

by Roberto Compagnoni

# HP metamorphic belt of the western Alps

The University of Turin, Dept. of Mineralogical and Petrological Sciences, Via Valperga Caluso, 35, 10125 TORINO, Italy.  
E-mail: roberto.compagnoni@unito.it

The understanding of the subduction-related processes benefited by the studies of the high-pressure (HP) metamorphic rocks from the western Alps. The most stimulating information was obtained from the inner part of the western Alpine belt, where most tectonic units show an early Alpine eclogite-facies recrystallisation. This is especially true for the Austroalpine Sesia Zone and the Penninic Dora-Maira massif. From the Sesia zone, which consists of a wide spectrum of continental crust lithologies recrystallised to quartz-eclogite-facies mineral assemblages, the first finding of a jadeite-bearing meta-granitoid has been described, supporting evidence that even continental crust may subduct into the mantle. From the Dora-Maira massif the first occurrence of regional metamorphic coesite has been reported, opening the new fertile field of the ultrahigh-pressure metamorphism (UHPM), which is now becoming the rule in the collisional orogenic belts.

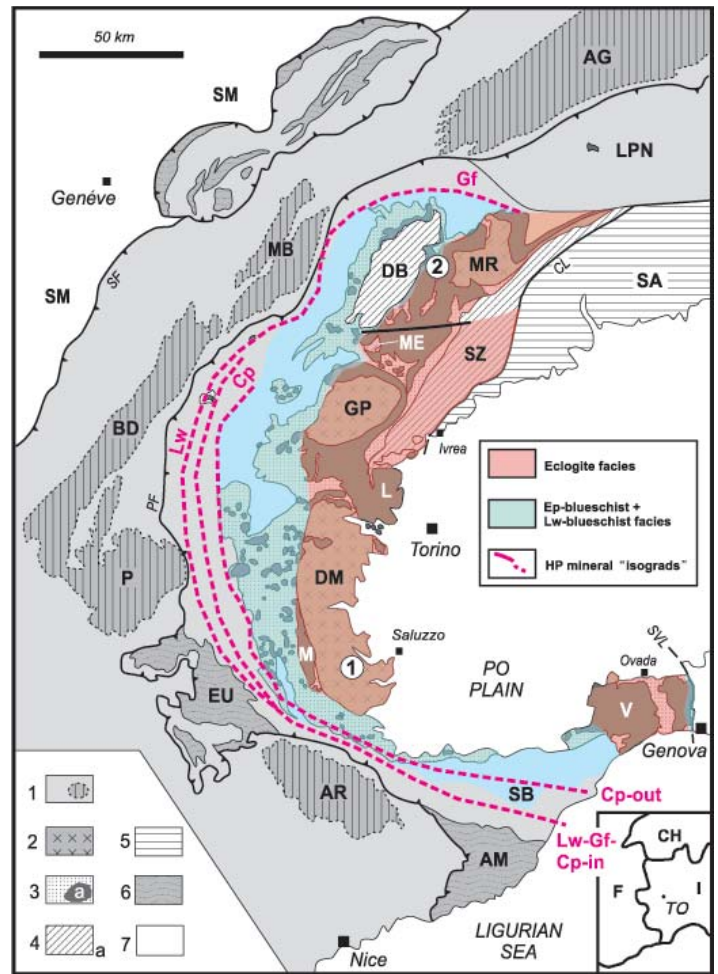
## Introduction

The western Alps extends from the Sestri-Voltaggio tectonic Line, which separates it from the non-metamorphic rocks of the Apennine chain, to the Lower Penninic Nappes of the Lepontine dome (LPN, Figure 1). On the internal side, the western Alps are bounded by the Quaternary post-orogenic clastic deposits of the Po Plain up to about the latitude of Torino, and from there northwards by the Canavese tectonic Line (CL), the SW extension of the Insubric Line (or Periadriatic lineament), which separates the pre-Alpine domain of the Southern Alps (Ivrea Zone + Strona-Ceneri Zone) from the western Alpine chain reworked during the Alpine orogeny.

The HP belt of the western Alps comprises most tectonic units of the Penninic and Austroalpine domains (Figure 1).

The Penninic Domain is a heterogeneous realm, which consists of both continent- and ocean-derived tectonic units (see Dal Piaz et al., this issue). The continent-derived units are (from the internal concave side toward the external convex side): the *Austroalpine Sesia-Lanzo Zone—Dent Blanche nappe system*, the “*Internal Crystalline Massifs*” of Monte Rosa (MR), Gran Paradiso (GP) and Dora-Maira (DM), and the *Briançonnais Zone* (or Grand Saint Bernard nappe system), which overthrust the Helvetic Domain: this tectonic boundary is known as “*Penninic Thrust Front*” (PTF) (Figure 1). The units derived from the Mesozoic Tethys ocean make up the *Piemonte Zone*, also named “*Zone of calc-schist* (French: “*schistes lustrés*”) with meta-ophiolite”, which consists of a number of thrust sheets with different high-pressure metamorphic recrystallisations (Figure 1).

The Austroalpine domain includes the Sesia-Lanzo zone (in the following referred to as the Sesia Zone) and the Dent Blanche Nappe system, which are fragments of Variscan granulite to amphibolite-facies continental crust intruded by late-Variscan granitoids, derived from the Southalpine (or Insubric) plate. The “*Eclogitic Micaschist Complex*” (EMC) of the Sesia zone and the Monte Emilius klippe of



**Figure 1** Simplified structural sketch-map of the Western Alps. 1: Jura, Helvetic Domain and external Penninic Domain. The dashed line contours the External Crystalline Massifs (AR: Argentera, P: Pelvoux, BD: Belledonne, MB: Mont Blanc-Aiguilles-Rouges, AG: Aar-Gotthard). SB: Grand St. Bernard Zone, LPN: lower Penninic nappes. 2: Internal Crystalline Massifs of the Penninic Domain (MR: Monte Rosa, GP: Gran Paradiso, DM: Dora-Maira). 3: Piemonte Zone (L: Lanzo Massif; M: Monviso Massif; V: Voltri Massif) and a) main meta-ophiolite bodies. 4: Austroalpine Domain (DB: Dent Blanche nappe, ME: Monte Emilius, SZ: Sesia Zone). 5: Southalpine Domain (SA). 6: Helminthoid Flysch nappes (EU: Embrunais-Ubaye, AM: Alpes maritimes). 7: Swiss Molasse (SM), Po Plain and Piemontese-Ligurian Tertiary basin. CL: Canavese line; SVL: Sestri-Voltaggio line; SF: Subalpine frontal thrust; PF: Penninic thrust front. (1) UHP Brossasco-Isasca Unit, Dora-Maira Massif; (2) UHP Lago di Cignana unit, upper Valtournenche, Piemonte Zone. Gf-in, from Bocquet (1974); Lw-in, and Cp-in and Cp-out from Goffé and Chopin (1986).

In the inset: CH: Switzerland; F: France; I: Italy; TO: Torino.

the Dent Blanche nappe are the best preserved examples of continental crust basement recrystallised under eclogite-facies conditions (Compagnoni, 1977; Dal Piaz et al., 1983).

Due to the widespread occurrence of unaltered HP metamorphic rocks, the western Alps have been the ideal area for the study of this type of metamorphism. Contributions to the knowledge of the HP metamorphism go back to the end of 19th century. The first eclogite-facies metapelite (named “eclogitic micaschist”) was reported by Stella (1894) from the EMC of the Sesia zone and later studied by Franchi (1900, 1902), who also described the reaction  $\text{jadeite} + \text{quartz} \Rightarrow \text{albite}$  (Franchi, 1902); the first eclogitised pillowed basalts were described by Bearth (1959) from the meta-ophiolites of the Piemonte zone from the Zermatt valley; the first eclogite-facies jadeite-bearing metagranite was reported by Compagnoni and Maffeo (1973) at Mt. Mucrone from the EMC of the Sesia zone; the first coesite in continental crust was reported by Chopin (1984) from the southern Dora-Maira massif; and the petrologic importance of Mg-Fe-carpholite<sub>ss</sub> for the blueschist-facies was first recognised by Goffé and Chopin (1986), studying Briançonnais lithologies previously considered unimportant for geobarometric estimates.

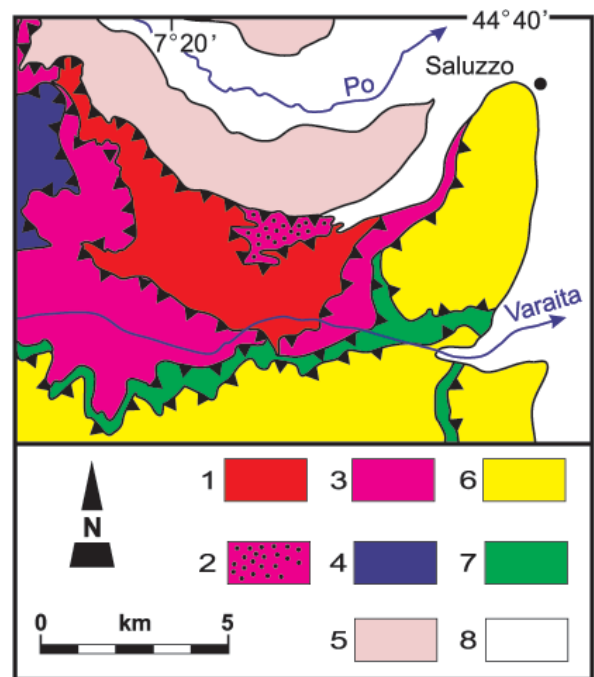
And finally, let's remember that the high-density, hard and tough Neolithic stone implements, excavated from all over the western Europe, are made of eclogite and jadeitite derived from the HP meta-ophiolites of the Piemonte zone (Compagnoni et al., 1996).

## Regional distribution of the HP metamorphism

Since Bearth's (1962) pioneering work, a number of attempts were made to trace the “isograds” of the HP metamorphism (for a review see Desmons et al., 1999). Many published and unpublished petrologic data were first summarised in the *Metamorphic Map of the Alps* (sheet 17 of the 1:1,000,000 *Metamorphic Map of Europe*, edited by Zwart, 1973) and then in the 1:500,000 *Map of the Alpine Metamorphism in the New Metamorphic Map of the Alps* (Frey et al., 1999).

Broadly speaking, at a regional scale the HP metamorphism in the western Alps includes from E to W eclogite-facies, epidote- and lawsonite-blueschist facies, and lawsonite-albite-chlorite facies rocks (Figure 1). The quartz-eclogite facies units prevail, but two small coesite-eclogite facies units have been recognised: the Brossasco-Isasca unit (BIU) from the southern Dora-Maira massif (Figures 1 and 2) and the Lago di Cignana unit from the Piemonte zone (Figure 1). This large-scale metamorphic zoning is considered as evidence showing that the northern European plate was subducted below the Adrian (or Insubric) plate (Ernst, 1971; Dal Piaz et al., 1972).

“Isograds” for most significant blueschist-facies minerals, such as glaucophane-in (Gf-in), lawsonite-in (Lw-in), and carpholite-in (Cp-in)-and-out (Cp-out) have been traced in the western Alpine belt, and provide a large-scale idea of their mineral zoneography in the most external Pennine zone (Figure 1). However, the increase of detailed petrographic studies showed that the HP mineral distribution is really much more complicated than originally supposed. For example, in the Aosta valley, the tectonometamorphic setting of the Piemonte zone consists of a quartz-eclogite facies unit or composite lithotectonic unit (“Zermatt-Saas zone”: Bearth, 1967) overlain by an epidote-blueschist facies unit or composite lithotectonic unit association (“Combin zone”). The main tectonic contact between the two zones is marked by the presence of a thin coesite-eclogite facies meta-ophiolitic unit (“Lago di Cignana Unit”: Reinecke, 1991) and of several Austroalpine continental crust slices, showing an Alpine quartz eclogite-facies overprint. This complex tectonometamorphic setting indicates the presence of a polyphase tectonic evolution, involving both compressional and extensional large-scale processes. Figure 2 illustrates the southern Dora-Maira massif, where a tectonic thrust sheet with Alpine coesite-eclogite facies overprint (Brossasco-Isasca Unit: T 750°C, P 3.5 GPa) is sandwiched between two



**Figure 2** Structural sketch map of southern Dora-Maira Massif. Continent-derived Dora-Maira Massif: Coesite-eclogite facies Brossasco-Isasca Unit (1); Quartz-eclogite facies San Chiaffredo Unit (2); Quartz-eclogite facies Rocca Solei Unit (3); Pre-Alpine basement and Permo-Triassic cover unit (4); Epidote-blueschist facies Pinerolo Unit (5); Quartz-eclogite facies Dronero-Sampeyre Unit (6); Ocean-derived Piemonte Zone: Epidote-blueschist facies metaophiolites and oceanic metasediments (7); Quaternary alluvial deposits (8).

quartz-eclogite facies units (San Chiaffredo and Rocca Solei units: 550°C, 1.5 GPa), bounded in turn by an epidote-blueschist facies unit (Pinerolo unit: 450°C, 0.8 GPa) and a quartz-eclogite-facies unit (Dronero-Sampeyre unit: 550°C, 1.5 GPa) (Compagnoni and Rolfo, 2003 with ref. therein).

## Peculiarities of the HP metamorphism

The Alpine eclogite-facies recrystallisation is especially well developed in the Eclogitic Micaschist Complex of the internal Sesia Zone, in the Monte Emilius klippe of the Dent Blanche nappe, and in the meta-ophiolites of the Piemonte Zone, while relics of eclogite-facies lithologies occur in the Internal Crystalline Massifs of Monte Rosa, Gran Paradiso, and Dora-Maira (Figures 1 and 2). Most units have been recrystallised under quartz-eclogite-facies conditions, except for the two small units of Brossasco-Isasca (BIU) (T=730 °C and P 3.3 GPa) from the southern Dora-Maira Massif (Figure 2) and Lago di Cignana (T 600 °C and P=2.6–2.8 GPa) from the Piemonte zone, which contain coesite relics.

## HP metamorphism in the oceanic lithosphere

Historically important are the pillow metabasalts of the Piemonte zone (Zermatt Saas zone: see later on) described by Bearth (1959) for the Zermatt valley, in which the dry pillow core was converted to a coarse-grained bimineraleclogite assemblage, whereas the hydrous rim was replaced by a glaucophane-rich rock. In the Monviso ophiolite of the Cottian Alps (Figure 1), a complete section of oceanic crust is exposed, including poorly deformed isotropic to lay-

ered cumulus gabbros, massive to pillowed basalts, and basaltic dykes, which recrystallised under eclogite-facies conditions (Schwartz et al., 2000).

The Lanzo ultramafic massif (Figure 1) is the largest portion of upper mantle peridotite exposed in the western Alps, which experienced Alpine eclogite facies metamorphism with  $P$  in excess of 2.0 GPa and  $T = 550^\circ\text{C}$ . Its central less-deformed portion still consists of spinel-plagioclase lherzolite and minor harzburgite—so fresh that the high- $T$  petrology and deformation may be studied (Boudier, 1976), and gabbro dykes are locally found which may preserve the original Ca-rich plagioclase. By contrast, its marginal portion has been converted to sheared serpentinite, which contains the eclogite-facies assemblage: antigorite, metamorphic olivine (Fe-richer than peridotitic olivine), clinohumite (mostly red-brown titanian clinohumite) magnetite, Fe-Ti alloys $\pm$ diopside $\pm$ Mg-chlorite $\pm$ apatite. Similar mineral assemblages may be found in the antigorite serpentinite of the whole eclogite-facies internal Piemonte zone, where olivine+Ti-clinohumite+Mg-chlorite $\pm$ apatite metamorphic veins occur, which in part at least developed at the expense of primary igneous dykes rich in ilmenite (Scambelluri and Rampone, 1999).

Poorly deformed metagabbros are the best-preserved ophiolitic lithologies, since the coarse grain-size and dry composition favoured preservation of the igneous protolith. Let's first mention the Allalin metagabbro (Bearth, 1967) from the Swiss Valais, in which all reaction steps from the original olivine gabbro to a coarse-grained eclogite may be observed (Meyer, 1983). The poorly-deformed metagabbros are characterised by a more complex mineral association than the sheared gabbros, because pseudomorphous reactions develop after each igneous mineral and coronitic reactions at the original boundaries between igneous minerals, respectively. For example, in coronitic Mg-Al-metagabbros, diopside-rich omphacite+talc develops after igneous clinopyroxene, jadeite-rich omphacite+garnet+zoisite $\pm$ quartz after plagioclase, and omphacite+talc+Na-amphibole after olivine. In coronitic Fe-Ti-metagabbros ferrian omphacite develops after igneous clinopyroxene, omphacite+garnet after plagioclase, and Na-amphibole+rutile after the hornblende-ilmenite intergrowth (Messiga and Scambelluri, 1988). In the pervasively deformed portions, Fe-Ti-metagabbros recrystallised to omphacite+garnet+rutile $\pm$ glaucofan $\pm$ epidote assemblages, whereas Mg-Al-metagabbros recrystallised to omphacite+garnet+rutile $\pm$ chloritoid $\pm$ talc $\pm$ chlorite assemblages. In the so-called "smaragdite" metagabbros, the original igneous Cr-diopside has been replaced by bright-green "smaragdite" (i.e., a Cr-bearing omphacite $\pm$ tremolite $\pm$ talc), plagioclase by jadeite-rich pyroxene+zoisite, olivine by talc $\pm$ tremolite, and ilmenite by rutile.

Mineral assemblages and mineral compositions are closely related to bulk rock chemistry: for example, in gabbros with high Mg/(Mg+Fe) ratio (such as Mg-Al-gabbros), Mg-Al minerals (such as chlorite and/or chloritoid) form, whereas the biminerallitic omphacite+garnet (+rutile) eclogite assemblage is produced only in Al-poor, Fe-Ti-rich gabbros. Similarly, garnet is almandine-richer in Fe-Ti-metagabbros, whereas it is pyrope-richer in Mg-Al-metagabbros.

Lawsonite-eclogites are extremely rare in the western Alpine belt and confined to some small tectonic units of Liguria. On the contrary, the widespread occurrence of lozenge-shaped white-mica+paragonite pseudomorphs up to about two cm-long indicates that porphyroblastic lawsonite was common during prograde eclogite-facies metamorphism.

In eclogites, veins locally occur, which indicate that the eclogite-facies metamorphism developed in the presence of a hydrous fluid phase. However, the fluid flow was limited during eclogite-facies metamorphism and fluid was mainly released by devolatilisation reactions of dense hydrous silicates (such as lawsonite) or during plastic crystal flow (Philippot, 1993).

Associated with eclogites derived from Fe-Ti-gabbros, very minor felsic rocks (plagiogranite or sodagranite) are locally found, which exceptionally occur as km-sized bodies (Castelli et al., 2002 with ref. therein): they are the only lithology among meta-ophiolites containing the association jadeite+quartz $\pm$ garnet.

In lithologies of unusual compositions belonging to the layered gabbros sequence, Cr-Mg-chloritoid and other Cr-bearing minerals have been found, most likely formed at the expense of chromite-rich bands of the cumulus layered gabbros (Messiga et al., 1999).

Rodingites, derived from both gabbroic or basaltic dykes, are ubiquitous within most serpentinitised peridotites and have a typical paragenesis of diopside, vesuvianite, ugranditic garnet, epidote, and Mg-chlorite; however, the local presence of Alm-rich garnet and omphacite indicates that some of them formed during HP metamorphism.

In the calc-schists and associated metasediments, eclogite-facies assemblages are more difficult to identify because typically they are more easily retrogressed. However, for suitable compositions, the eclogite assemblage appears to be phengite+Alm-rich garnet+rutile $\pm$ paragonite $\pm$ zoisite $\pm$ chloritoid $\pm$ porphyroblastic lawsonite, mostly replaced by paragonite+epidote pseudomorphs. Noteworthy is also the Mn-deposit of Praborna, Saint Marcel (Aosta Valley), where a number of eclogite-facies Mn-bearing minerals or mineral varieties have been described (Martin and Kienast, 1987).

## HP metamorphism in continental crust

The best preserved portion of eclogitised continental crust in the western Alps is the Eclogitic Micaschist Complex of the Sesia Zone. In this complex, derived from a Variscan amphibolite-facies basement intruded by late-Variscan granitoids (Compagnoni, 1977), the whole spectrum of continental lithologies from paragneiss to orthogneiss, from marble to metabasic rock, may contain one or more quartz-eclogite facies minerals, such as garnet, Na-pyroxene (omphacite and jadeite), high-celadonite phengite (3T polytype), paragonite, glaucophane, zoisite, and chloritoid.

Well-preserved relics of Variscan crystalline basement also occur in the Internal Crystalline Massifs. The best examples of undeformed lithologies are the coronitic metagranitoids, which are exposed in the central Gran Paradiso massif, at Monte Mucrone in the "Eclogitic micaschist Complex" (EMC) of the Sesia zone, and in the Brossasco-Isasca unit (BIU) of the Dora-Maira massif. In all three units, metabasic rocks have been converted to the eclogite assemblage, but metagranitoids show significant differences: in the Gran Paradiso metagranitoids (about 400–500 °C and about 1.0 GPa) the igneous structure and mineralogy are mainly preserved; in the Monte Mucrone metagranitoids, Sesia Zone (about 550 °C and 1.6–1.8 GPa) igneous quartz and K-feldspar are preserved, but plagioclase is pseudomorphically replaced by jadeite+zoisite+quartz $\pm$ kyanite $\pm$ K-feldspar; in the BIU metagranitoids, Dora-Maira massif (about 750 °C and 3.5 GPa) igneous quartz is also replaced by a granoblastic polygonal aggregate of metamorphic quartz, inverted from former peak pressure coesite (Biino and Compagnoni, 1992).

However, the most interesting continental crust lithology of the western Alpine HP belt is the "silvery micaschist", which occurs as cm- to m-thick lens-like layers within the orthogneiss of the Internal Crystalline Massifs and is interpreted as a metasomatic rock formed at the expense of a granitoid protolith along shear zones (Compagnoni and Hirajima, 2001, with ref. therein). This rock, which is important petrologically because its phase relationships can be modelled in the relatively simple KMAH system (Chopin, 1981), is usually referred to as "whiteschist" for its characteristic kyanite+talc (or talc+phengite) assemblage, indicative of pressures in excess of about 1.0 GPa (Schreyer, 1977). The best-known and unique whiteschist is that from the Dora-Maira massif first described by Chopin (1984), which contains in addition to kyanite, phengite, talc, rutile, and accessories, a pale-pink idioblastic pyrope (up to 98 mole% of the Mg-Al end-member). Pyrope crystals are up to 20 cm across and host, in addition to abundant kyanite, unusually large coesite relics. A number of new minerals (such as bearthite, ellenbergerite and phosphellenbergerite) or minerals of unusual composition (such as magnesiodumortierite, magnesiochloritoid, magnesiochaunite), sug-

gestive of UHPM conditions, have been found in the pyrope crystals (Chopin and Ferraris, 2003 with ref. therein).

## Age of HP metamorphism

Up to the end of the 1980s, most radiometric ages relevant to the HP metamorphism from the western Alps, recognised as indicative of an Early-Alpine or Eoalpine metamorphic event fell into the range of 140–60 Ma, further subdivided into an early eclogite-facies stage (140–85 Ma) and a later blueschist-facies and cooling stage (85–60 Ma) (for a review see: Hunziker et al., 1992). The younger Tertiary ages (around 50 Ma) were interpreted as the evidence of two episodes of HP metamorphism (Monié et al., 1989).

The first work, which suggested the possibility of a Tertiary age for the eclogite-facies metamorphism from the western Alps, was that by Tilton et al. (1991, with ref. therein) who dated U-Pb on minerals from the UHPM Brossasco-Isasca Unit (BIU), southern Dora-Maira massif (DMM). However, the major change in the age determination of the eclogite-facies metamorphism in the western Alps was brought about by the *in-situ* U-Pb dating of high closure-temperature minerals, such as zircon, with the Sensitive High Resolution Ion-Microprobe (SHRIMP), assisted by cathodoluminescence imaging (Rubatto et al. 2003, with ref. therein). The most complete geochronological work was done on the UHPM rocks of the southern Dora-Maira massif, previously studied by Tilton et al. (1991) (Gebauer et al., 1997 with ref. therein): the new U-Pb ages, consistently fell at the Eocene-Oligocene boundary (~35 Ma) and were later confirmed by the results from Lu-Hf dating of garnet (Duchêne et al., 1997).

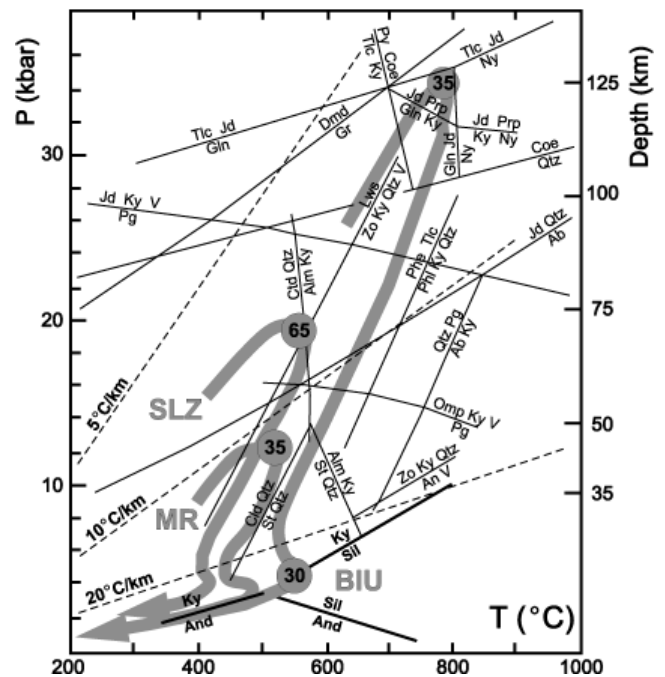
At present, with the exception of the Cretaceous age (~65 Ma) of the quartz eclogite-facies metamorphism of the Sesia zone (Rubatto et al. 2003), other U-Pb SHRIMP ages on the western Alps eclogites are all Tertiary (35–45 Ma).

## P-T-t paths of the HP metamorphism

The tectonic units of the western Alps recrystallised under eclogite-facies conditions, independently of their peak P conditions, consistently show a similar P-T-path, which is characterised by two thermal peaks. The first thermal peak, which corresponds to the high- to ultrahigh-pressure climax, is followed by significant decompression coupled with moderate cooling. The second thermal peak is at low-P (about 0.4–0.6 GPa), and corresponds to the greenschist-facies event of the Alpine literature. It is followed by significant cooling coupled with moderate decompression. In Figure 3, the P-T paths of the most significant units of continental crust (i.e. Monte Rosa, Sesia zone and BIU) are reported. From their comparison, it is evident that all the P-T paths are clockwise, and that the highest is the peak pressure, the tightest is the P-T loop. This feature, initially difficult to explain, is now believed to be the best evidence that the whole subduction/exhumation process is much faster than formerly supposed. For example, subduction and exhumation speeds of about 2 cm/a have been suggested by Rubatto et al. (1999) for the EMC of the Sesia zone and by Rubatto and Hermann (2001) for the BIU of the Dora-Maira massif.

## Conclusions

The existence of two age clusters, initially interpreted as evidence for two metamorphic events of Cretaceous and Tertiary ages, affecting the whole western Alps, have turned out to be the record of separate events in different units. Therefore, the different units were subducted and exhumed at different times, implying that at the same time subduction and exhumation were active in different portions of the orogenic belt. This diachrony of the HP and UHP metamorphism of the Western Alps gives rise also to a nomenclature problem, since



**Figure 3** P-T-t paths of representative continental eclogite-facies units from the western Alps. BIU: UHPM Brossasco-Isasca Unit of Penninic Dora-Maira Massif (from Compagnoni et al., 1995, modified). SLZ: Austroalpine continental Sesia Lanzo Zone (from Tropper and Essene, 2002, modified). MR: Penninic Monte Rosa nappe of the Internal Crystalline Massifs (Borghi et al., 1996). Mineral abbreviations after Bucher and Frey (1994). Circled numbers are SHRIMP radiometric ages in Ma for BIU (Rubatto and Hermann, 2001), SLZ (Rubatto et al., 1999), and MR (Rubatto and Gebauer, 1999), respectively.

the so-called early-Alpine or Eoalpine metamorphism, previously considered to be Cretaceous in age and subduction-related, is not a single coeval event throughout the western Alps.

The preservation in both ocean- and continent-derived units of poorly deformed lithologies, which preserve the protolith structure and even part of the primary mineralogy, indicates that at any scale the HP deformation (and metamorphic recrystallisation) mainly occurred along shear zones. This mechanism was favoured by both the relatively low fluid content in continental and oceanic lithologies and the unusually high speed of the whole subduction/exhumation process, which took place in a time span of only a few millions of years. The high speed of the tectonic processes, the scarcity of a free fluid phase, and the continuous cooling during exhumation also account for the local superb preservation of the HP peak mineral assemblages.

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**Dr. Roberto Compagnoni** is Professor of Petrology at the University of Torino, where he graduated in Geology in 1964. He has been teacher of Petrology and Metamorphic Petrology at the University of Torino, and at the University of Calabria. His research activity includes the study of metamorphism of meta-ophiolites and crystalline basements from the Western Alps and the Calabrian-Peloritanian Arc of southern Italy, with special attention to the relationships between mineral growth and deformation, and reconstruction of the P-T-t paths. During the last ten years his research has been mainly devoted to the study of the UHP metamorphism of western Alps, and Dabieshan-Sulu, China.

