UHP TERRANES IN THE WESTERN ALPS

COMPAGNONI, R., ROLFO, F.& TAMAGNO E., Dipartimento di Scienze Mineralogiche e Petrologiche, Torino, Italy.

Introduction

In the Western Alps, two tectonic units with ultra-high pressure metamorphic (UHPM) overprint have been discovered: the continental Brossasco-Isasca Unit of the southern Dora-Maira Massif, and the oceanic Lago di Cignana Unit of the Piemonte zone. In both units the UHPM recrystallisation, acquired during the early stages of the Alpine orogeny, is largely obliterated by a late-Alpine greenschist-facies retrogression, more pervasive in the felsic lithologies of the Brossasco-Isasca Unit.

The Brossasco-Isasca Unit, southern Dora-Maira Massif

The Brossasco-Isasca Unit, in the following referred to as BIU (Compagnoni *et al*. 1995), is exposed in the southern Dora-Maira massif (DMM), Penninic domain of the western Alps (Chopin 1984) (Fig. 1). It is a small tectonic sheet, approximately 10x4x1 km, sandwiched between two tectonic units, characterised by quartz-eclogite-facies recrystallisation with HP peak estimated at ca. 550 °C and ca. 15 kbar (Chopin *et al*. 1991; Schertl *et al*. 1991). Regional geology, detailed petrographic descriptions of the various tectonic units exposed in the southern DMM, and inferred P-T paths are given in a series of articles (e.g. Chopin 1984; Chopin *et al*. 1991; Schertl *et al*. 1991; Michard *et al*. 1995).

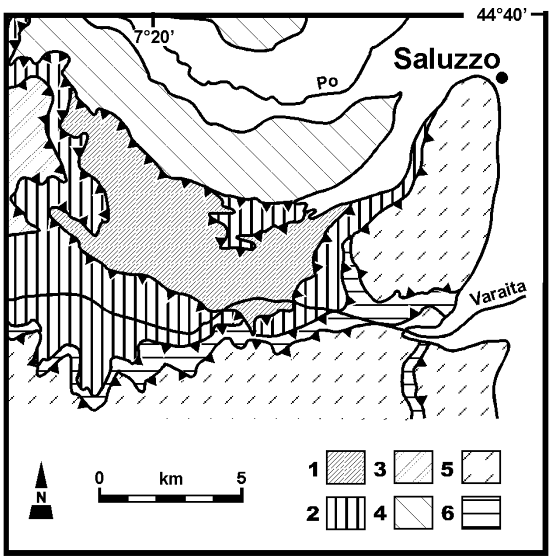

Fig. 1 - ***DORA-MAIRA MASSIF*** (1) Coesite-eclogite facies continental Brossasco-Isasca Unit; (2) Quartz-eclogite facies continental San Chiaffredo (to the N) and Rocca Solei (to the S) Units; (3) Pre-Alpine basement and Permo-Carboniferous + Permo-Triassic cover; (4) Epidote-blueschist facies Pinerolo Unit; (5) Epidote-blueschist facies Upper-Paleozoic and Lower-Triassic units. ***PIEMONTE ZONE*** (6) Lawsonite blueschist facies oceanic metasediments and metaophiolites.

In spite of the pervasive Alpine polyphase tectono-metamorphic reworking, locally undeformed portions are found, which preserve pre-Alpine lithologies and their relationships. These rocks are mainly metagranitoids, which locally retain xenoliths and relics of the original intrusive contacts with hornfelses (Compagnoni *et al*. 1995). From such evidence, it was concluded that the BIU is a fragment of European continental crust, consisting of Variscan amphibolite-facies metamorphics intruded ca. 275 Ma ago (Gebauer *et al*. 1997) by late-Variscan porphyritic granitoids. During the Alpine orogeny this portion of Variscan continental crust experienced an early-Alpine coesite-facies and a late-Alpine greenschist-facies recrystallisation; the Variscan amphibolite-facies basement was converted to the present "Polymetamorphic Complex", and the late-Variscan granitoids to the "Monometamorphic Complex" (Compagnoni *et al*. 1995).

Relict coesite or its polycrystalline quartz pseudomorphs are found in most lithologies as inclusions in garnet, kyanite, jadeite, omphacite, zoisite and even in zircon (Sobolev *et al*. 1994). The peak conditions of the UHPM were estimated at 750 ± 30°C and 33 ± 3 kbar (Schertl *et al*. 1991; Compagnoni *et al*. 1995), and dated at about 35 Ma by Gebauer *et al*. (1997, with ref. therein), combining cathodoluminescence and SHRIMP technique on zircon single crystals. The UHPM peak was followed by a significant decompression coupled with a moderate cooling, leading to a second low-P thermal peak at T close to the greenschist-amphibolite facies boundary. This second thermal peak was followed by a continuous cooling under decompressional conditions.

The ***Monometamorphic Complex*** mainly consists of orthogneiss relics and augengneiss, derived from the Alpine tectono-metamorphic reworking of the late-Variscan intrusives locally preserved as metagranitoids. In the orthogneiss, characterised by a widespread greenschist-facies overprint, the only evidence for the early coesite-eclogite-facies recrystallisation is the local presence of porphyroclastic highly celadonitic phengite, wrapped around by the greenschist-facies foliation, and aggregates of titanite (after former rutile) + grossular-rich garnet. However, the most peculiar lithologies of the Monometamorphic Complex, which best preserve the UHPM mineral assemblages, are lens-like layers of pyrope-bearing whiteschist with minor jadeite-kyanite quartzite, and sodic whiteschist and jadeite-almandine orthogneiss.

Pyrope whiteschist. The pyrope whiteschist, really a kyanite-phengite-pyrope-quartz/(coesite) granofels, occurs within the orthogneiss of the Monometamorphic Complex as layers from a few cm to ca. 20 m thick and from a few m to hundreds of m long (Chopin 1984). The whiteschist mainly consists of pyrope embedded in a matrix of quartz (inverted from former coesite), 3T-polytype phengite, kyanite, minor talc, rare jadeite, and accessory rutile, zircon, and monazite. The pyrope grain-size is variable from a few mm up to ca. 20 cm across; the largest crystals exhibit a trapezohedron habit, usually rounded by the post-crystalline deformation. Pyrope (up to Prp_{96-98}) is poorly zoned with a reddish core and pale pinkish rim. Pyrope megablasts are systematically crowded with minerals, including prograde phases such as Mg-chlorite, talc, and paragonite, phases stable at peak conditions, such as coesite, and retrograde phases, most likely formed during early decompression, such as corundum, enstatite, and gedrite. In addition to these more or less common minerals, pyrope megablasts also preserve inclusions of rare or new minerals such as magnesiostaurolite, bearthite, magnesiodumortierite, ellenbergerite and phosphellenbergerite (Chopin & Sobolev 1995, with ref. therein). The whiteschists, formerly considered as the metamorphic product of original Mg-rich pelite in an evaporitic environment (Schertl *et al.* 1991), are now accepted to be derived from a granitoid protolith, which suffered a metasomatic process along ductile shear zones in the presence of a hydrous fluid phase (Compagnoni & Hirajima 1993; Gebauer *et al.* 1997). The rare presence within a few whiteschists of superzoned garnets, with a compositional range from $Alm_{70}Prp_{25}Grs_5$ in the core to $Alm_{14}Prp_{84}Grs_2$ in the rim, have been interpreted as evidence that the metasomatic process involved both the granitoid and the included paraschist xenoliths and occurred during prograde UHPM (Compagnoni & Hirajima 1993). For a more detailed structural, mineralogical and chemical description of the whiteschist see the review papers by Schertl *et al.* (1991), Compagnoni *et al.* (1995), Chopin & Sobolev (1995), Michard *et al.* (1995).

Sodic whiteschist. This peculiar variety of whiteschist is a coarse-grained rock consisting of the UHPM peak assemblage: pyrope-rich garnet (Prp_{76} Alm_{22} Grs_2) + jadeite (Jd_{82} Di_{18}) + glaucophane (close to the pure Mg-Al end-member) + phengite ($Si_{3.6}$) + coesite + rutile (Kienast *et al.* 1991). This unusual lithotype is very interesting since it supports experimental data, which indicate that pure glaucophane in the NMASH system is stable at ca. 33 kbar and 750 °C.

Jadeite-kyanite quartzite. The jadeite-kyanite quartzite, really a pyrope-jadeite-kyanite-quartz/coesite granofels, occurs within a few pyrope whiteschists as folded layers from 10 to 20 cm thick and several m long (Chopin 1984, Schertl *et al.* 1991). The UHPM peak assemblage consists of coesite + jadeite + kyanite + garnet + minor phengite and local talc, with accessory rutile, apatite, and zircon. This rock is significant, since the jadeite + kyanite assemblage is the high-P analogue of paragonite. Garnet is a pyrope with composition Prp_{70-80} Alm_{20-30} Grs_{1-5}, jadeite is very pure with average composition Jd_{95} Di_4 Ae_1, and phengite is a 3T polytype with Si from 3.41 a.p.f.u in the core to 3.25 in the rim.

Schreyer *et al.* (1987) and Sharp *et al.* (1993) have considered this unusual rock type as the possible product of partial melting of the host whiteschist protolith, but convincing evidence for this interpretation is still lacking.

Jadeite-almandine orthogneiss. This rock, really a phengite-jadeite-almandine-quartz/(coesite) granofels, occurs as dm- to m-thick layers within both the Monometamorphic and the Polymetamorphic complexes. The UHPM peak assemblage is coesite + jadeite (Jd_{95}) + almandine-rich garnet ($Alm_{70-80}Prp_{10-20}$ Grs_{5-20}) + minor phengite ($Si_{3.25-3.41}$) + accessory apatite, rutile, and zircon. The jadeite-almandine orthogneiss exhibits a polyphase retrogression, which includes a series of Na-pyroxenes in equilibrium with albite/oligoclase, progressively decreasing in the jadeite component from omphacite (Jd_{55}) to aegirine (Jd_0), and zoned amphiboles ranging in composition from ferronyböite to taramite (Hirajima & Compagnoni 1993). On the ground of bulk chemical composition and field occurrence, this rock most likely derives from a former granitoid dyke.

Metagranitoids and related rocks. Several tens of lens-like bodies of relict metagranitoids, from a few m to several m in length, which escaped polyphase Alpine deformation, occur within the greenschist-facies orthogneiss of the Monometamorphic Complex. At the contact between the Monometamorphic and Polymetamorphic complexes, remnants of xenoliths within the metagranite and of the Variscan thermally metamorphosed country paragneiss in the metamorphic basement are locally preserved. Due to perfect preservation of primary microstructures, the UHP transformations of pre-Alpine igneous and metamorphic minerals have been studied in detail (Biino & Compagnoni 1992; Compagnoni *et al.* 1995). This study showed that the UHP recrystallisation occurred in a closed system, even for the water fluid phase (Bruno, 1998); this is in agreement with the results of a geochronologic study by Tilton *et al.* (1997), who concluded "that the minerals of the undeformed metagranites failed to reach isotopic equilibration during Alpine subduction to > 100 km with temperatures > 700°C".

The ***Polymetamorphic Complex*** consists of a wide spectrum of lithologies, including orthogneiss, micaschist and minor marble and eclogite (Chopin *et al.* 1991; Compagnoni *et al.* 1995).

Quartz/(coesite)- jadeite-garnet-kyanite-phengite micaschist. The most peculiar basement lithotype is a micaschist, characterised by the UHP mineral assemblage: quartz/(coesite), phengite, porphyroblastic garnet and kyanite, jadeite (Jd_{90-95}), minor zoisite, and accessory rutile, apatite, tourmaline, and rare bearthite ($Ca_2AlPO_4{\cdot}2OH$: Chopin & Sobolev 1995, with ref. therein). Porphyroblastic garnet, up to 2 cm across, shows a prograde compositional zoning (from Alm_{80} Prp_{20} in the core to $Alm_{60}Prp_{40}$ in the rim), coupled with a change in the mineral inclusions, which are chlorite, chloritoid (up to ca. 50 mole % of the Mg-chloritoid end-member), staurolite, kyanite, jadeite, paragonite, and quartz in the core, but only jadeite, kyanite, and coesite in the rim (Chopin *et al.* 1991). Both garnet zoning and distribution of mineral inclusions indicate a continuous prograde growth from the quartz to the coesite stability fields.

Eclogite. Fine- to medium-grained eclogites usually occur as dm-thick boudins in the paragneiss. They consist of garnet and omphacite with accessory rutile, apatite, and rare zircon and graphite. Locally, phengite and quartz may be very abundant, and kyanite or zoisite may be present. The eclogites are locally banded with alternating garnet-rich and omphacite-rich layers and may show a folded foliation defined by phengite and/or a strong lineation defined by omphacite. Prograde Na-Ca-amphiboles of katophoritic to taramitic and barroisitic compositions locally occur as inclusions in garnet and omphacite, and a post-climax porphyroblastic edenitic hornblende commonly overgrows the eclogite foliation. A detailed petrologic study of the eclogites was performed by Kienast *et al.* (1991). The presence of sagenitic rutile in garnet of the phengite–bearing eclogite suggests its derivation from a biotite-bearing protolith, most likely a Variscan biotite amphibolite.

Marble. Marbles usually occur as lenses from a few m to tens of m long and from a few dm to several m thick, but a body is ca. 800 m long and 70 m thick. They consist of both calcite- and dolomite-rich layers locally with thin interlayers of micaschist and Ca-silicate granofels, and boudins of eclogite. The grain-size is usually coarse, but very fine-grained mylonitic types locally occur, reflecting different stages of the polyphase tectono-metamorphic evolution. In addition to calcite and/or dolomite, impure marbles consist of clinopyroxene (diopsite to omphacite), phengite, garnet, epidotes (zoisite, Fe-poor and Fe-rich epidote), K-feldspar, minor talc, Mg-chlorite, phlogopite, rare quartz, and accessory rutile, titanite, tourmaline, apatite, opaques, zircon and graphite. Recently, two types of marbles have been studied in detail: a dolomite-poor marble and a dolomite-rich marble with relics of pre-Alpine minerals (Castelli *et al.* 1999). The *dolomite-poor marble* consists of calcite + garnets + pyroxene + quartz + highly celadonitic phengite (up to 65% MgAl-celadonite) + Fe-epidote (Zo_{45-51}) + titanite with relics of rutile. Two types of garnet are evident, most likely corresponding to different microchemical sites: a reddish type and a pinkish type with compositions Alm_{53-57} Grs_{16-26} Adr_{14-23} and Grs_{36-54} Alm_{39-52} Adr_{0-8}, respectively. The deep green pyroxene is a diopside with Jd_{5-14} and Aeg_{4-16}. The *dolomite-rich marble* consisted of the UHPM assemblage bluish corundum (Crn II) + clinochlore + dolomite + aragonite (now calcite) + rutile. This marble contains very rare relics of a pre-Alpine (most likely Variscan) mineral assemblage, including bluish-green spinel, colourless corundum (Crn I), ilmenite, dolomite, possibly calcite, and a calcic plagioclase, completely consumed by the Alpine UHP metamorphic reactions.

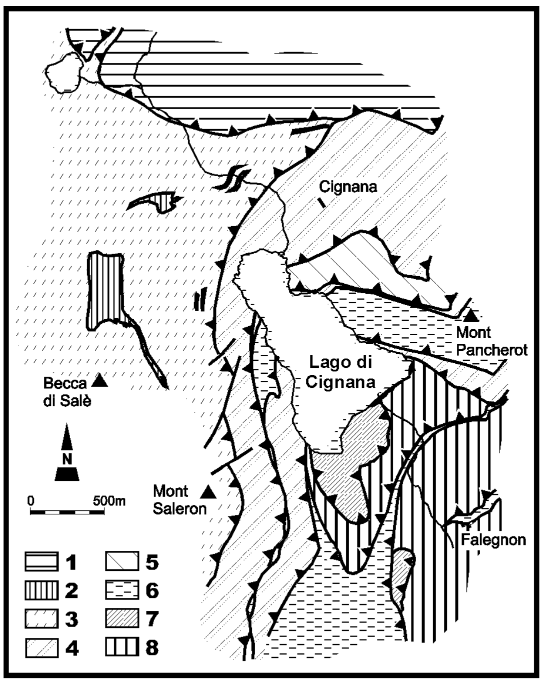

Fig. 2 - AUSTROALPINE DOMAIN: ***DENT BLANCHE NAPPE*** (1) Valpelline Series; (2) Roisan Zone; (3) Arolla Series. **PENNINE DOMAIN:** ***PIEMONTE ZONE*** (4) Upper Combin Zone; (5) Pancherot - Cime Bianche - Bettaforca Unit; (6) Zermatt - Saas Zone serpentinite; (7) Lago di Cignana Unit; (8) Zermatt - Saas Zone eclogite and metagabbro.

Lago Di Cignana Unit, Upper Valtournenche, Val d'Aosta

The Lago Di Cignana Unit (LCU) crops out on the southern side of the artificial lake in the Conca di Cignana, upper Valtournenche, Val d'Aosta (Reinecke 1991, 1998). The unit consists of two small slivers less than 50 m thick, exposed over an area of about 0.5 km^2 (Fig. 2). The LCU is part of a stack of thin nappes, consisting of meta-ophiolite and metasediments of the Piemonte zone, Pennine Domain, overlain by the continental Dent Blanche nappe, Austroalpine Domain. The LCU is sandwiched between two meta-ophiolitic nappes: the underlying unit, which consists of interlayered metagabbro and eclogite with bodies of forsterite-Ti-clinohumite-bearing antigorite serpentinite, may be referred to the Zermatt-Saas Zone, characterised by early-Alpine quartz-eclogite-facies overprint; the overlying unit, which mainly consists of interlayered calcschist and prasinite, may be ascribed to the Combin zone, characterised by early-Alpine epidote blueschist-facies overprint. The LCU is made of metabasites and metasediments metamorphosed under coesite-eclogite-facies conditions during the Alpine orogeny. The age of UHPM was determined at ca. 44 Ma by combining cathodoluminescence and SHRIMP technique on zircon single crystals (Rubatto *et al.* 1998). Peak metamorphic conditions have been estimated to be 615 ±15°C and 2.8 ± 1.0 GPa (Reinecke 1991, 1998).

The **metabasites** are fine-grained banded *coesite-eclogites*, with alternating darker glaucophane-rich and lighter epidote-rich layers. Most eclogites show an evident foliation and a marked omphacite lineation and consist of the peak assemblage omphacite + garnet, minor zoisite, phengite, quartz/coesite, local carbonate, and accessory rutile and apatite. Clinozoisite + phengite pseudomorphs after former prograde lawsonite are ubiquitous. Glaucophane, usually porphyroblastic, mainly developed after the eclogite foliation. The presence of inclusions trails in garnet and the garnet-matrix omphacite relationships suggest a polyphase HP-UHP metamorphic evolution.

The **metasedimentary cover** is mainly composed of calcschist grading to micaschist with minor impure marble and quartzite interlayers with cm- to dm-thick nodules or boudins of quartz garnetite and eclogite, and dm- to m-thick lenses of sheared serpentinite, "metagabbro" and "flasergabbro". Two types of quartzite are present: garnet-omphacite quartzite with dm-thick omphacitite nodules, and Mn-bearing quartzite with mm- to dm-thick hematite-braunite-rich aggregates most likely derived from former Fe-Mn-rich nodules. The non-felsic lithologies intercalated within the sedimentary cover, such as serpentinite, "metagabbro", "flasergabbro", eclogite and garnetite, are interpreted as ophiolitic detritus derived from erosion of the oceanic lithosphere, tectonically exposed on the floor of the Mesozoic Tethys. The metasediments of this "ocean-type" cover also contain a detrital fraction derived from a continental source, as suggested by the discovery in a quartzite of zircons with Precambrian to Jurassic inherited cores (Rubatto *et al.* 1999).

Rare relict coesite, originally discovered in a tourmaline from a quartzite (Reinecke 1991), was later found as tiny inclusions in garnet, omphacite, epidotes of most lithologies, and apatite (Reinecke 1998). On the base of detailed petrologic studies on calcschists, banded Mn-bearing oxidised quartzschists and quartzites, Reinecke (1991, 1998) defined the prograde and retrograde P-T path, the latter being characterised by strong decompression coupled with moderate cooling from ca 600°C in the coesite stability field, to ca 500°C below 15 kbar, to less than 400°C below 6 kbar. New petrologic data indicate the presence of a second low-P thermal peak similar to that described for the BIU.

Garnet-phengite-quartz-calcschist. In the calcschist, the inferred UHP peak assemblage is garnet + dolomite + coesite + lawsonite (now epidote + phengite ± paragonite) + phengite ($Si_{3.35-3.34}$) + aragonite (now calcite) + rutile.

Piemontite-garnet-phengite-talc-quartz schist. In the "Al-rich" domains of the Mn-bearing quartzschist, the inferred UHPM peak assemblage is coesite + kyanite + talc + phengite + garnet + hematite + rutile + paragonite + piemontite + zircon; garnet is zoned from Prp_{19} Sps_{67} Grs_{14} in the core through Prp_{36} Sps_{55} Grs_{9} in the intermediate to Prp_{21} Sps_{70} Grs_{9} in the rim. In the "Al-poor" domains (the former Fe-Mn nodules), the inferred UHPM peak assemblage is coesite + phlogopite + talc + phengite + garnet + piemontite + hematite + rutile + braunite + ardennite + dravite + apatite + paragonite + zircon; garnet is zoned from Prp_{21} Sps_{67} Grs_{12} in the core through Prp_{35} Sps_{55} Grs_{10} in the intermediate to Prp_{20} Sps_{71} Grs_{9} in the rim. In this lithology, a calderitic ($Mn_3Fe_2Si_3O_{12}$) garnet is locally found with composition $Cald_{44-83}$

Adr_{5-14} Sps_{47-7} Prp_{1}, which is peculiar of high-pressure conditions (Lattard & Schreyer 1983).

Aegirine-augite – garnet-phengite quartzite. In the quartzite, the inferred UHPM peak assemblage is garnet I + phengite ($Si_{3.38}$) + coesite + Mn-epidote + aegirine-augite (Jd_{26-36} Aeg_{42-51} Aug_{13-24}) + hematite + rutile ± apatite ± dravite.

Conclusions

In spite of their different origin, size and tectonic position, the Brossasco-Isasca and the Lago di Cignana units are small (BIU) or very small (LCU) thrust sheets that show similar P-T trajectories. These trajectories, which are also similar to those inferred from other tectonic units of the internal western Alps, are characterised by a post-eclogitic decompressional path coupled with a moderate cooling and a second thermal peak at low pressure. Since this P-T path is peculiar to eclogite-facies units of the internal western Alps, but different from those described from other UHPM belts, it is suggested that different tectonic mechanisms were responsible for exhumation of subducted continental crust in different continental orogenic belts.

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