are present. There is structural evidence of at least two stages of lawsonite growth in the metasedimentary rocks, inclusion-rich cores being rimmed by inclusion-free rims, and lawsonite grains being associated with different S planes. Carpholite is locally present (STEEN and BERTRAND, 1977). Metacherts may contain, in addition to quartz and white mica, the following H-P/T minerals: Aeg, Lws, Fe–Na–Am, Ttn ± deerite and opaque minerals. Cr-bearing minerals, such as Cr-phengite (mariposite), Cr-chlorite, Cr-jadeite, Cr-pumpellyite and Cr-lawsonite have been found locally (e.g. BOCQUET [DESMONS], 1974; MEVEL and KIENAST, 1980). Mn-rich rocks contain sursassite, spessartine, piemontite, etc. (MARTIN and POLINO, 1984–87; MARTIN and LOMBARDO, 1995).

A more pervasive H-P/T recrystallization occurred in ophiolitic rocks that had been affected by ocean-floor metamorphism and shearing. Elsewhere the reactions generally were completed only in microdomains (at grain-scale), so that a single rock sample may exhibit the whole sequence of associations from the magmatic stages through ocean-floor to the H-P/T and greenschist phases.

2.1.6. Ophiolite-bearing units of the Ligurian Alps

In the Palmaro-Caffarella unit of the Voltri Group, an assemblage of Na–Am (Gln to Mg–Rbk), Czo-Ep, chlorite, Ttn is widespread in metabasite and Na–Ca Cpx ($Jd_{\leq 98}$) ± Lws, or Aeg-rich Cpx ± Rt ± Sps-rich Grt in metagabbro. This blueschist facies metamorphic peak developed syn- to post-kinematically with respect to a main schistosity. Pumpellyite is a rare occurrence in olivine-rich metagabbro. Metacherts contain Sps, Rbk, Stp, piemontite and sursassite. The inferred temperature is 400 °C for P ≥ 3 kbar (CABELLA et al., 1994; CORTESOGNO et al., in prep.).

The Cravasco-Voltaggio and Montenotte units (CORTESOGNO and HACCARD, 1984) are characterized by Ab, Na–Am, Chl, commonly coexisting with Lws, Pmp, Ep and locally Na–Ca–Cpx ($Jd_{\sim 70}$).

Textural evidence shows the growth of lawsonite to have been both pre- and post-kinematic relative to the early schistosity. Temperatures are inferred to have been about 300–350 °C at about 8 kbar (CABELLA et al., 1994; CORTESOGNO et al., in prep.).

Lower metamorphic grades are recorded in meta-ophiolites of the M. Figogna unit in the Sestri-Voltaggio zone, and in associated Cretaceous flysch. The most significant assemblage is Pmp + Act + Ep + Chl, whereas lawsonite occurs rarely within albitized plagioclase phenocrysts. The temperature is inferred to have been 350 °C (CORTESOGNO and VENTURELLI, 1978; LEONI et al., 1996) and the pressure 8 kbar. Among the meta-ophiolites, only those of the Varazze unit do not record H-P/T assemblages, but widespread greenschist re-equilibration.

In the calcschist-bearing Montaldo unit, which belongs to the "Piemonte" domain, metabasic boudins preserve relics of H-P/T assemblages: Na–Ca Cpx, Na–Am, Lws (DALLAGIOVANNA, 1995). The pyroxene and phengite compositions allow a temperature ≤ 400 °C and a pressure higher than 12 kbar to be inferred.

2.1.7. Dent Blanche nappe

In the Dent Blanche nappe there is some evidence of medium-to-high pressure and low temperature metamorphism. Various H-P/T minerals have been reported: blue amphibole and greenish pyroxene from the Mt Mary (Arolla series) and from the Mesozoic cover in the region west of Arolla (AYRTON et al., 1982), as well as Sps-rich Grt associated with Na–Am in the same Mesozoic cover (BALLÈVRE and KIENAST, 1987); Grt, Ky, Agt, Phe, Na–Am and Zo–Czo from mylonites at the contact between Valpelline and Arolla gneisses (PENNACHIONI and GUERMANI, 1993; DE LEO, 1984). In the Triassic cover of the southern Dent Blanche nappe, aegirine-augite, various amphiboles (actinolite, crossite, magnesioriebeckite, winchite) and phengite ($Si_{\leq 3.56}$) were formed during the first, nappe-forming deformation phase (HÖPFER and VOGLER, 1994). The latter authors also presented the first Alpine pressure-temperature-deformation path for the Dent Blanche nappe (shown below in Fig. 2c). This discreet and local H-P imprint is not shown on the map.

2.1.8. Second Diorito-Kinzigitic zone

In the Second Diorito-Kinzigitic zone, Alpine metamorphism is mostly developed at the base of the nappe and along cross-cutting shear zones. The most significant H-P/T recrystallization is observed at the base of the nappe, where the pre-Alpine kinzigites (high-grade Grt-Bt-Pl gneisses) have been sheared and developed a new, tighter, foliation defined by phengitic white mica and glaucophane. The eclogite occurrences reported by LARDEAUX et al. (1982) at the nappe base and interpreted as evidence of an eclogite facies overprint of this base, are most likely tectonic slices dragged during emplacement from the underlying Eclogitic Micaschist complex (or equivalent unit) and tectonically included within the thrust zone (REDDY et al., 1996).

2.2. CHRONOLOGICAL DATA

2.2.1. Geological data

In each zone the possible age range of the H-P/T imprint lies between the stratigraphic age of the youngest beds and the age of the first greenschist facies imprint, for which 38 ± 2 Ma, approx. late Bartonian, perhaps may be taken as a general date (see the companion paper). In the Briançon cover, including the Ligurian Alps, the youngest paleontological data, a bit imprecise because of metamorphism, indicate Paleocene-Lower Eocene ages (references in DEBELMAS and DESMONS, 1997). A Jurassic age may be assumed for the denudation of the peridotite-gabbro basement in the Combin zone from the occurrence in Jurassic marbles of ophiolite-derived clastic rocks and minerals such as serpentine sands and ophiolitic breccias in Queyras (LAGABRIELLE, 1987) and Montgenèvre (POLINO and LEMOINE, 1984; BERTRAND et al., 1984), and diopside and chromite grains in the Mt Jovet klippe (DESMONS, 1992). Paleontological evidence supports a lowermost Upper Jurassic age of the basalts. In the Combin zone the depositional sequence reached Upper Cretaceous (DEVILLE et al., 1992, and references therein).

Structural investigations indicate that Na-amphibole predates D_1, this D_1 deformation following the main thrusting, in the Dent Blanche the en-bloc thrusting of the Arolla and Valpelline series (PLATT and LISTER, 1985; MAZUREK, 1986; LEMOINE and TRICART, 1993).

There is no evidence that the very low- to low-grade H-P/T imprints have been coeval in all zones. We shall come back to this point in the conclusions.

2.2.2. Radiometric data

From the Combin zone, the Briançon basement, the Mesozoic cover of the Dent Blanche nappe and the basal shear plane of the Second Diorito-Kinzigitic zone there is a wide range of $^{40}Ar/^{39}Ar$ plateau ages, K–Ar ages and Rb–Sr ages which may have been obtained from minerals generated under glaucophane-schist or lawsonite-albite-chlorite facies (see compilation of the radiometric data up to 1992 in HUNZIKER et al., 1992, and references therein; TAKESHITA et al., 1994). The spread, especially in the K–Ar ages, only demonstrates the absence of Ar-isotopic equilibrium in these minerals which, moreover, may have been re-opened during the subsequent greenschist imprints, GS_I and/or GS_{II}. These dates cannot be used to support any hypothesis on metamorphic timing of the H-P facies in these zones, for which, at present, geological evidence gives the best chronological constraint: the post-Paleocene-Lower Eocene thrusting.

In the Ligurian Alps there are no radiometric data relevant to blueschist and lawsonite-albite-chlorite metamorphic rocks.

The available geological and radiometric data thus are inconsistent mutually and, as it will be explained in the paragraph on the age of the eclogites, with data from the other facies. One commonly held opinion is that the glaucophane-schist imprint represents the first step of the Paleogene metamorphic history in both Briançon basement and cover, as well as in the Dent Blanche nappe and the Combin zone. Ar-radiometric results older than Eocene, in this opinion, would be affected by Ar-inheritance. To accept them as true ages would imply a decoupling between the basement rocks, which bear glaucophane and jadeite, and the cover rocks, which are as young as Eocene, a decoupling which is real but may not have induced any significant disturbance of the metamorphic zoneography.

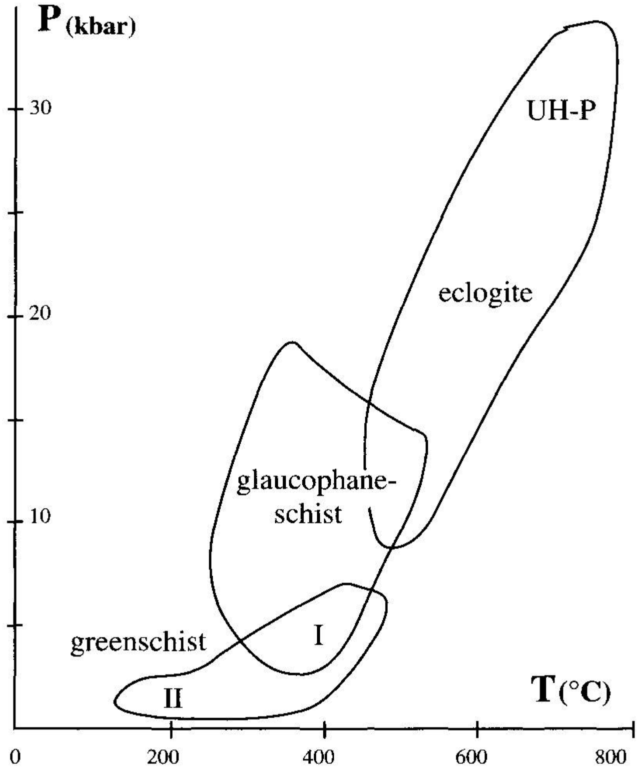

Fig. 1 P and T estimates for eclogite, glaucophane-schist and greenschist facies. Note the wide spread of the glaucophane-schist values, partly toward the P-T eclogite field (epidote-blueschist estimates?), partly toward higher P/T ratios (lawsonite ± jadeite glaucophane-schist estimates?). The greenschist estimates express two geothermal gradients, corresponding respectively to GS_I and GS_{II}. Overlapping fields are evidence of incorrect attribution of minerals to parageneses. In addition to references mentioned in the text, see SALIOT et al. (1980), GOFFÉ (1984–86), and PHILIPPOT and CABY (1986).

2.3. P-T-t EVOLUTION

The complete suite of characteristic mineral assemblages is best observed in basic rocks, but pelitic rocks have also been used to constrain the P and T conditions. The range of conditions proposed for the various glaucophane-schist and lawsonite-albite-chlorite imprints, based on element distribution coefficients, experimental data and thermodynamic calculations, is particularly wide, even for similar zones: from 300 to 525 °C and from 3 to 12 kbar (Fig. 1). Detailed figures, if not given in the text, can be found in the papers mentioned. The most likely values are shown in the P-T-t paths of figure 2c and 3.

In former eclogitic rocks (see following chapter), glaucophane-schist facies metamorphism includes a sluggish suite of reactions leading from Gln + Jd, locally through Gln + Lws, to Lws + Chl + Ab assemblages (e.g. MEYER, 1983; CHOPIN, 1979). The P and T conditions ascribed to the glaucophane-schist imprint in these rocks are in the same range as in the eclogite-free zones.

In Vanoise cover aluminous rocks ± aragonite, a counterclockwise path has been proposed by GOFFÉ and VELDE (1984) and GILLET and GOFFÉ (1988) for the whole H-P/T to greenschist evolution. In the Valais zone, a P value as high as 17–18 kbar for 350 °C has been proposed for an association of $Phe_{Si3.4}$ and Fe–Cp of low Mg-content ($mg_{0.4}$), for which GOFFÉ and BOUSQUET (1997) assumed a pre-eclogitic H-P/T phase. The discussion of such values (which would also correspond to the lowest geothermal gradient ever proposed in the Western Alps) and assumption is beyond the scope of this paper.

3. Eclogite facies metamorphism

The eclogite facies includes the typical mafic eclogite and other metamorphic rocks of various bulk chemical composition (e.g. whiteschist), containing mineral assemblages that indicate pressures ranging from high to very high (the latter qualified as UH-P). Eclogite, whiteschist and, very locally, UH-P metamorphic rocks considered as Alpine metamorphic products occur in the Zermatt and Voltri zones, the Internal Penninic massifs, the Sesia Eclogitic Micaschist complex and the related klippen, the Lanzo massif, in the small Clapey outcrop of the Versoyen in the Valais zone, and only in these zones. These eclogitic assemblages predate glaucophane schist ± Jd ± Lws or Ep-glaucophane schist (epidote blueschist) or barroisite-bearing assemblages, themselves generally followed by greenschist assemblages. There is also evidence of glaucophane-schist assemblages predating the eclogite assemblages at least locally. The eclogite facies rocks have been given the closest attention from Alpine scientists and the relevant literature is fairly abundant (review papers are: DAL PIAZ and LOMBARDO, 1986; DROOP et al., 1990; SPALLA et al., 1996).

3.1. METAMORPHIC FACIES AND THEIR DISTRIBUTION

3.1.1. Zermatt zone

The Zermatt ophiolites are famous for the eclogitic pillow-lavas which demonstrated that rocks once cooled down on the surface could be eclogitized (BEARTH, 1967). It also is a coherently eclogitic region, that is, eclogitic rocks, even if indicating different pressures of formation, here are predominant on km^2-wide areas, not being isolated relics within amphibolite facies terrains. Typical is a widespread assemblage of Omp + Grt ($Alm_{\leq 45}$ $Prp_{\leq 25}$ Grs_{20-35}) ± Pg ± Zo ± Ep ± Lws ± Tlc ± Mg-Cld ± Ky ± Mg–Chl ± Rt ± Qtz ± allanite, beautifully displayed in metabasalts and metagabbros of the Zermatt region (BEARTH, 1963, 1967; OBERHÄNSLI, 1980, 1982; MEYER, 1983; BARNICOAT, 1988a; COLOMBI, 1989), around and south of the Gran Paradiso massif (CHOPIN, 1979; SANDRONE et al., 1986; CASTELLI et al., 1995), in the Rocciavrè (POGNANTE, 1981, 1985) and the Viso areas (MONVISO, 1980; BURG and PHILIPPOT, 1991). Mg-chloritoid is common in the northern Zermatt zone, Mg-chlorite in the southern part of the zone (Rocciavrè, Viso) where Mg-chloritoid is scarce (MESSIGA et al., 1997).

Both pervasively deformed and undeformed gabbro are affected by eclogitic transformations. Only pseudomorphous and coronitic reactions are developed in undeformed gabbro, which preserves the original igneous texture and locally the igneous mineral composition. The best example is the Allalin gabbro near Zermatt, as well as the gabbros intruded into the ultramafic Lanzo massif (see below). In such metagabbros, due to low element diffusion rate, the garnet-omphacite Fe–Mg exchange geothermometer does not give reliable results.

The eclogitic assemblage post-dates some granulite and amphibolite facies relics from an ocean-floor metamorphism (see the companion paper). In the Allalingabbro near Zermatt (MEYER, 1983), in the Lanzo massif (COMPAGNONI et al., 1984), as well as in the Erro-Tobbio unit in the Voltri Group (MESSIGA et al., 1995), it post-dates also an ephemeral granulite facies corona stage estimated in Zermatt at 650–725 °C, > 18 kbar and $P_f < P_{tot}$, with olivine and orthopyroxene transformed into talc, chlorite, garnet and zoisite. In the Allalin gabbro, peak eclogitic conditions of more than 20 kbar and 600 °C have been inferred (MEYER, 1983). The pyrope content of garnet reaches 55% next to pseudomorphosed olivine. Stable isotope measurements on Zermatt H-P meta-ophiolites have shown that the signature acquired during ocean-floor metamorphism has been retained (BARNICOAT and CARTWRIGHT, 1995).

In one sheet, ≤ 300 m in thickness, at Lago di Cignana in upper Valtournanche, coesite relics are included in tourmaline and in pyrope-rich rims of spessartine-garnet from metachert (garnet core: Sps_{75-60} Prp_{14-27} Grs + And_{10-13}; coesite-bearing garnet rim: Sps_{64-54} Prp_{27-36} Grs + And_{4-12}), and in omphacite and almandine garnet from eclogite (REINECKE, 1991, 1998). Such relics would indicate a pressure as high as 28 to 30 kbar and a temperature of 600 °C.

In eclogites, especially in the fine-grained types, lozenge-shaped aggregates of Zo–Czo + Pg ± Phe are found, which have been interpreted as pseudomorphs after prograde or retrograde lawsonite porphyroblasts. In the Viso massif these pseudomorphs are interpreted as grown together with phengite during the retrograde path, under K-metasomatic conditions (BALLÈVRE et al., 1997). Formation of glaucophane-schist assemblages (Gln ± Cld ± Pg ± Phe) in rocks hydrated during ocean-floor metamorphism may have been coeval with eclogite formation in unaltered dry rocks. Eclogites have also been interpreted as developed by prograde reaction from glaucophane schist (BARNICOAT and FRY, 1986), but glaucophane schists are generally replacing the eclogite assemblages. Amphiboles of a wide compositional range, including Gln, Act, Ed, winchite, richterite, Hbl-Prg, have been described in eclogite (e.g. BENCIOLINI et al., 1984–87), and coexisting actinolite and glaucophane investigated (REYNARD and BALLÈVRE, 1988). In felsic rocks of the ophiolite sequence, the assemblage is Jd + Qtz + Grt (e.g. POGNANTE, 1989a, SANDRONE et al., 1986). Cr-Omp (the so-called "smaragdite"), Cr–Mg–Cld (KIÉNAST and MESSIGA, 1987) and other Cr-bearing minerals have been reported.

In ultramafic rocks of both Zermatt zone and Lanzo massif, metamorphic Ol (Fe-richer than peridotitic olivine) + Atg ± Di + Mag + Fe–Ni alloys developed. The formation of eclogite facies metamorphic veins bearing metamorphic olivine + Ti-clinohumite + Mg-chlorite ± apatite is remarkable.

Rodingites are rather common, as they are in the Lanzo massif (see below), deriving either from ocean-floor, H-P/T or greenschist facies metamorphisms (e.g. DAL PIAZ, 1967; BOGATTO and CASTELLI, 1997).

In calc-schists and other associated metasedimentary rocks the typical eclogitic assemblage is found in basic fragments from melange. The schists themselves contain Phe ± Pg + Grt ± Cld ± Zo ± Rt. The association of talc, phengite and Mg-chloritoid has been studied west of the Gran Paradiso massif by CHOPIN (1981b). Glaucophane-schist assemblages are common in special rock types such as metachert, Mn-ore and other mineralized occurrences (DAL PIAZ et al., 1979; MOTTANA, 1986; MARTIN and KIENAST, 1987; MARTIN and TARTAROTTI, 1989).

3.1.2. Voltri Group

In all units of the Voltri Group, garnet and omphacite preserve textural and mineralogical indications of crystallization under nearly static eclogitic conditions, and they largely re-equilibrated syn- to post-kinematically, both also under eclogitic conditions. Textural evidence shows Grt_{II}, Omp_{II} and Na–Am to have been in equilibrium during the second re-crystallization phase. Pre-kinematic Omp_{I} commonly shows some replacement by Na–Am or Omp_{II}. Also Grt_{I} can be replaced by Na–Am ± Czo.

The highest metamorphic grade during the H-P/T event is recorded within the Erro-Tobbio lherzolite unit. In ultramafite, Ol, Di, Ti-clinohumite coexist with Ant and Mag in veins, or replace primary Pl, Cpx and Fe–Ti oxides in basic dykelets. The following assemblage developed in metagabbroic dykes and lenses, and in rarer metabasalt dykes: Na–Cpx + Grt + Tlc + Cld + Zo/Czo + Chl. For this assemblage P and T have been estimated at 450–550 °C and 13–16 kbar (SCAMBELLURI et al., 1991). The growth of Mg-chloritoid appears to depend on the bulk rock chemical composition, being typical of Al-Mg-metagabbro (MESSIGA et al., 1995).

Similar metamorphic conditions have been inferred for the Beigua-Ponzema unit and associated cover. Coexisting Ant, Di, Ol, Ti-clinohumite are widespread in ultramafite, and olivine is often pseudomorphous after serpentine. In Fe-Ti-oxide gabbro and basalt, Omp, Grt, Rt coexist with Czo. In gabbroic rocks the assemblage is: Omp, Grt, Wm, Zo/Czo and Na–Am. In ophicarbonate rocks Di or Na–Ca–Cpx coexists with Cal, Grt, Tr and Ol (CORTESOGNO et al., 1981). The metamorphic peak is estimated at T = 475 ± 25 °C and P > 13 kbar (CIMMINO et al., 1980; CORTESOGNO et al., 1981; MORTEN and BONDI, 1984; BORSI et al., 1994; BOCCHIO and LIBORIO, 1996).

Slices of meta-ophiolites, mainly gabbroic rocks and basalts, locally associated with quartz-schists and micaceous schists, are considered as forming a dismembered unit, the Cascine Parasi unit, which geometrically overlies the Beigua-Ponzema unit. Metabasites contain Grt, Omp, Lws, Na–Am ± Rt ± Ttn associated with pre- and post-kinematic textures. A nearly bimineralic assemblage of jadeite and omphacite is characteristic of diorite to plagiogranite compositions. In quartz-schist a polyphase re-crystallization of Na-Am, Phe and Sps characterizes the H-P/T phases. Pressure in excess of 13 kbar and temperature in the range of 400–450 °C have been inferred.

3.1.3. Internal Penninic massifs

Eclogites are common both in the basement and overlying sedimentary rocks (the Furgg zone in the Monte Rosa) of the Internal Penninic massifs. The grain size is usually finer than in the Zermatt zone. The eclogites consist of Omp + Grt + Rt ± Zo/Czo ± Phe ± Pg. A deformation event is commonly seen to have been accompanied by recrystallization of the eclogite assemblage, especially omphacite. Paragonite + zoisite/clinozoisite aggregates which may be interpreted as pseudomorphs after lawsonite occur only in some eclogites in Valeille, on the northern slope of the Gran

Paradiso massif (unpubl. data). In this massif, porphyroblastic glaucophane grew statically at the expense of omphacite, but probably still within the omphacite stability field. Margarite relics have been found in a chloritite (a sheared enclave in granite ?) within augengneiss (CHOPIN, 1977); possibly associated with lawsonite it could be younger than the eclogite association.

Most metagranitoids preserve the original igneous plagioclase. Kyanite pseudomorphing former regional fibrolitic sillimanite or contact prismatic sillimanite and andalusite have been reported from both the Gran Paradiso (COMPAGNONI and PRATO, 1969) and Monte Rosa (DAL PIAZ, 1971) massifs. Metapelites consist of the assemblage: Grt + Phe ± Cld ± Pg ± Gln. In the Gran Paradiso, jadeite (Jd_{96}) has been reported from the Bonneval orthogneisses in the westernmost part of the massif. It has also been found in a thermally metamorphosed schist close to the metagranite in the Orco valley, near Locana (COMPAGNONI, unpubl. data). For this reason, the pressure peak of the Gran Paradiso is considered to have occurred very close to the Ab to Jd ± Qtz breakdown curve; a temperature of about 550 °C has been inferred for a pressure of 13 kbar (BORGHI and SANDRONE, 1995).

A peculiar rock type is the silvery micaschist, a rock derived by metasomatic process from the host orthogneiss (BEARTH, 1952; COMPAGNONI and LOMBARDO, 1974), and which is characterized by high Si, Mg, Al, K and very low Ca, Fe and Na contents. In such rocks, in the following called whiteschists, the assemblage Phe ($Si_{3.4-3.6}$) + Tlc + Cld (mg_{25-45}) + Chl + Qtz is found in the Gran Paradiso (CHOPIN, 1981a; see also discussion in KOONS and THOMPSON, 1985), Phe + Tlc + Ky + Cld (mg_{74-96}) + Qtz in Monte Rosa (CHOPIN and MONIÉ, 1984), and Prp ± Jd ± Phe + Ky + Cs in the UH-P Brossasco-Isasca sheet of southern Dora-Maira (CHOPIN, 1984; HIRAJIMA and COMPAGNONI, 1993; COMPAGNONI et al., 1995).

In the southern Dora-Maira massif, the Brossasco-Isasca unit, less than 1 km in thickness, is characterized by an UH-P metamorphic imprint, whereas the sheets above and below contain assemblages typical of lower-pressure eclogitic metamorphism (about 530 °C for 13 kbar, BORGHI and SANDRONE, 1995). In the Brossasco-Isasca unit, coesite relics are found as inclusions in most eclogite facies peak minerals, such as Grt ($Prp_{(70)90-98}$, SIMON et al., 1997), Omp, Jd and Zo (CHOPIN, 1984; HENRY et al., 1989; HIRAJIMA and COMPAGNONI, 1993; COMPAGNONI et al., 1995). The eclogites, which indicate a recrystallization temperature of about 680–750 °C (KIENAST et al., 1991) and a pressure in excess of 30 to 32 kbar, may contain kyanite, in addition to the assemblage Omp + Grt + Rt ± Phe ($Si_{3.55}$) ± Qtz ± Zo. The micaschists consist of the assemblage Qtz/Cs + Phe + Grt + Ky + Rt ± Jd_{70}, whereas the few high-P/T leucogneisses contain Jd + Qtz/Cs + Alm + Phe. Phlogopite has been mentioned as a syn-eclogitic, post-peak, mineral resulting together with Phe and Ky from Grt (SCHERTL et al., 1991). Uncommon H-P/T minerals such as ellenbergerite, Mg-dumortierite, Mg-staurolite, bearthite, ephesite, Fe-nyböite, and minerals generally found in the granulite facies such as sapphirine, orthopyroxene-enstatite, are present as inclusions within pyrope of whiteschist (CHOPIN, 1986; CHOPIN et al., 1993; HIRAJIMA and COMPAGNONI, 1993; FERRARIS, 1995; SCHERTL et al., 1991; SIMON et al., 1997).

As in Monte Mucrone in the internal Sesia zone, a number of small metagranitoid bodies are preserved within the orthogneisses, where pseudomorphous and coronitic reactions are found, but the chemical composition of the minerals suggests higher temperature than in Sesia. Interestingly, in addition to metagranitoids, thermally metamorphosed country schists and marbles also escaped pervasive Alpine deformation, and UH-P transformation of the pre-Alpine minerals can be observed in such rocks.

Eclogite assemblages have not been found in the Pinerolo unit where the metamorphic conditions probably never attained eclogitic values. However, suitable mafic rock compositions may be lacking.

Basic rocks of the basement unit of Torrente Visone, located in the Ligurian Alps, north of the Voltri massif, show relics of an eclogite paragenesis, locally associated with a blastomylonitic texture. Temperatures are considered to have been about 550 ± 30 °C and pressures about 15 kbar (CABELLA et al., 1990; MESSIGA et al., 1992).

3.1.4. Sesia zone

In the *Eclogitic Micaschist complex* a wide spectrum of continental crustal rock types bear eclogitic assemblages, including (COMPAGNONI, 1977; COMPAGNONI et al., 1977; CASTELLI, 1991; and references therein):

In micaschist: Phe ± Grt ± Omp or Jd ± Gln ± Zo ± Cld ± Qtz ± Zo/Czo ± Ca–Na–Am (± Gln) + Rt ± Phe ± Pg ± Ky.

In marble: Cal ± Dol ± Omp/Di ± Grt (Grs, rare Sps) ± Phe + Zo ± Al-rich Ttn.

In orthogneiss: Phe + Grt + Omp ± Pg + Rt (± Grt $Alm_{<72}$ $Prp_{<17}$ $Sps_{\sim 1}$ $Grs_{>14-52}$) (KOONS et al. 1987).

In leucogneiss: Jd + Kfs + Phe ± Al-rich Ttn ± Zo.

Phlogopite is a syn-eclogitic mineral in eclogites of peculiar composition.

An unusual eclogitized rock is the Monte Mucrone metagranodiorite where only pseudomorphous and coronitic reactions occurred due to perfect preservation of the igneous fabric (COMPAGNONI and MESSIGA, 1994, and references therein). Temperature and pressure conditions of 500 to 600 °C, > 15 to 17 kbar and $P_f < P_{tot}$ have been proposed.

In the lower Val d'Aosta, the plagioclase-rich layers of a former igneous layered complex dated as Early Carboniferous by RUBATTO (1998) commonly contain, in addition to garnet and omphacite, zoisite + paragonite pseudomorphs after porphyroblastic lawsonite. In addition, fresh lawsonite, frequently porphyroblastic in shape, occurs between the Orco valley and the Lanzo massif. These lawsonite occurrences most probably belong to separate tectonic units, described as a whole by POGNANTE (1989b) as "Rocca Canavese thrust sheets". The different thrust sheets are separated by blueschist facies blastomylonites of Alpine age (POGNANTE, 1989c, 1991).

In the *Gneiss Minuti complex*, usually considered as not affected by eclogitic metamorphism, relics of omphacite were found in mafic boudins enclosed in orthogneiss of the Val d'Aosta section (WILLIAMS and COMPAGNONI, 1983; SPALLA et al., 1991). However, the occurrence of fresh igneous plagioclase armoured in K-feldspar phenocrysts of orthogneisses deriving from Late Variscan porphyric granitoids, suggests that the pressure, though high, has not been high enough to produce the albite breakdown. For this reason, it is possible that a metamorphic H-P/T gradient existed along strike, i.e. from NNE to SSW in present orientation. The assumed pressure is 11 to 12 kbar and the temperature 400 to 550 °C. Phengite and pseudomorphs after former glaucophane are not uncommon in orthogneiss. In addition, a glaucophane-schist pre-eclogitic prograde stage has been assumed by REINSCH (1977).

The sparse *monometamorphic cover* described by VENTURINI (1995), consisting of Mn-nodule-bearing quartzite and predominant carbonate metasediments of assumed Permo-Triassic age, exhibits an eclogitic metamorphic imprint, consistent with that of the nearby basement rocks.

3.1.5. Lanzo massif

The peculiarity of the Lanzo massif is the huge extent of this ultramafic exposure. It now consists of a core of very well preserved peridotite surrounded by an envelope of serpentinized peridotite and a rim of sheared antigorite serpentinite. Gabbro and diabase dykes cross-cut the peridotite. High-P/T eclogitic assemblages can be seen everywhere, both in metabasic and ultrabasic rocks.

Gabbro and diabase recrystallized to assemblages of Tlc + Omp/Jd + Grt + Zo + Cld + Rt. The ultramafic rocks contain antigorite, and locally Alpine recrystallized olivine and Ti-clinohumite. In some places the plagioclase (belonging to plagioclase peridotite derived from spinel peridotite within the mantle) was converted to jadeite (COMPAGNONI, unpubl. data).

Rodingites, which derive from both gabbro and basalt dykes, occur all over the Lanzo massif as well as in the Zermatt zone serpentinized ultramafites. The gabbroic or basaltic nature of the protolith can be recognized from the rodingite grain size, reflecting the original igneous one. In rodingites, both omphacite (after igneous pyroxene) and jadeite (after igneous plagioclase), and chlorite can be found together with garnet. However, most rodingites appear to have formed during greenschist facies conditions, since they contain Di, Ves, Ca–Grt (grossular, hydrogrossular and/or andradite), Ep and clinochlore. COMPAGNONI et al. (1993) described a remarkable polyphase rodingite occurrence between Sesia gneiss and Lanzo ultramafic rocks.

3.1.6. Versoyen zone (Valais zone, near the Ptt St-Bernard pass)

In the Pointe Clapey, where assemblages of Na–Am ± Jd ± Cld are also found (BOCQUET [DESMONS], 1974), rare relics of Omp (Jd_{68-84}), Grt of very variable Fe, Mn and Ca contents, and Pg (LASSERRE and LAVERNE, 1976; SCHÜRCH, 1987) point to an eclogite facies, commonly assumed to be Alpine in age.

The Clapey body, the Pte Rousse acidic gneisses which contain jadeite (see above) and a few ultramafic bodies constitute small tectonic slices isolated within the host glaucophane schists and greenschists of the Roignais-Versoyen unit. In addition to the peculiar metamorphic assemblages, the type of magmatism and the tectonic position, normal for Clapey but overturned for prasinites and calc-schists, also differentiate these slices from the enclosing schists. For such reasons, these exotic slices may be considered as exhumed from the eclogitic depths and tectonically incorporated into the host schists before the lower-grade imprints. (This contrasts with the interpretation mentioned above, under 2.1.4., of an eclogitic phase affecting not only the Clapey body but also the whole Versoyen and Ptt St-Bernard units of the Valais zone). It is also proposed (by J.D.) to consider the Clapey, Pte Rousse and other slices of the Valais zone of the Western Alps as constituting very modest lateral equivalents of the Adula, Mte Leone or other Simplon-Ticino basement nappes of the Central Alps (Lower Penninic units) and, beyond, of the Tauern window (cf. DESMONS, 1993).

3.2. CHRONOLOGICAL DATA

3.2.1. Geological data

The youngest age limit of eclogitic (including UH-P) metamorphic phases is constrained by: (1) the age of unmetamorphosed dykes intersecting Sesia eclogite facies rocks, radiometrically dated as 30 Ma, and the coeval, paleontologically determined, Oligocene age of the volcaniclastic cover of the same Sesia rocks; (2) the Lutetian to Bartonian age of the thrust-related greenschist facies overprint (38 Ma according to some radiometric measurements, see the companion paper, DESMONS et al., 1999), Oligocene for the second greenschist assemblages (being a regional thermal metamorphism, the imprint of the latter must have been coeval in all regions); (3) the age of the glaucophane-schist imprints, an age which at least in the eclogite-free zones seems to be related to the thrusting phase; and (4) Upper Eocene breccias of the Ligurian Alps (Pianfolco Formation and Breccia di Costa Cravara) which contain clasts of all tectono-metamorphic units of the Voltri Group. These breccias also lie discordantly upon folded structures considered to have developed during the exhumation phases (CORTESOGNO and HACCARD, 1984).

The oldest age limit is stratigraphically poorly constrained by comparison of the sedimentary sequence overlying Zermatt basalts with the Apennine (which, however, constituted another, unrelated, basin according to some of the present authors, see the structural chapter in the companion paper, DESMONS et al., 1999), where similar sediments are paleontologically dated as Callovian-Oxfordian.

Structural data are available for the Sesia zone (WILLIAMS and COMPAGNONI, 1983; RAMSBOTHAM et al., 1994), according to which D_1 would have been associated with peak eclogitic and retrograde blueschist conditions; D_2 and D_3 under greenschist facies conditions would be present mainly in the Gneiss Minuti complex and in the transition area between the two complexes.

3.2.2. Radiometric data

The protolith age of eclogitized members of the ophiolitic sequences has been radiometrically measured as Middle Jurassic by Sm–Nd and zircon U–Pb measurements of Voltri plagiogranite and Zermatt gabbro (BORSI et al., 1996; RUBATTO et al., 1998). In the Internal Penninic massifs and the Sesia zone, the Permian radiometric age of the youngest metagranitoids contained in the eclogitic sheets also constrains the oldest possible age of the eclogite imprint.

Recent radiometric measurements yield for the eclogitic event dates much younger than previously considered. The oldest ages available until the very last years (see compilation in HUNZIKER et al., 1992, and references therein) were Early to mid-Cretaceous ages, from K–Ar and $^{40}Ar/^{39}Ar$ measurements of white mica of the Sesia zone and Monte Rosa whiteschists (Furgg zone), and the eclogite assemblages were considered as due to one single imprint. Generally considered as cooling ages after the eclogitic metamorphism, these radiometric ages now appear to be affected by excess Ar (ARNAUD and KELLEY, 1995; RUFFET et al., 1995, 1997).

According to the data recently obtained with SHRIMP, Lu–Hf, and Sm–Nd methods (GEBAUER et al., 1997; DUCHÊNE et al., 1997; RUBATTO, 1998; RUBATTO et al., 1998; and references therein; also GEBAUER, 1999, this volume) the eclogitic H-P/T and UH-P metamorphisms have not been coeval all over the chain. The oldest age of eclogitic metamorphism, 65 Ma, is found in the Eclogitic Micaschist complex of the Sesia zone. The same age has been obtained with other methods from the same Sesia zone. In the UH-P meta-ophiolites of the Lago di Cignana unit in the Zermatt zone, a metamorphic mean age of 44 Ma was found in both the eclogitic metabasic rocks and the associated metasedimentary rocks. A similar age was obtained with Sm–Nd and Rb–Sr methods (BOWTELL et al., 1994; AMATO et al., 1997). At Gornergrat, considered to be the monometamorphic cover of the Monte Rosa nappe, a U–Pb zircon SHRIMP age of about 35 Ma was determined for the eclogitic metamorphism (RUBATTO, 1998), which is consistent with radiometric data from the UH-P Brossasco-Isasca unit of the southern Dora-Maira massif and also those from the Adula nappe in the Central Alps (GEBAUER et al., 1992). In the Viso massif, Sm–Nd isochron ages of around 61 Ma are yielded by garnet and clinopyroxene, whereas a 40 Ma Rb–Sr age of phengite (CLIFF et al., 1998) is interpreted as dating the eclogitization of a mylonitic metagabbro. If the Sm–Nd ages are meaningful, it implies that the authors assume a H-P regime lasting at least 20 Ma for the same unit.

Fission track measurements of zircon from the southern Dora-Maira massif indicate that the critical temperature was crossed at a time given by the different authors as 30 ± 1.5 Ma, i.e. Early Oligocene (GEBAUER et al., 1997), or Late Eocene (BRANDON, in RING, 1995) thus older than 34 Ma, or 32 ± 4 Ma (BRIX, in VAN DER KLAUW et al., 1997).

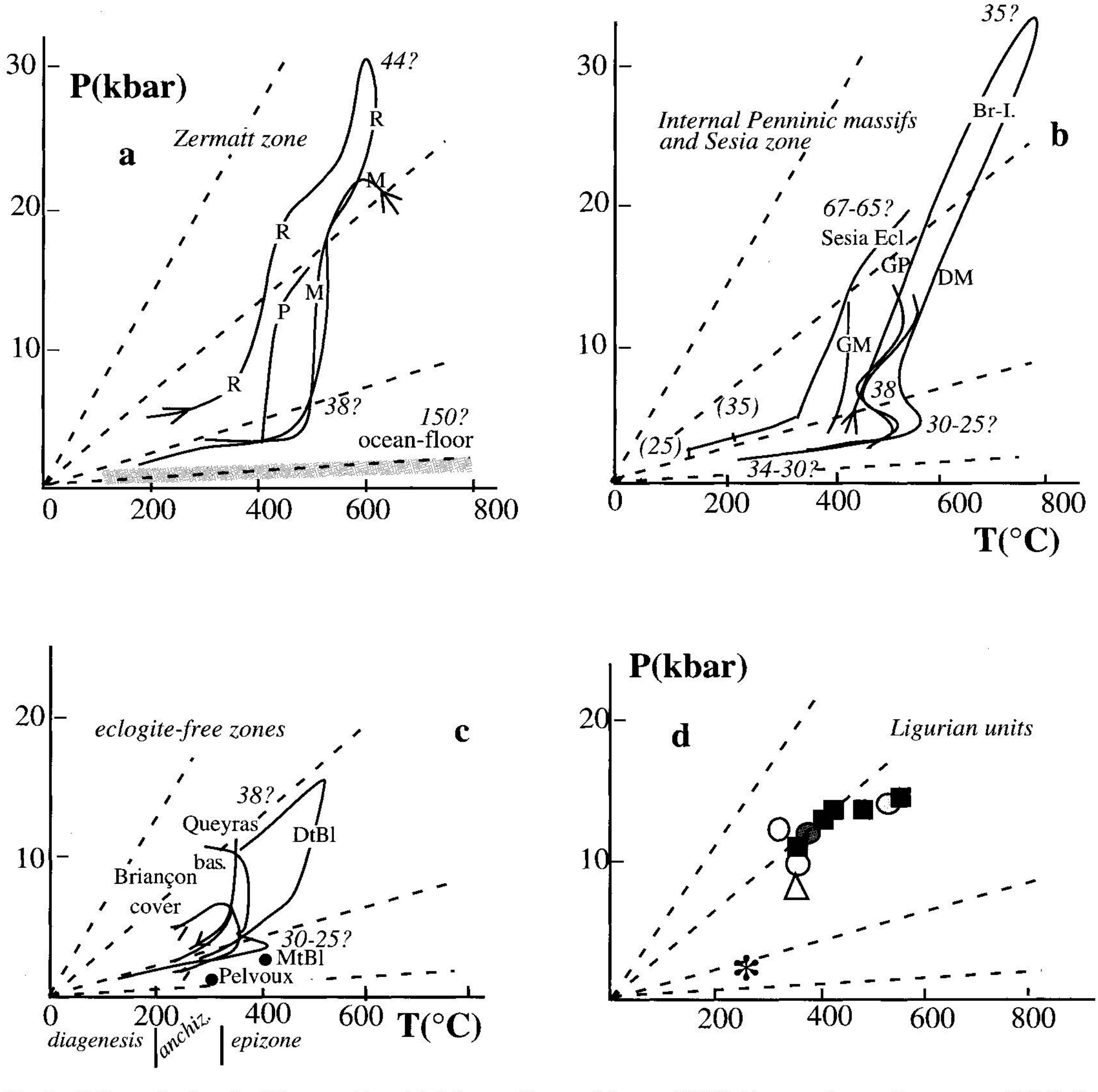

Fig. 2 P-T-t paths for the Western Alps: (a) M according to MEYER (1983), P according to POGNANTE (1991), R according to REINECKE (1998); (b) Br-I. Brossasco-Isasca unit of Dora-Maira according to COMPAGNONI et al. (1995), DM. Dora-Maira, and GP. Gran Paradiso, according to BORGHI et al. (1996), Sesia Eclogitic Micaschist and Gneiss Minuti (GM) complexes according to POGNANTE (1991), ages between brackets according to HURFORD (1991); (c) Briançon basement according to DEBELMAS and DESMONS (1997), Briançon cover according to GOFFÉ and VELDE (1984), DtBl. Dent Blanche according to HÖPFER and VOGLER (1994), Queyras according to POGNANTE (1991), MtBl. Mont Blanc and Pelvoux veins according to POTY et al. (1974); (d) Ligurian data of figure 3 shown on the same scale for comparison; solid squares, ophiolitic Piemontese-Ligurian units; solid circles, "Piemonte" units metamorphosed as the Piemontese-Ligurian units; open circles, Briançon units; open triangle, Piemontese-Ligurian unit not involved in the subduction event, but only in the accretion wedge; star, Apennine Bracco-Val Graveglia unit shown for comparison (LUCCHETTI et al., 1990; MARESCOTTI and GIORGETTI, 1995). Source of ages: see text. Dashed lines represent T/P gradients of 5, 10, 30 and 120 °C/km respectively.

Radiometric dating is still lacking from Ligurian eclogitic rocks.

At present these ages are not easy to reconcile with many greenschist facies ages and with geological constraints. There must have been a time gap of sufficient length between the eclogitization, which indicates the presence of the rock body at great depth, and its cooling to the temperature characteristic of the zircon fission track interpretation. This time period corresponds first to a change in the geodynamic setting and then to exhumation of the eclogitized rocks. This point will be taken up again in the conclusions.

3.3. P-T-t EVOLUTION

Examples of whole Alpine P-T-t paths proposed for eclogitic zones are shown in figures 2 and 3.

On account of the small size of the involved units (≤ 300 m thick Lago di Cignana unit in the Zermatt zone, ≤ 1 km thick Brossasco-Isasca sheet in southern Dora-Maira), the cooling after the UH-P peak is assumed to have been very rapid. In the meta-ophiolitic sequences of the Ligurian Alps, however, nearly adiabatic retrogression is assumed to have followed the H-P imprints.

In addition to T and P, μ_{CO_2} and μ_{H_2O} are of importance in the formation of eclogite and glaucophane-schist (Barnicoat, 1988b). Phase relationships in P-T-X_{CO_2} space indicate that even in impure marbles of the Sesia zone the mineral assemblages coexisted with H_2O-rich fluids (X_{CO_2} < 0.03) during the entire Alpine evolution (Castelli, 1991). Pognante (1991) assumed a comparatively low μ_{H_2O} for the transition between glaucophane schists and eclogite.

The post-eclogite H-P/T evolution under glaucophane-schist facies is common with many other Internal zones mentioned above.

Before approaching in the conclusions the constraints imposed by the metamorphic data on the palaeotectonic evolution of the Western Alps, it must be emphasized that the kilobars derived from thermodynamic calculations or experimental data, even in the case of assumed equilibrium and reversed experiments, must not be directly and simply translated into precise numbers of kilometers of overburden, as is done too often in reconstructed cross-sections. Differences between experimental and natural behaviour have to be taken into account, especially possible in low-grade reactions. Moreover, as explained in the discussion of eclogites (§ 4.4 below), peak conditions may not be registered and the P-T-t paths may thus be fallacious.

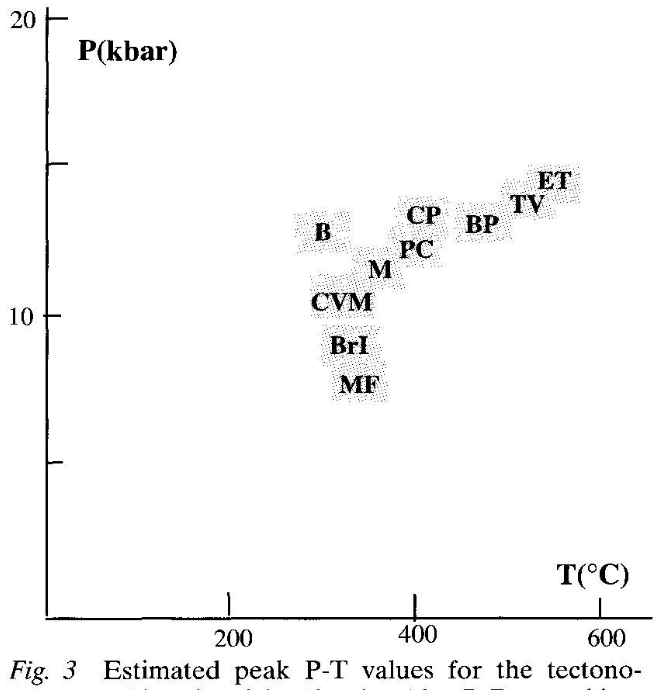

Fig. 3 Estimated peak P-T values for the tectonometamorphic units of the Ligurian Alps. B. Bagnaschino, BP. Beigua-Ponzema, BrI. Internal Briançon zone, CP. Cascine Parasi, CVM. Cravasco-Voltaggio and Montenotte, ET. Erro-Tobbio, M. Montaldo, MF. Monte Figogna, PC. Palmaro-Caffarella, TV. Torrente Visone. See text for references, and figure 4 for the relative structural position of the units.

4. Discussion and conclusions

1. Assemblages indicative of *various H-P/T facies* occur in the Internal Western Alps: eclogite including UH-P metamorphism, jadeite-, lawsonite- or epidote-glaucophane schist, and lawsonite-albite-chlorite facies including Fe–Mg-carpholite-bearing assemblages.

In spite of the Permian metamorphism, oceanic metamorphism, H-T and L-T eclogite, glaucophane-schist and greenschist overprints, there remain pre-Alpine metamorphic minerals, and magmatic minerals such as olivine, orthopyroxene, garnet, etc., and even minerals as sensitive as plagioclase or biotite. This fact indicates non-pervasive fluid flow during the various H-P events and also suggests locally weak greenschist overprint.

2. From its *cartographic distribution* the eclogite facies imprint clearly predates a major thrust-piling-up event, since the metamorphic boundaries coincide with Alpine tectonic boundaries, as already noted at the time of the first metamorphic map of the Alps (explanatory text by Zwart et al., 1978). The age of major thrust contacts is Lutetian to Bartonian, i.e. ~ 38 Ma, as geologically determined in the eclogite-free Briançon and Combin zones, and this age may be considered as also valid

at least for a re-working of the main thrust contacts between eclogite-bearing zones; the timing of these main contacts between eclogite-bearing zones, however, is so far poorly constrained.

The distribution of eclogite and glaucophane-schist facies metamorphism is not a result of the metamorphic zoneography during a single H-P/T event: (i) In eclogite-bearing zones, glaucophane outlasted eclogite, and elsewhere lawsonite outlasted glaucophane. (ii) According to recent radiometric data, the H-P/T assemblages are not coeval, ranging in age from latest Cretaceous in the internal Sesia zone, through Middle Eocene in the Zermatt zone, to Late Eocene in the Internal Penninic massifs. Moreover, there are eclogites devoid of any glaucophane schist overprint. A possible zoneographical pressure gradient has to be considered only for strictly coeval metamorphic imprints and within a same tectonic zone. The H-P/T metamorphic distribution is thus in contrast with the greenschist facies which have overprinted the whole Western and Central Alps.

3. *Glaucophane schists.* We must admit that each zone may have reacted to H-P/T generating settings at different times. This works against the common opinion that the required unusual P-T conditions occurred once and did not likely persist for a long time. It suggests that these conditions rather have been realized repeatedly during the Alpine evolution. In the Briançon basement glaucophane appears to be related to thrusting events; it shortly predates the first greenschist facies related to D_2, the pressure character of which was, as elsewhere, imposed by the thickness of the overload. In the eclogite-bearing zones the growth of glaucophane-schist facies minerals is commonly seen as a continuous retrogressive process related to exhumation. However, some authors consider that glaucophane also developed as pre- and syn-eclogitic mineral. These opinions have to be explored further.

4. *Eclogites.* Eclogites are present in the Sesia zone, the Zermatt and Voltri zones and the Internal Penninic massifs, implying that these zones resided at least for a while at deep crustal level. Moreover, the presence of coesite in the Brossasco-Isasca sheet of southern Dora-Maira and in the Lago di Cignana sheet of the Zermatt zone, commands to consider mantle depths in the evolution of these sheets. At the moment, the hypothesis of the UH-P metamorphism being pre-Alpine is disregarded (RADELLI and DESMONS, 1987, note 10; such an age would be supported, though certainly not proved, by the unusual size of the pyrope in Dora-Maira, by the granulite mineral relics, and, especially, by the P difference of ≥ 15 kbar indicated by the coesite-bearing assemblages of the Brossasco-Isasca sheet with respect to the adjacent L-T eclogitic rocks; moreover, as emphasized by VAN DER KLAUW et al., 1997, there is no structural or mineral record of the return path corresponding to these 15 kbar; a pre-Alpine return would easily account for the lack of any such traces, which would have been erased during the poly-orogenic and metamorphic history of these rocks). Nonetheless, such pre-Alpine hypothesis is inconsistent with the radiometric data interpreted as indicating Permian granitoid magmatism and Eocene UH-P metamorphism. Thus, according to current opinion, a severe selection would have been tectonically operated during the exhumation process, telescoping the intra-subduction-zone zoneography so that sheets metamorphosed under different pressures were finally superposed to each other, in reverse order.

The recent isotopic measurements on zircon ascribe the eclogite metamorphism in Sesia to latest Maastrichtian, in the Zermatt zone to Middle Eocene (Lutetian) and in the Internal Penninic massifs to Late Eocene (Priabonian). There is some difficulty in reconciling the Late Eocene age (35 Ma) with geological (the Middle Eocene age of the first greenschist event, corresponding to ~ 38 Ma) and fission track data (between older than 34 and 30 ± 4 Ma). According to these fission track data, a time-span from < 1 to 5 ± 4 Ma would be allowed for the change in paleodynamic setting and the exhumation from an assumed depth of 100 km. It would also imply a very fast growth of the whole eclogitic rims of the U–Pb measured zircons just before the exhumation. Furthermore, the exhumation of the Brossasco-Isasca unit of southern Dora-Maira would not have started before melt generation of the peri-Adriatic magmas (from around 42 to around 25 Ma), which indicate quite another geodynamic setting and were associated with a regional thermal metamorphism of low-P character on the scale of the whole Alpine belt. Any evolution model including such chronological basis leads to peculiar reconstructions.

To get out of this possible conflict (i) the geological and tectonic constraints can be re-examined; indications on this topic are briefly given in the last section; (ii) the path of a rock to be eclogitized and exhumed can also be re-examined; and (iii) the interpretation of radiometric results must be evaluated. The following remarks (by J.D.) can be made as concerns points (ii) and (iii).

(a) In undeformed rocks, the magmatic or metamorphic mineral association may persist metastably. Any deformation phase before, during or after their residence in depth will transform them into eclogites, or granulites, depending on the T/P gradient of the place. If the basic/ultrabasic rocks have been underplated a long time before their exhumation, and quietly resided a long time at depth, what is the meaning of an age measured on them? Probably neither the time of their entering eclogitic P and T conditions, nor peak conditions.

(b) In the Bergen eclogites (e.g. AUSTRHEIM, 1986–87) eclogite crystallization occurred only when it was triggered off by a sudden shearing event which introduced fluids, independently of the time when the rock body was first submitted to eclogitic P-T conditions. In the Alps, such a tectonic event, for instance, could have been associated with the exhumation process (and indeed described as such by VAN DER KLAUW et al., 1997, in the Lago di Cignana unit). In such a case, garnet or zircon dating would not yield the time of the burial at mantle depth. Peak conditions may not be registered, neither in the mineral assemblage nor in the isotopic ratios. The deformations accompanying the unroofing of the subducted rock bodies will trigger off the crystallization of eclogite assemblages, which can be called "mineralogical eclogitization". This eclogitization may occur at various levels and at various times, depending on the triggering deformation, as long as the rocks remain in a domain where the P-T conditions are eclogitic.

(c) The "radiometric eclogitization", i.e. the age measured on eclogitic minerals, may in some cases coincide with the mineralogical eclogitization, but it may also correspond to some time during the exhumation process, within or even outside of eclogitic P and T conditions. The concordance of the zircon ages from a same tectonic zone seems to point to only one event in each zone. However, during the tectonic incorporation of the various tectonic zones into the upper crust through multiple extensional events, many are the conceivable times when the various isotopic clocks may have started ticking (or when new zones are added to the grains, in the case of minerals growing in zones and alien to subsequent isotopic re-equilibration). Zircon growth occurs in an eclogite if zirconium is released by a reacting mineral such as garnet, clinopyroxene or hornblende, and the time of such reaction will be dated, which is not necessarily the time of peak conditions (see also FRASER et al., 1997). It may also be that the reported measured age is a closure age after an event unrelated to eclogitization, e.g. in the case of a mylonitized white mica, or of a heating event due to a younger magmatic phase if such disturbances have not been traced by thermobarometric investigation.

(d) Finally, it must be questioned (i) how far the U–Pb isotopic system of zircon can be disturbed by diffusion at eclogitic temperatures (this question is partly answered by experiments such as those of LEE et al., 1997, showing strong and rapid diffusion of Pb at very high temperatures, higher however than those assumed for UH-P eclogite imprint: ~ 0.5 cm after 45 Ma at 1100 °C), (ii) how far such temperatures, which are of the same order as those of granitic melting, can induce limited melting and a similar zoned crystallization of zircon, and (iii) whether there may be incorrect labelling of the measured spots (as magmatic, eclogitic, etc.). Limited melting during exhumation, associated with the breakdown of zirconium-bearing minerals, might have induced zircon oscillatory growth (as suggested to be the case of granulite by ROBERTS and FINGER, 1997) and the not-oscillatory rim labelled metamorphic in this case would be related not to eclogite, but to the later, greenschist to amphibolite, facies. Isotopic disturbance has indeed been assumed in order to explain age spreading in the Sesia zone, as well as zircon growth in veins at low temperature, thus not from a melt (RUBATTO, 1998; RUBATTO et al., 1998). It should be thoroughly investigated how the amphibolite facies of the Lepontine culmination has been recorded in zircon growth and why it was not registered in the Monte Rosa case, whereas the greenschist imprint is suggested to have affected the zircon age in the Cervino gabbro. It may also be recalled that Sm–Nd internal isochrons are not reliable if garnet and clinopyroxene are not in perfect isotopic equilibrium and this leads to underestimating the real age (CLIFF et al., 1998). Moreover, the method is imprecise because of the commonly small spread of Sm and Nd values.

Future work will show whether these remarks and distinctions are significant or not for the history of the eclogites in the Western Alps. From an opposite point of view it may be noted that (i) careful sampling and microscopic investigation of the relationships between blastesis and deformation may eliminate many sources of errors; and (ii) there is evidence (from the thinness of the UH-P sheets and unpubl. data) that the exhumation even from very great depths must have been very fast.

5. In the *Ligurian Alps* two main metamorphic cycles are envisaged (VANOSSI et al., 1984–86; MESSIGA, 1984; CABELLA et al., 1991 a, b): eo-Alpine (pre-Eocene) and meso-Alpine (post-Middle Eocene). The eo-Alpine event affected the Voltri, Montenotte and Sestri-Voltaggio ophiolites, the basement unit of Torrente Visone, and the Triassic-Liassic platform sequences originated from the "Piemonte" domain. The pre-Upper Eocene age of the eo-Alpine metamorphism is

documented by the occurrence of reworked clasts within breccias of that age and by their discordant position upon folded structures considered to have developed during the exhumation phases (see above the paragraph 3.2.1.).

In the "Piemonte" ophiolite-bearing units the H-P/T event occurred at different P and T conditions which in a P/T diagram (cf. Fig. 3) plot along a line corresponding to a *similar* T/P gradient of about 20 °C/km, different from the gradient inferred for the Ligurian Briançon units which have been metamorphosed later (and also from that of the Ligurian Apennine ophiolites, e.g. the Monte Figogna unit in Fig. 3). Such a similar gradient for all "Piemonte" ophiolites indicates that they have been metamorphosed either along a single subduction zone, or along subduction zones of similar dip and subduction rate. In contrast, the H-P metamorphism of the Briançon continental rocks occurred under lower T/P and lower T_{max} conditions, and in the case of the Ligurian Apennine ophiolites, which are interpreted to have been metamorphosed in an accretion wedge, the T/P gradient was higher and the P_{max} lower. For the prograde part of the metamorphic evolution there is hardly any evidence available.

In the basement, the Permo-Carboniferous and the Triassic to Cainozoic covers of the Briançon domains the metamorphic evolution is considered as Tertiary in age (meso-Alpine) on the ground of the occurrence of H-P/T assemblages in Eocene sedimentary rocks. A Tertiary age likely also applies to part of the evolution of the sequences belonging to the "Piemonte" zone.

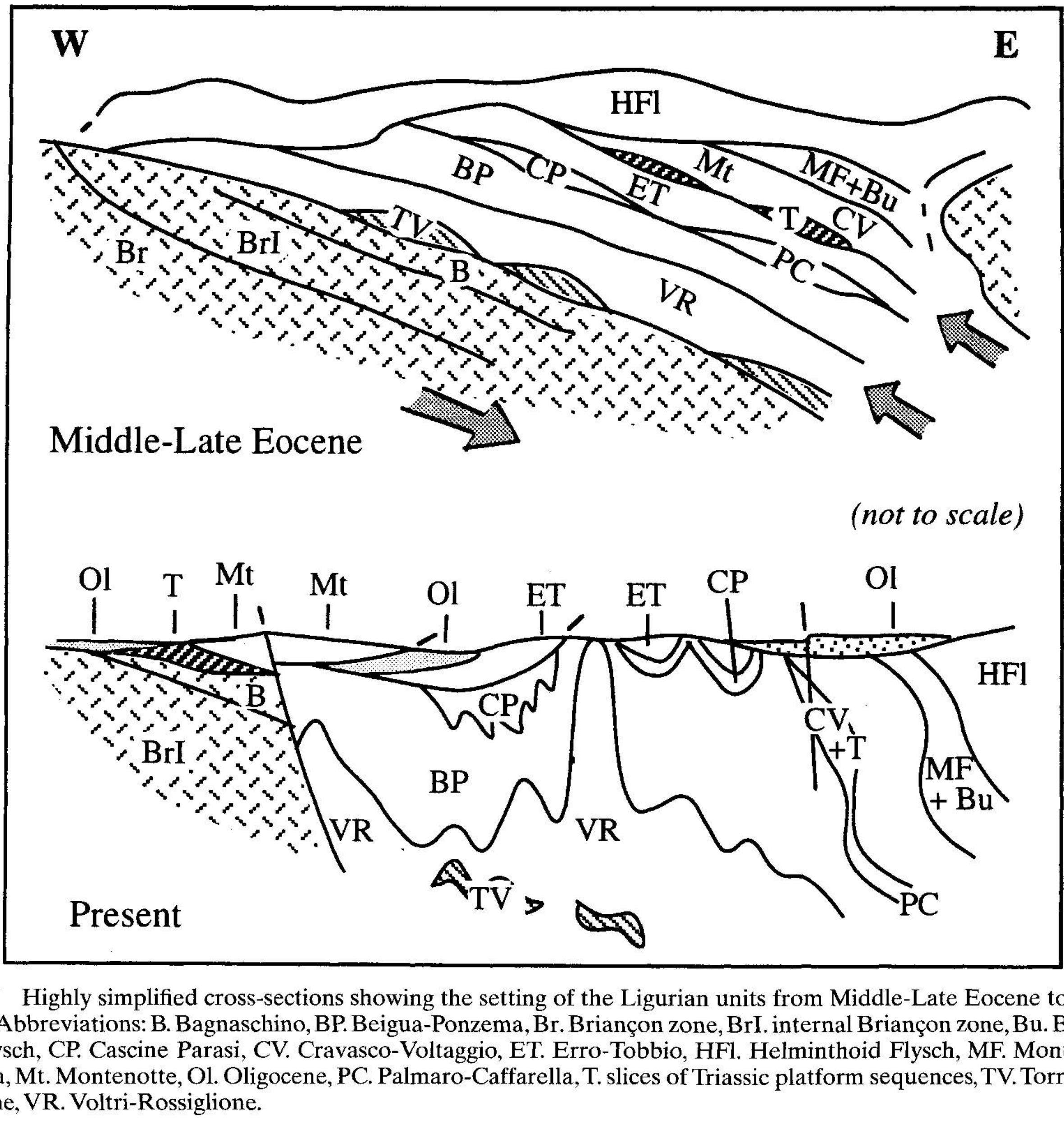

Fig. 4 Highly simplified cross-sections showing the setting of the Ligurian units from Middle-Late Eocene to Present. Abbreviations: B. Bagnaschino, BP. Beigua-Ponzema, Br. Briançon zone, BrI. internal Briançon zone, Bu. Busalla Flysch, CP. Cascine Parasi, CV. Cravasco-Voltaggio, ET. Erro-Tobbio, HFl. Helminthoid Flysch, MF. Monte Figogna, Mt. Montenotte, Ol. Oligocene, PC. Palmaro-Caffarella, T. slices of Triassic platform sequences, TV. Torrente-Visone, VR. Voltri-Rossiglione.

In all ophiolite-bearing units of the Ligurian Alps, the retrograde P and T conditions were associated with a folding event post-dating H-P/T structures and related to a new schistosity. In the various units, the intensive parameters support a retrograde path under decompressive, nearly adiabatic conditions. At the highest metamorphic grade, this phase was characterized by the stability of subcalcic hornblende with albite and epidote. This event, which occurred between the H-P and greenschist overprints and was generally associated with scarcely pervasive deformation, is well known and described in the Beigua-Ponzema and some calcschist units (CIMMINO et al., 1975; CHIESA et al., 1977; CORTESOGNO et al., 1977). A further re-equilibration under greenschist facies conditions followed the first retrograde event.

The subsequent phases mark a sequence of retrograde conditions until greenschist facies, followed, at least locally, by brittle phases associated with the development of zeolite assemblages. A tentative sketch of the evolution of the Voltri unit and adjacent units is given in figure 4.

6. Various *models* have been published in the last few years as concerns the metamorphism and the exhumation of eclogitic rocks of the Western Alps. In these models, deep subduction is the mechanism adopted for the generation of all H-P metamorphic facies. One or several subduction zones are assumed according to the adopted palaeogeography: one in the case of a single oceanic space including all Zermatt, Combin and Tethys basins (e.g. MICHARD et al., 1996; papers in PFIFFNER et al., 1997), or in the single long-lived subduction complex of DAL PIAZ et al. (1989) and POLINO et al. (1990), several in the case of individual basins subducted each in its own zone (AVIGAD et al., 1993; PLATT, 1986; etc.). The subduction was considered by AVIGAD et al. (1993) as pre-collisional and intra-oceanic. In this section we (LR and JD) briefly give interpretations of *all* the reported metamorphic imprints on a scale that is not only crustal but lithospheric. More details on these interpretations will be given elsewhere.

The *Permian metamorphism* examined in the paper on pre-Alpine metamorphism (DESMONS et al., this volume) was due to the heat developed by the magmatic underplating represented by the Ivrea mafic-ultramafic complex, and by the associated Permian-Triassic magmatism which is found in all basement Internal zones: the Briançon zone, the Internal Penninic massifs, the Sesia and Dent Blanche zones (see RADELLI, 1995). Such magmatism and metamorphism point to a common position of the involved zones within an active Gondwanian plate margin, and imply

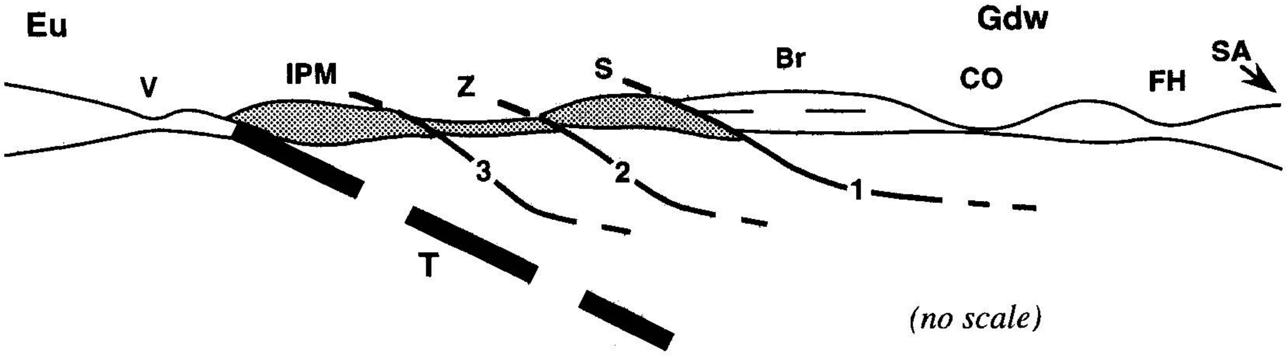

Fig. 5 Sketch illustrating the palaeogeographical position of the zones after Tethys subduction and before the subduction of the Internal Penninic massifs, the Zermatt and the Sesia zones, according to the two hypotheses concerning the age of Zermatt oceanic rocks.
Abbreviations: Eu. European plate, Gdw. Gondwanian plate, T. Tethys, V. Valais, IPM. Internal Penninic massifs, Z. Zermatt, S. Sesia, Br. future Briançon zone, CO. Combin basin, FH. Helminthoid Flysch basin, SA. future Southern Alps. CO and FH indicate only the relative position of these basins.
If Z is pre-Jurassic, Z was a marginal basin, IPM and S were sialic arcs; IPM, Z and S were supra-subduction-zone units. If Z is Jurassic, IPM and S were the outer part of the active Gondwana margin.
1, 2 and 3 are the future Benioff planes along which IPM, Z and S will be subducted. If Z is Jurassic, these Benioff planes are Early Cretaceous in age; if Z is pre-Jurassic these Benioff planes are latest Triassic (to Liassic?).
Dotted areas: units that after subduction will constitute an eclogitic wedge. If Z is pre-Jurassic the dotted areas represent a "neo-Europe"; if Z is Jurassic only IPM and S constituted such a "neo-Europe" after the Triassic collision.
The Valais zone possibly is derived from a basin individualized at the same time as Combin but within the European lithosphere. If this was the case, the Valais would have been involved in the accretion wedge of one of the Cainozoic A-subduction zones. Thus, the Valais and its basement, the Simplon-Ticino crystalline nappes, would represent the sole Penninic units of entirely European derivation.

the subduction of an ocean of wide extent underneath. Additional evidence for the consumption, and disappearance, of the Tethys towards the end of the Triassic is the convergence, from the Jurassic onwards, of European and Gondwanian faunas which previously, in Upper Permian and Triassic times, denoted, respectively, boreal and tropical positions. Such a subduction of an ocean is generally not followed by any exhumation process which would bring eclogitized rocks back to the surface.

The evolution of this geodynamically weak transition zone between Europe and Gondwana was characterized by Jurassic and Early Cretaceous extensional phases which created intracontinental basins, and by Late Cretaceous to mid-Cainozoic convergence which eventually closed each basin. The contents and floor of these basins were either deeply subducted along with their bounding continental arcs, or expelled and buried at relatively moderate depths. The *eclogite facies metamorphism* is explained by deep subduction. Distinctions have been made in a preceding section between peak metamorphic conditions, mineralogical and radiometric eclogitization. A cross-section showing the relationships of the units before subduction is given in figure 5, which mentions alternative hypotheses according to the assumed age of the Zermatt eclogites.

Exhumation of the eclogitic rocks must have occurred as a result of extensional forces. Late Cretaceous or mid-Tertiary are possible times from the tectonic-lithospheric point of view. Examining the uplift of the H-P rocks, PLATT (1986, 1987, 1993) suggested a mechanism of ductile extension of a composite accreted wedge in response to its progressive thickening. Calculations show that eclogites could be exhumed in about 10 Ma. A rheological model of ocean crust delamination within subduction zones has been developed by PHILIPPOT and VAN ROERMUND (1992). The differences in metamorphism between both Zermatt and Combin zones in the Viso-Queyras area and the Val d'Aosta have been taken into account by BALLÈVRE et al. (1990), BALLÈVRE and MERLE (1993) and MERLE and BALLÈVRE (1992). They interpreted the tectonic contact between both zones as a major normal ductile fault which cross-cut earlier-formed nappe contacts and was reactivated under greenschist facies conditions. The extension associated with this detachment fault would have contributed to the exhumation and the tectonic denudation of the H-P metamorphic units. The contact of non-eclogitic upon eclogitic rocks along this Combin fault is, however, claimed by RING (1995) to have resulted from contractional deformation.

Some Internal units of the Western Alps did not suffer eclogite facies metamorphism: the Briançon zone, the Combin zone, the Dent Blanche and the Sesia Gneiss Minuti. The *glaucophane-schist and lawsonite-albite-chlorite facies* imprints which are found in those zones thus indicate much shallower burial and lower T/P conditions than eclogite facies. Such conditions may have occurrred during the piling-up of the units, which also affected the exhumed eclogitized units. Afterwards, the P-T conditions evolved towards Barrovian gradient, producing the Eocene GS_I *greenschist facies* associations described in the companion paper.

As emphasized by RADELLI and DESMONS (1997), the magmatism and the thermal metamorphism characteristic of active plate margins are again found during Oligocene-Early Miocene. The magmatic arc was related to the A-subduction of the European plate under the Internal and Southern Alps. The deep-seismic profiles give the image of this subduction in the Western Alps. The GS_{II} *greenschist facies* imprint, of high T/P character, resulted from the heat generated in this magmatic arc.

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