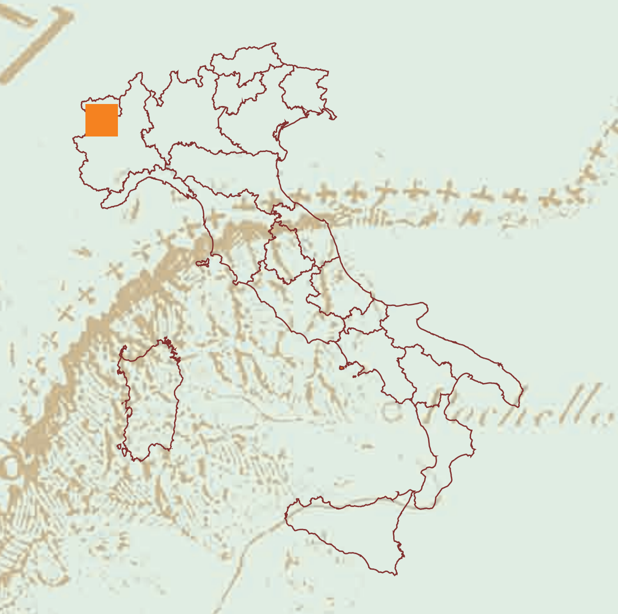

Mapping of oceanic crust with "HP" to "UHP" metamorphism: The Lago di Cignana Unit (Western Alps)

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ABSTRACT

Lago di Cignana is an ultra-high pressure (UHP) metamorphic unit in the Western Alps (reaching 590-630°C, 2.6-2.8 GPa) (REINECKE, 1991). The UHP slice is only hundreds of metres across and is extensively boudinaged (Fig. 7). Interlayers of metasediment and metabasite preserve structures and mineral assemblages that suggest a multi-stage and complex exhumation history (cf. KLAUW *et alii*, 1997; REDDY *et alii,* 1999, 2003) beneath a km-scale extensional ductile shear zone in which intense fabrics are developed. Low-angle faults formed in the late stages of movement. The extensional structures shortened during their more recent history, forming regionally developed upright folds and dome and basin structures that decorate and emphasize the UHP boudins.

AIMS

This study aims at illustrating the tectonometamorphic evolution of metabasite and metasediment derived from the Mesozoic Piemonte oceanic basin, which were subducted during the Alpine orogeny to depths of about 100 km, corresponding to coesite-eclogite facies conditions. During the subsequent fast exhumation in an extensional regime such units were brought to near-surface and the eclogite-facies minerals were partly retrogressed to greenschist-facies assemblages.

KEY WORDS

Ultrahigh pressure metamorphism (UHPM), Western Alps, Extensional shear zones, Exhumation, Piemonte oceanic lithosphere

RIASSUNTO

L'Unità del Lago di Cignana è una scaglia tettonica di pressione molto alta (UHP: 590-630°C; 2,6-2,8 GPa: REINECKE, 1991), che affiora nell'alta Valtournenche (Valle d'Aosta), Alpi occidentali. La scaglia di UHP è larga solo alcune centinaia di metri ed è fortemente boudinata. Alternanze di metasedimenti e metabasiti conservano strutture ed associazioni minerali, che suggeriscono una complessa storia di esumazione polifasica (cfr. KLAUW et alii, 1997; REDDY et alii, 1999, 2003), che si è sviluppata al di sotto di una zona di taglio duttile di tipo estensionale a scala chilometrica in cui si sono sviluppati marcati "fabric". Faglie a basso angolo si sono formate nelle fasi finali del movimento. Durante la successiva evoluzione, le strutture estensionali si sono accorciate formando a scala regionale pieghe raddrizzate e strutture a duomi e bacini, che avvolgono e mettono in evidenza i boudin con paragenesi di UHP.

GEOLOGICAL MAP OF THE ULTRA-HIGH PRESSURE REGION AT LAGO DI CIGNANA, VAL D'AOSTA (NW ALPS)

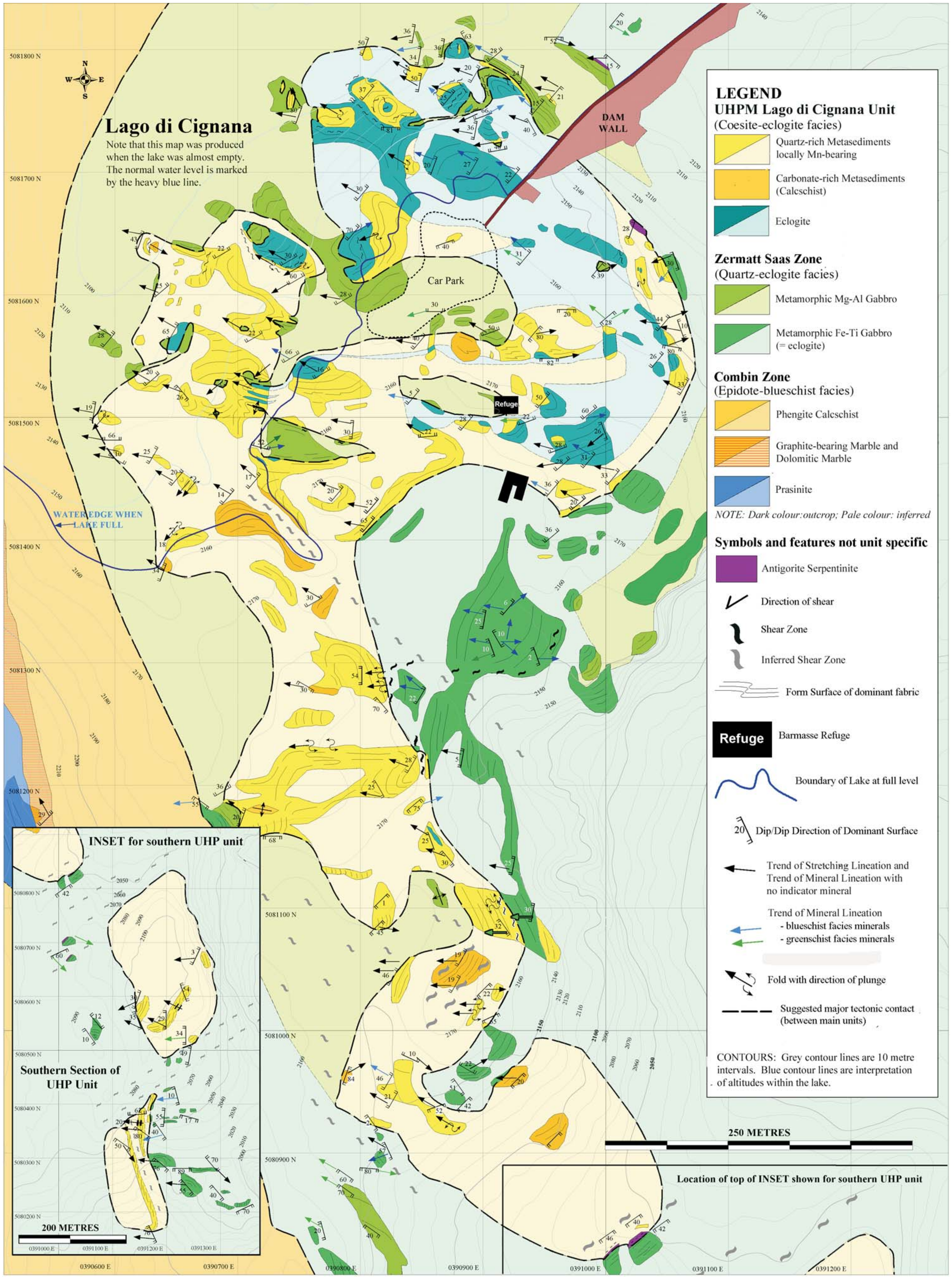


Fig. 1 - *Structural map of the region around Lago di Cignana, NW Italy. A sliver of ultra-high-pressure (UHP) coesite-bearing lithologies occurs at this locality, where the Zermatt-Saas Zone and the Combin Zone of the Piemonte meta-ophiolites are juxtaposed. The contacts are all tectonic. Note that the inset is the southern, topographically lower section of the UHP Unit. The schistosity shown on the map is the main regional schistosity associated with boudin formation, although relict older fabrics and overprinting younger fabrics occur throughout the UHP Unit. Various deformational events have occurred, in particular several different stages of shear zone formation. Several distinct stretching lineations are evident.*

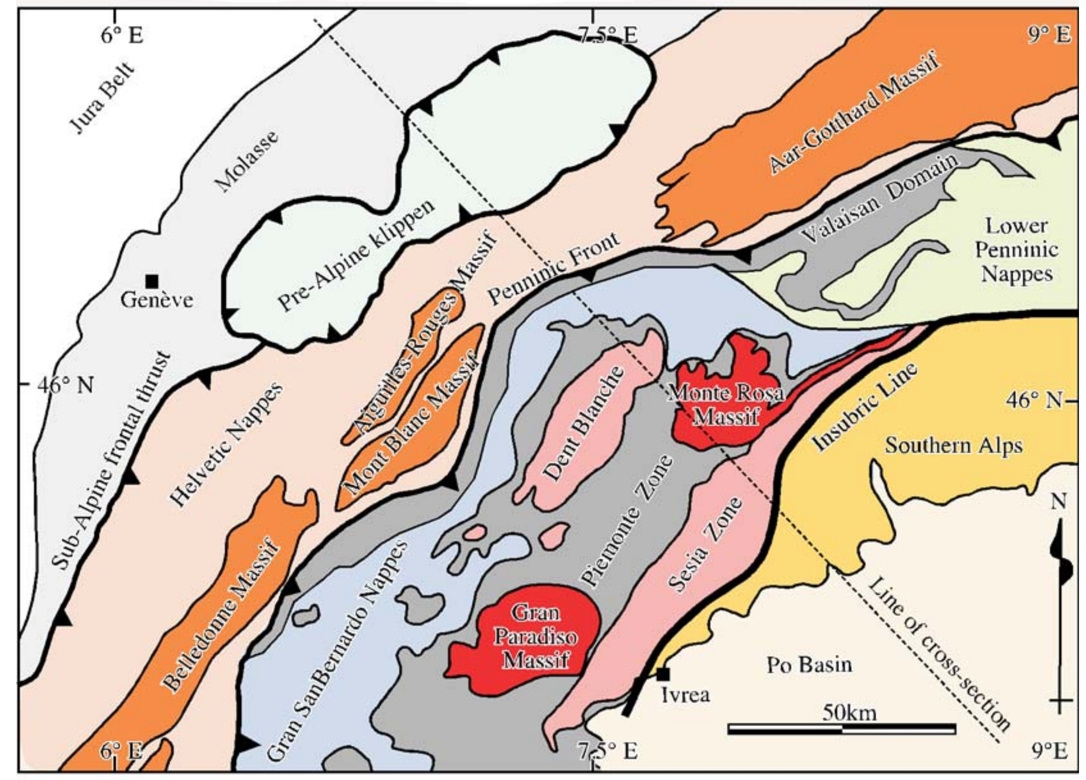


Fig. 2 - *Tectonic map of the North-Western Alps. Note cross-section, marked with dotted line trending NW-SE, corresponds to Fig. 3.*

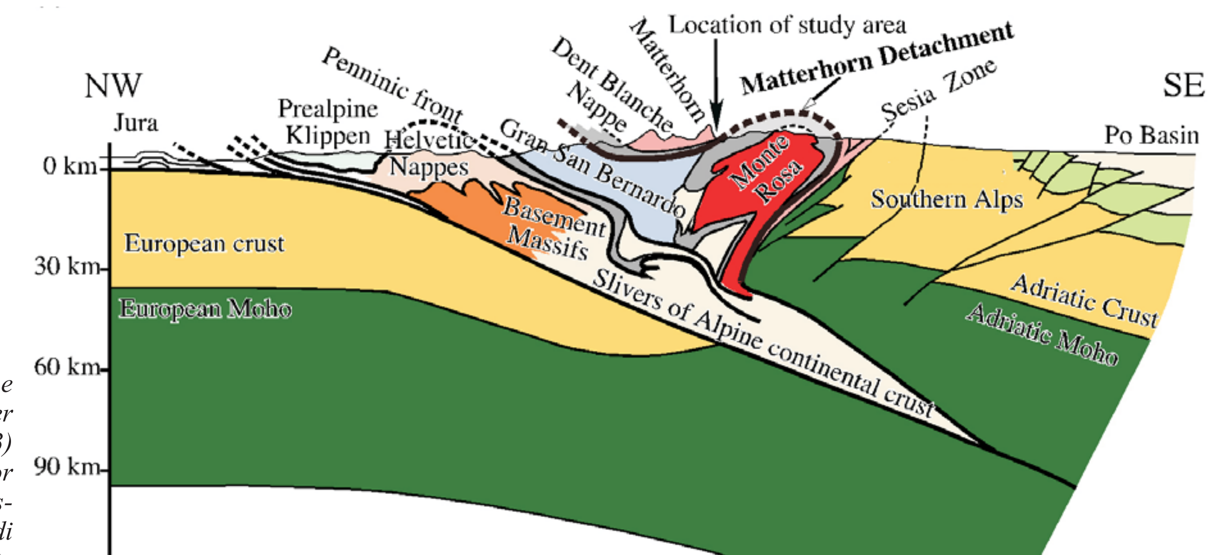


Fig. 3 - *Cross section of the Western Alps modified after* Ballevre & Merle *(1993) and* Escher et alii *(1997). For the location of the cross-section see Fig. 2. Lago di Cignana lies west of the Monte Rosa massif, in the Piemonte zone, beneath the arrow shown in the cross-section.*

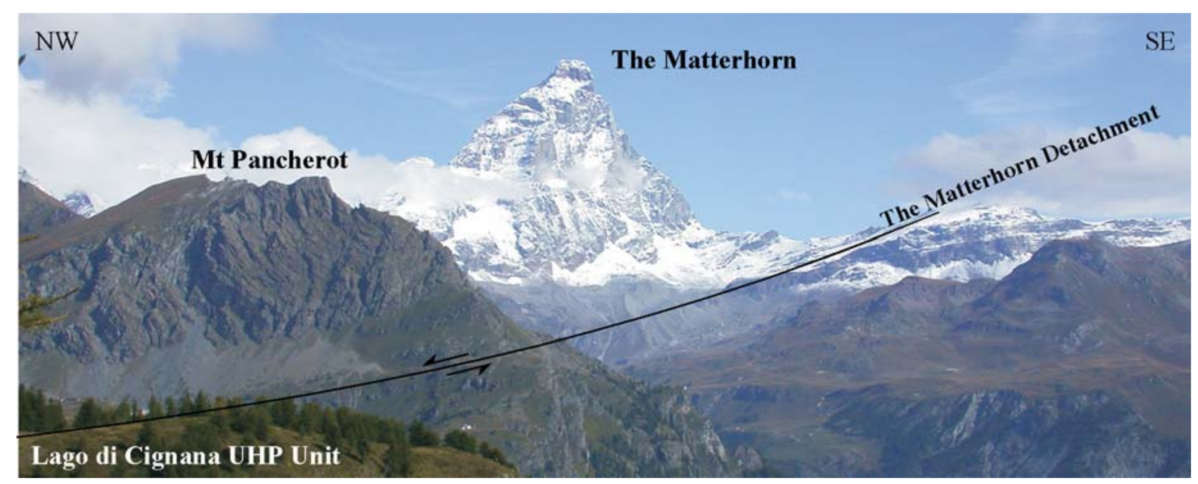


Fig. 4 - *Lago di Cignana is located approximately 10 km south of the Matterhorn, near the Swiss-Italian border. The ridge immediately in view in front of the Matterhorn is Mt Pancherot, a jointed km-scale boudin of serpentinite in the Combin extensional shear zone. The base of this extensional shear zone is the Matterhorn Detachment (marked on photo). The dominant sense of shear at the base of the Combin zone is top-to-the-NW (as shown). The UHP Unit is located at the left hand side of the photograph on the grassed flat lying ledge. It is a thin tectonic sliver at the top of the Zermatt-Saas ophiolite. The gently dipping planar feature that defines the base of Mt Pancherot is a tectonic contact within the Combin Zone. Photograph is taken looking north.*

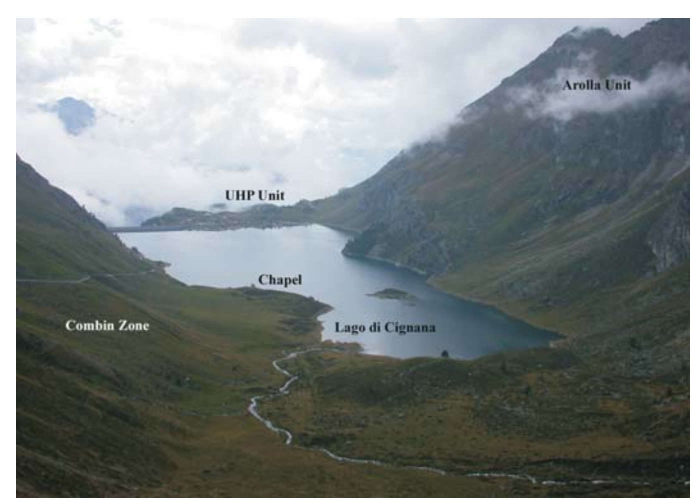


Fig. 5 - *Lago di Cignana is a glacial valley enclosed between Mt Pancherot and Mt Saleron in the Valle d'Aosta (NW Alps). The UHP unit is on the distant bank of the lake. The topographically and structurally higher regions in the foreground and eastern and western sides of the lake are the Combin zone. Photograph is looking south-south-east.*

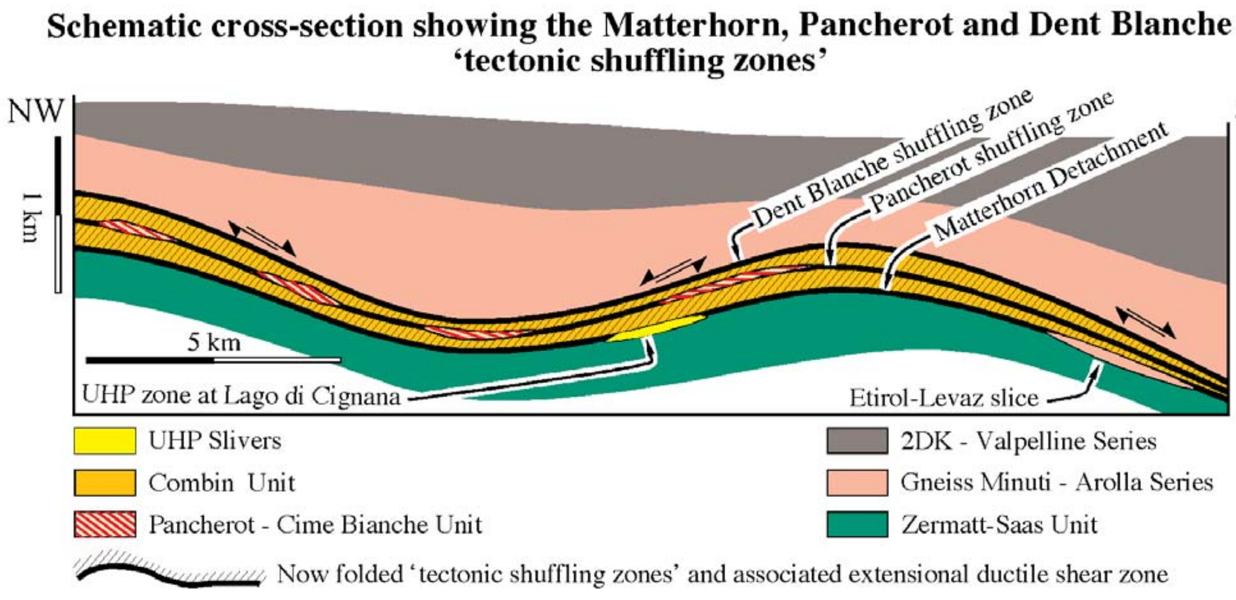
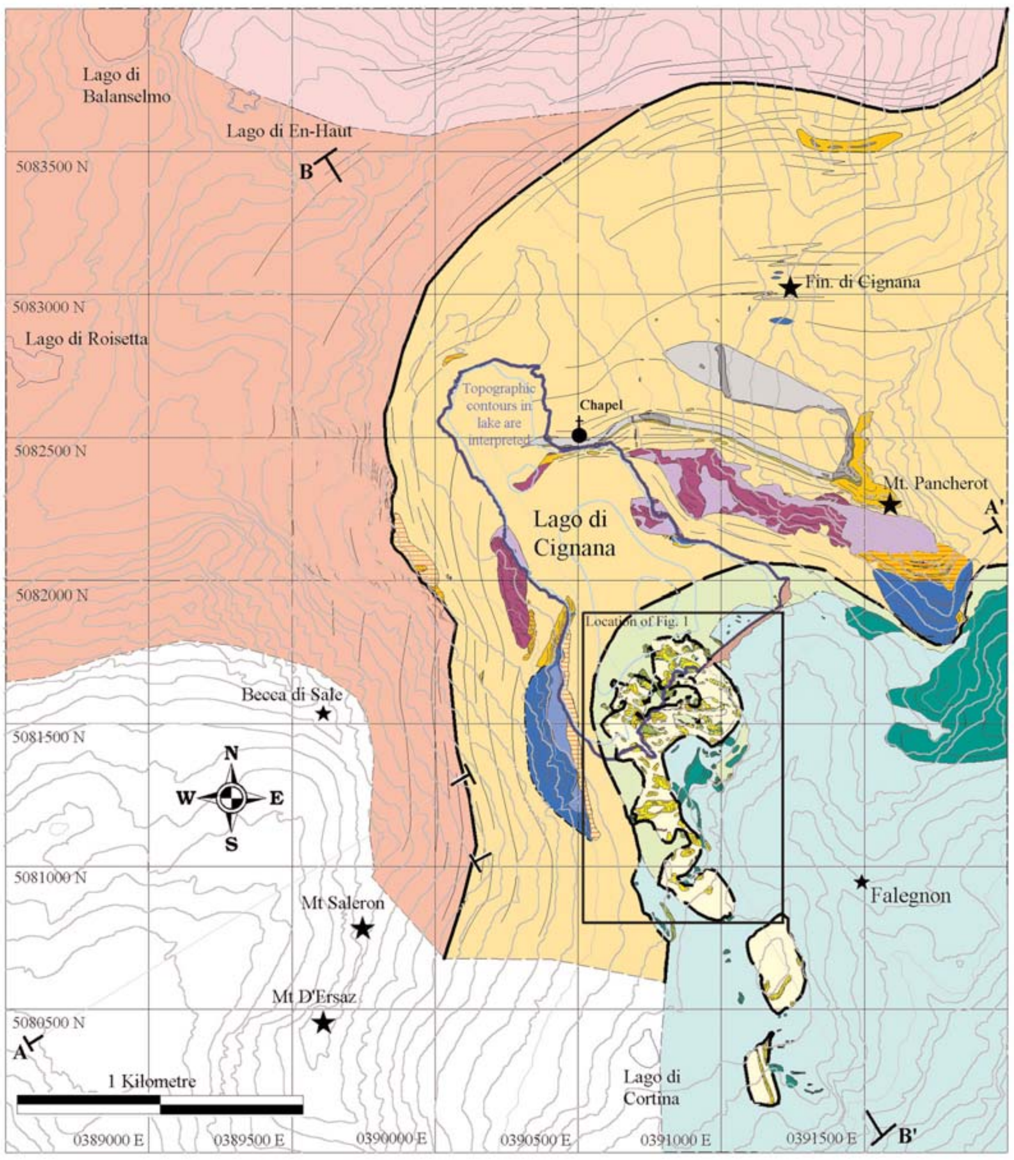
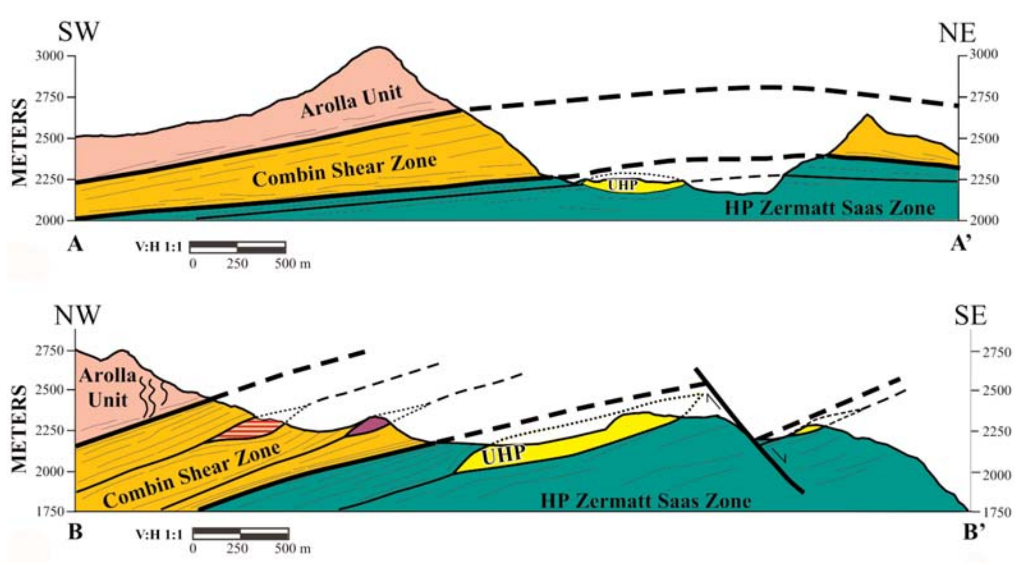


Fig. 6 - *The diagram shows structural relations as would have applied at the end of the extensional phase (at ca 36 Ma). Post ca 25 Ma the Alpine crust was folded to produce the present geometry (as shown in Fig. 3). The base of the extensional shear zone that affected the Combin Zone is cut off by the semi-brittle Matterhorn Detachment. A similar fault may exist at the Dent Blanche contact, where a narrow more intense shear zone is also observed. Tectonic shuffling zones may be the result of thrusts that have been re-activated as detachment faults/shear zones, stranding anastomosing lenses of higher pressure rocks. Crustal-scale boudinage during the later stages of movement may have overprinted adjacent parts of the shear zone differently, producing shear sense variation as shown. The shear zones at Lago di Cignana were affected by NW-directed sense of shear at this time, while zones to the southeast (e.g. Gressoney) were affected by SE-directed sense of shear (*Reddy *et alii* 2003*).*





Definitive outcrops in bold and interpretative lithologies in corresponding pale colour.

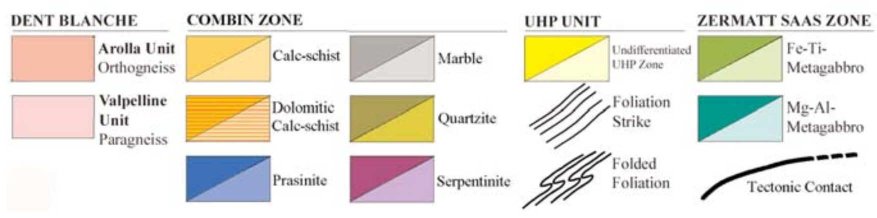


Fig. 7 - *Geological map of the Lago di Cignana region. Legend shows map units, with outcrop in vivid colour and the inferred extent in the equivalent pale colour. The UHP Unit occurs in the uppermost structural levels of the Zermatt-Saas Zone, overlain by a thin, highly deformed slice of metagabbro. The structurally higher Combin Zone contains boudins of varying lithologies such as serpentinite, dolomitic calc-schist and prasinite.*
Marble and quartzite lenses occur in spatial association with the dolomitic lenses. The cross-sections are both perpendicular and parallel to the dominant NW/SE trending stretching lineation.
The perpendicular section is along line ***A-A'*** *on the map, while the parallel section is along line* ***B-B'****. Note that several different lithologies, distinguished in the map, have been grouped in the cross-sections.*

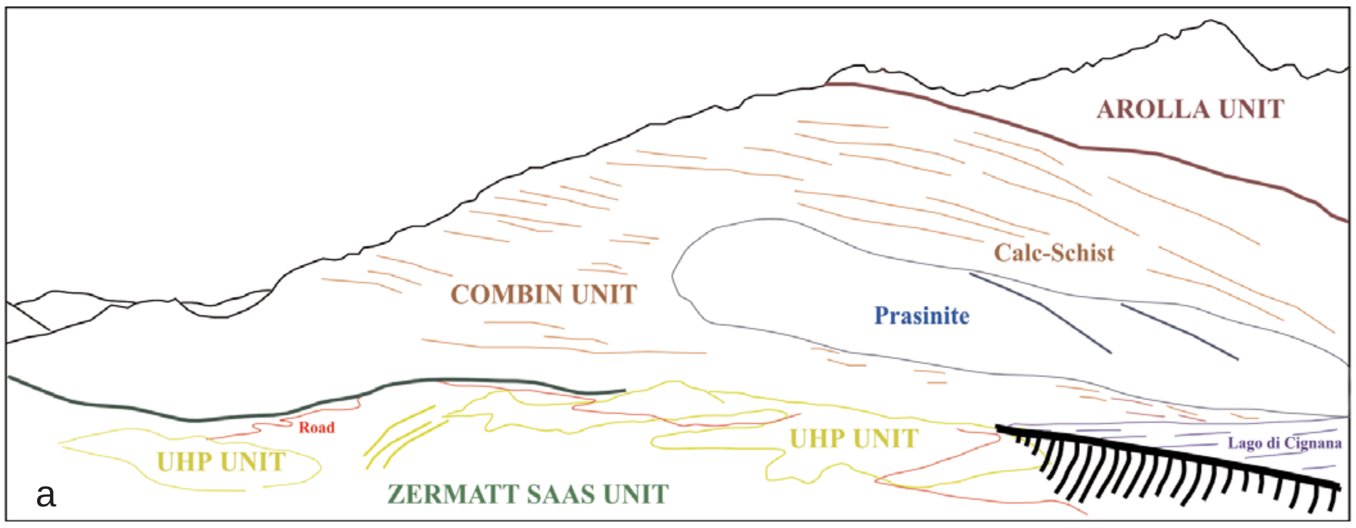
INTRODUCTION

The aim of this study was to map the exposure of UHP rocks at Lago di Cignana (Valle d'Aosta, NW Italy), one of the only two known coesite locations in the Alps, in order to determine the 3D geometry of lithologies, planar and linear fabrics, faults and folds. In this way, we intend to constrain the movement picture that led to the exhumation of these remarkable rocks, from as deep down as 100 km in the Earth up to their present location. This datum provides a 3D-time geometrical constraint that allows us to test different models: some models suggest that exhumation is driven by local effects, namely the relative buoyancy of individual sheets of rock, while others suggest that the crust is torn apart by regional sub-horizontal extension, with a movement focussed in crustal-scale extensional shear zones. These periods of intense crustal extension may closely follow individual episodes of high-pressure metamorphic mineral growth.

In regions, where several distinct episodes of high-pressure metamorphism have taken place (such as around Lago di Cignana), it follows that several episodes of intense crustal shortening followed by intense crustal extension might be discerned. Such a history of tectonic mode switches, marking the end of stages in a sequence of "inversion cycles", would produce distinctive patterns of fabric and microstructural evolution, and characteristic outcrop-scale and map-scale geometries.

A team effort was required in order to understand this complex evolution, involving a group of individuals that combined the expertises of field mapping, structural geology, metamorphic petrology and geochronology. Key fabrics and microstructures were subsequently analysed under the microscope. Microprobe mineral analyses allowed geothermobarometric calculations, while the painstaking separation of minerals grown in specific microstructural events allowed the processing of geochronology to be initiated. The production of a detailed geological map is the first and most important stage in this systematic and objective methodology, for it provides the framework on which all else is based. The preliminary results of this analysis are given on the following pages.

The UHP lens is located close to or at the upper boundary of the HP metamorphic Zermatt-Saas Zone, directly below the dominantly greenschist



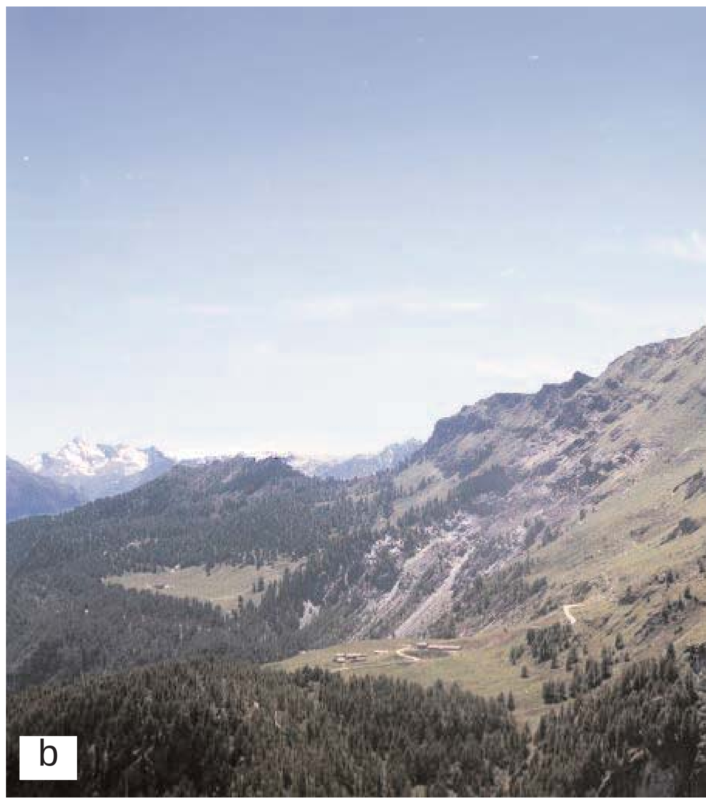


Fig. 8 - *a) The sketch shows the main lithological units and major structural contacts between the units seen in photograph Fig. 8b).*
b) Panorama photograph of the Arolla Unit on the high mountain peak and the Combin Zone directly below. The cliff in the centre of the photograph is a prasinite boudin within the Combin Shear Zone: the contact with the UHP Unit is directly below this boudin. Complex slivers of prasinite, calc-schist and serpentinite occur at the tectonic contact with the underlying UHP Unit. The UHP Unit is on the grassed area in the foreground, from left to centre of the picture, as well as in the tree area on the far left hand side. The Zermatt-Saas Zone is the cliff region in the centre base of the photograph. Photograph is looking west.

Fig. 9 - *A major mylonite zone is located on the eastern side of the lake, marking the tectonic contact between the Zermat-Saas Zone and the overlying Combin Zone. Eclogite facies assemblages are still identifiable in the Zermatt-Saas rocks, although retrogression has occurred. (E:0391805 N:5081755)*

Fig. 10 - *An intense shear zone marks the base of the Combin Zone. On the western side of the lake, slivers of calc-schist (brown lens at the centre of the photograph) are interleaved into a prasinite boudin (the pale blue outcrop). Intense shearing and serpentinite occur around the calcschist sliver. David Giles stands at the centre for scale. (E:0390440 N:5081727)*

Fig. 11 - *The* UHP *unit occurs as three distinct lenses, all surrounded by Zermatt-Saas metagabbro. A mylonitic greenschist facies shear zone is located between the main* UHP *lens and the lens at Cortina Lake, suggesting movement between these two lenses at a late-stage in their ductile history. The fault dips to the southeast, with complex crenulations occurring in the chloritic zone.*
(E: 03901000 N: 5080816)

facies Combin Zone (Figs. 7, 8, 12 and 13). The characters of the upper and lower contacts of the UHP lens are different, and rendered complex by overprinting deformational events (e.g. a NW-trending extensional event and late-stage NW/SE shortening). The UHP Unit is overlain by a dissected thin sheet of highly deformed Fe-Ti metagabbro from the Zermatt-Saas Zone, observed at the northern boundary of the UHP Unit (below high water level) and at several locations on the upper surface of the UHP lens (Figs. 17 and 18). The lower contact with the Zermatt-Saas Zone is not well defined and is difficult to locate. Zermatt- Saas metabasics are characterised by planar layering, while the UHP eclogitic metabasics are deformed boudins. Tectonic slices derived from the Zermatt-Saas Zone thus enclose and wrap the UHP boudins (Figs. 1, 12, 13 and 18).

The upper tectonic contact of the UHP lens was later folded and cut by late-stage ductile and brittle deformation. Calcschist occurs within the UHP Unit, and is observed as a structurally higher lithology, with tight upright folds, and commonly intensely sheared by young shear zones. This calc-schist may belong to the Combin Zone, caught up in the structurally higher regions of the UHP Unit, or it may have undergone the same deformational and metamorphic history as the quartz-rich metasediment layers. The UHP lens preserves an earlier deformational history and direction of movement when compared to the fabrics in the overlying Combin Zone.

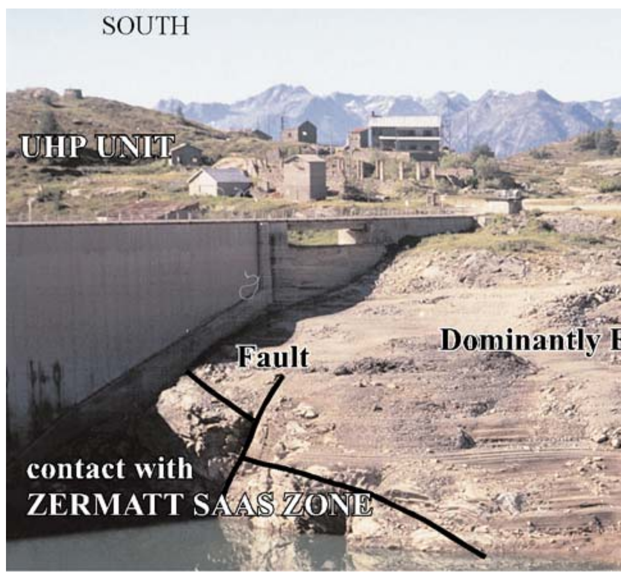
The Combin Zone localizes a major extensional shear zone, and the UHP lens has been exhumed beneath this structure.

This shear zone extends throughout the region (Fig. 6, REDDY *et alii*, 2003) and can be extrapolated northward from Lago di Cignana and beneath the Matterhorn. A comparison of the sense of shear on shear zones between the Combin Zone and the UHP Unit suggests a multi-stage episodic exhumation of the UHP Unit. The low-angle faults formed during the late stages of movement, while the extensional structures shortened more recently (Fig. 3), forming regionally developed upright folds and dome and basin features at a km- to outcrop-scale.

GEOLOGICAL SETTING

The study area is exposed within the calc-schists and meta-ophiolites of the Piemonte zone, which consists of a pile of tectonic slices including both Alpine epidote-blueschist facies ('Combin Zone') and eclogite facies ('Zermatt-Saas Zone') metamorphic rocks. In the Valtournenche area, the ocean-derived rocks of the Piemonte Zone are sandwiched between the overlying Austroalpine Dent Blanche nappe and the underlying Penninic Monte Rosa nappe.

Fig. 12 - *Lago di Cignana was emptied of water in mid-2001, and the project was undertaken while the lake was empty and the* UHP *Unit was fully exposed. Many of the mounds that can be seen in the photograph are* UHP *boudins with flat-lying schistosity on the upper surface and steep to moderate dipping schistosity on their terminations. The cliff below the dam wall comprises mainly Fe-Ti metagabbro belonging to the Zermatt-Saas Zone, immediately overlain by the lens of* UHP *eclogitic metabasites and metasediments. The darker boudins on the left side are metabasites. Metasediments dominate the right-hand side of the photograph and the wooded, grassy hill. Photo taken facing SSE.*



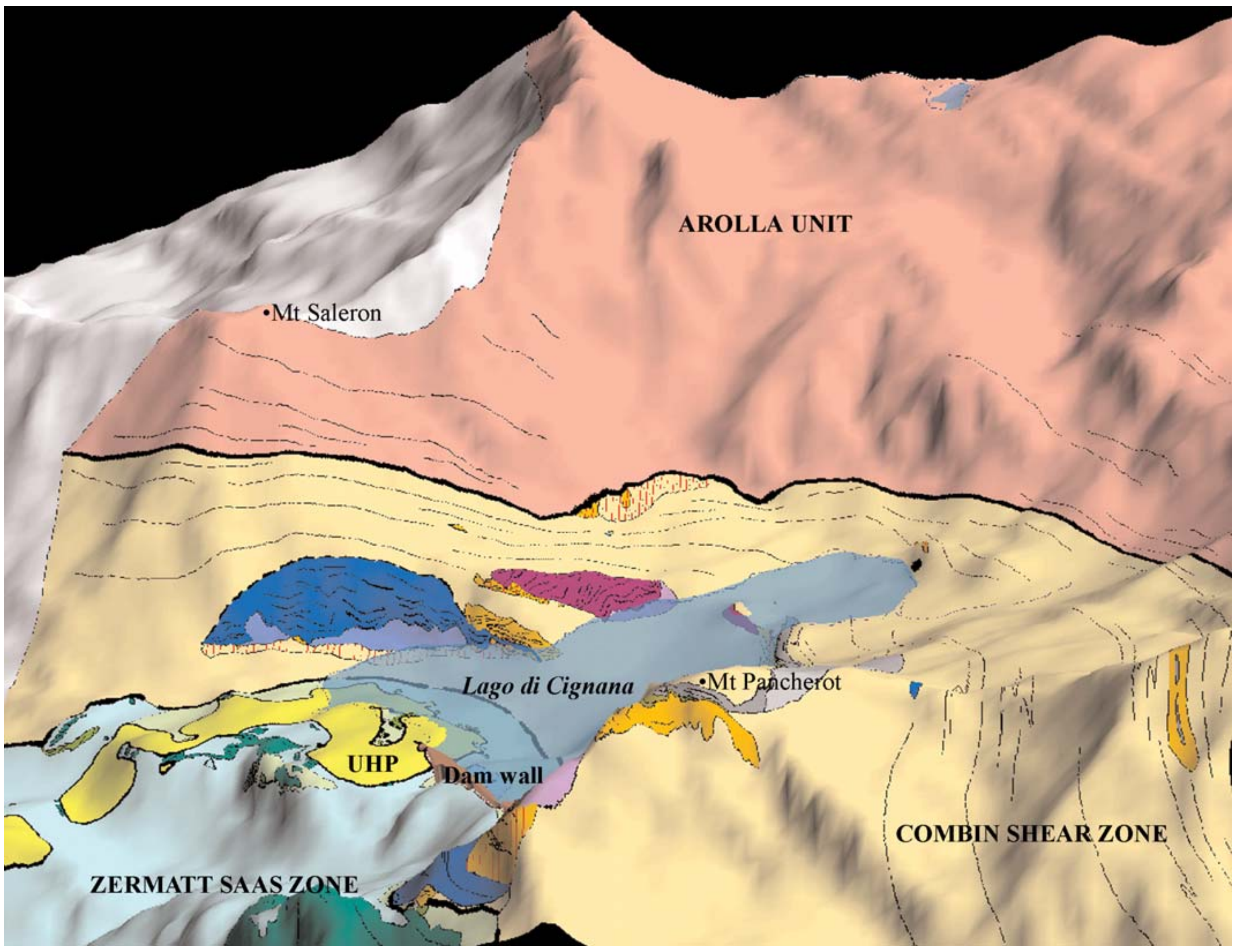


Fig. 13 - *3D image of the geology of the Lago di Cignana area. The picture was produced using GOCAD software. The 3D topography is based on the topographic contours from geological maps (Figs. 1 and 7). The lake has been filled in order to provide a more realistic perspective.*
The bold black lines are tectonic contacts. Note the planar contact with the Arolla Unit. The fault/shear zone truncates recumbent folds formed earlier. Colours match the legend for the geological maps (Figs. 1 and 7). The white area has not been mapped.

Fig. 14 - *The quartz-rich metasediments of the* UHP *unit were isoclinally folded prior to the deformational event that produced the recrystallization and formation of boudins. An axial planar cleavage associated with this folding event can be detected. FOV ~3 metres.(E: 0390805 N: 5081285).*

Fig. 15 - *An example of the boudins that characterize the* UHP *unit. This eclogitic metabasite boudin is bounded by flat-lying schistosity on the upper and lower boundaries with steep-dipping schistosity at the ends of the boudin. The boudin is ~1.5 metres across.*

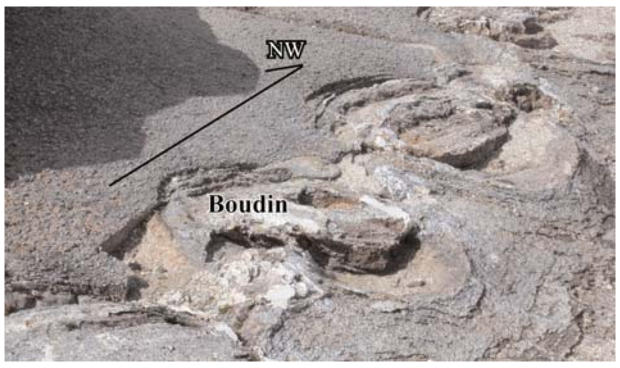


Fig. 16 - *Foliation boudinage in the quartz-rich metasediment. Abundant garnets are found immediately below the overlying tectonic contact with the Zermatt Saas Zone. The trend of the boudinage is NW/SE, parallel to the dominant stretching lineation. FOV ~4m. (E:0390724 N: 5081418).*

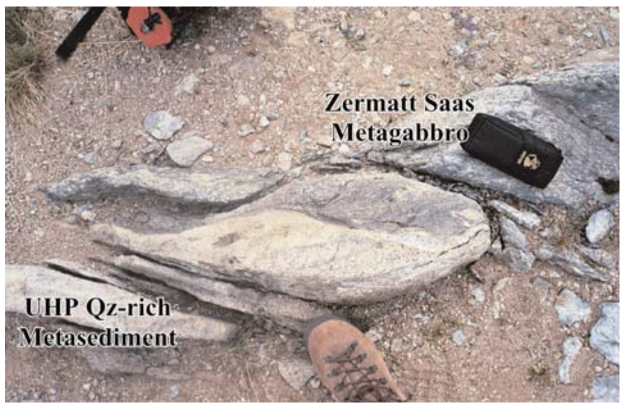


Fig. 17 - *A tectonic contact between UHP metasediment and Zermatt-Saas Zone Fe-Ti metagabbro is overprinted by boudinage and a compressional event, observed in the structurally highest region of the* UHP *Unit. (E:0390712 N: 5081505).*

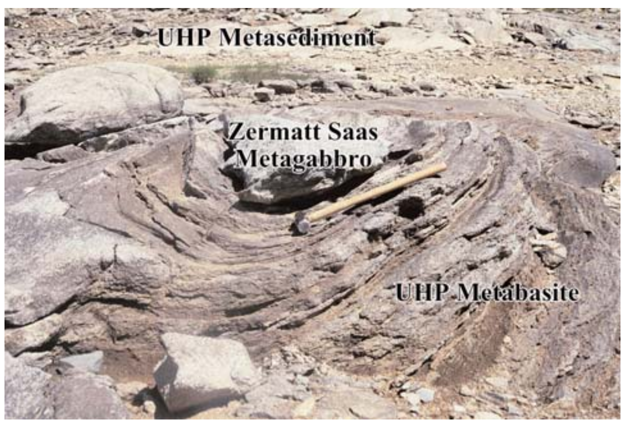


Fig. 18 - *Zermatt-Saas Fe-Ti metagabbro overlying* UHP *metabasites. Shearing is most intense immediately adjacent to this tectonic contact. A late-stage, NW/SE compressional event has caused metre-scale folding, here downwarping the overlying Zermatt-Saas metagabbro sheet.*

FIELD IDENTIFICATION OF LITHOLOGIES AND FABRICS

The methodology used in the field by structural geologists and metamorphic petrologists relies essentially on the identification of fabrics and lithologies (in this case, in respect both to protoliths and their deformed and metamorphosed equivalents). This requires field work to focus on a range of different scales, from microscale to map-scale, as it is impossible to carry out such a study without such wide-ranging attention to detail.

This page focuses on illustrating the fabrics and lithologies that can be observed at Lago di Cignana in order to enable readers of the Volume to readily identify critical aspects during a visit to this classic field location. Protoliths can be hard to identify because of the variable extent of overprinting metamorphic mineral growth, in some cases due to multiple episodes. More important are the effects of deformation, varying from minor modification of the original fabrics to extreme stretching and total disruption of original textures and early fabrics. Key features are illustrated in individual photographs, and described in figure captions. The photographs are presented according to their position in individual tectonometamorphic slices.

The highest structural levels are in the upper-plate, above the Matterhorn Detachment and its precursor extensional shear zone. Here remnants of the Dent Blanche nappe - recumbently folded and later sheared augengneisses of the Arolla Unit (Fig. 19) - are found. Lithologies caught in the underlying extensional shear zone are illustrated in Figs. 20 to 22. The UHP Unit and the Zermatt-Saas Zone are in the lower plate (Figs. 23 to 36).

Note that the UHP slice is intercalated with slices of the Zermatt-Saas Zone (Figs. 1 and 7). The uppermost tectonic slice of the lower-plate is a deformed metagabbro belonging to the Zermatt-Saas Zone. This tectonic slice lies above the anastomosing boudins of the ultra-high pressure unit. Because the detachment slices through anastomosing boudins and tectonic slices, the Combin Zone may also be in contact with the UHP slice locally.

The Matterhorn Detachment and the extensional Combin Shear Zone appear to be responsible for the exhumation of the UHP slice and of the HP rocks of the Zermatt-Saas Zone.

Fabrics and mineralogy reveal that the Combin Shear Zone has operated through blueschist facies conditions until greenschist facies metamorphic conditions were reached. Intense fabrics are developed.

For a detailed description of metamorphic petrology for UHP lithologies refer to COMPAGNONI & ROLFO (1999).

AROLLA UNIT:
In order to examine the contact with the Arolla Unit one needs to climb the steep grass slopes and cliffs west of Lago di Cignana. Samples vary from metagranitoids to augen mylonites, with platy foliations anastomosing around feldspar clasts. These gneissic fabrics are themselves crenulated, with gently-dipping axial planes. Larger-scale recumbent folds can be discerned in the rock walls, that may be equivalent in timing to these structures. Shallowly-inclined (detachment?) faults and intense ductile shear zones at the contact cut through these folds and the earlier formed gneiss fabric.

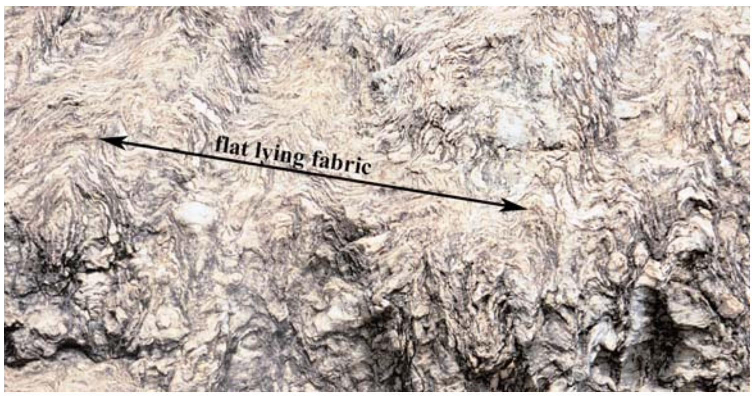


Fig. 19 - *Crenulations of an older mylonitic fabric in boulders of augengneiss that have fallen from the Arolla slice down the steep slopes besides Lago di Cignana. FOV 15cm across.*

COMBIN ZONE:
The Combin Zone is dominated by calcschist, with several large boudins of serpentinite and prasinite (Figs. 7 and 12). Structurally above these boudins is a sequence of quartzite, marble and dolomite (Fig. 20). The calcschist in the structurally higher regions of this zone is increasingly graphitic and more intensely deformed closer to the overlying tectonic contact with the Arolla Unit. Intensity of deformation also occurs adjacent to its lower boundary (Figs. 21 and 22). Intensity of shearing varies remarkably throughout the Combin Zone.

Fig. 20 - *Marble and dolomite boudins occurring in the central region of the Combin Zone and locally mylonitized. FOV ~1.3 m.*

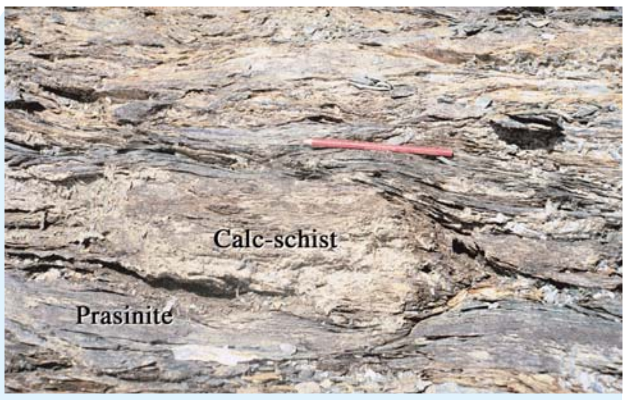


Fig. 21 - *Interleaved calc-schist and prasinite intensely sheared at the tectonic contact between the Combin Zone and the underlying Zermatt-Saas metaophiolite. FOV 56 cm.*

Fig. 22 - *Calc-schist immediately adjacent to the lower tectonic contact of the Combin Zone that has undergone extreme shearing, and was later locally kinked or crenulated. Low mica content produces a gneissic character. FOV 32 cm.*

ZERMATT SAAS ZONE:
The Zermatt-Saas Zone consists of an ophiolite sequence, deformed and metamorphosed later under eclogite and blueschist facies conditions. There are occurrences of suspected pillow-basalts (some more deformed and retrogressed than others), large volumes of serpentinite, and numerous lenses of Fe-Ti or Mg-Al metagabbros (Figs. 23 and 24). Thin basalt dykes (now mainly replaced by chlorite) - a sought after stone for sculpture - occur. Bands of serpentinite, rodingite and talc often mark metasomatic zones associated with faulting, and/or late-stage shear zones. Serpentinites often contain porphyroblasts of Ti-clinohumite that are easily mistaken for garnet. The lithologies and fabrics are generally flat-lying and occur in cliff faces below the dam wall at the lake.

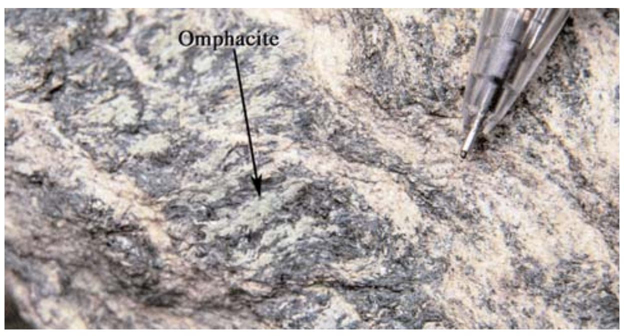


Fig. 23 - *Fe-Ti metagabbro occurs within the Zermatt Saas Zone. These rocks best preserve original igneous textures in spite of the quartz-eclogite and greenschist facies overprints. This sample has not undergone intense shear and has preserved omphacite within small lenses. Early Na-amphibole and later albite overprint the eclogitic assemblage. Location in a low-strain zone east of the UHP unit (E:0390940 N: 5081740). FOV 6 cm.*

Fig. 24 - *A Mg-Al metagabbro within the Zermatt-Saas Zone, converted to quartz-eclogite/blueschist mineral assemblages. This lithology has similar characteristics to the eclogites from the* UHP *unit and it can be difficult to differentiate between these two units. Microstructural analysis and geothermobarometric estimates provide definitive tests. FOV ~8 cm.*

THE ULTRA-HIGH PRESSURE (UHP) UNIT

The UHP unit is a narrow sequence of lenses (Fig. 7) that has undergone UHP metamorphism. It is less than 150 m in thickness and is characterised by a sequence of boudins ranging from ~100 m to 1 cm in length. Some of the boudins have been truncated by late-stage, high-angle normal faults or related late-stage shear zones. Others have been almost totally or totally scraped away by glaciation. The UHP Unit is located within the structurally highest levels of the Zermatt-Saas Zone, overlain only by a thin, highly-deformed slice of Zermatt-Saas metagabbro. The UHP Unit consists of metasediments and metabasites, with much variation occurring within these lithologies (Figs. 25 to 36). It is difficult to differentiate between the metabasites of the UHP unit and the Zermatt-Saas Zone without P-T estimates or the occurrence of coesite. Boudins of eclogite in the UHP Unit have been found to be coesite-bearing. Adjacent, flat-lying, highly-stretched sheets of eclogite appear to be structurally part of the Zermatt-Saas Zone.

Fig. 25 - *Quartz-rich metasediments can occur as thin layers and/or boudins (up to 10s metres in length) within a eclogitic metabasic matrix. The most intense fabrics occur within metabasic material (as seen above). Younger, small-scale shear zones may mantle these boudins and may truncate them at their ends, usually with steep dips (up to 80°). Schistosity within the boudins is usually flat lying. FOV ~80 cm.*

Fig. 26 - *Boudins of metabasic eclogitic material occur at the lower boundary of the* UHP *metasediments. The boudins vary in the degree of deformation, some being more round than elongated. This boudin is one of a sequence that occurs on the southern side of the dam wall, below the access road. Boudin is ~1.5 m long.*

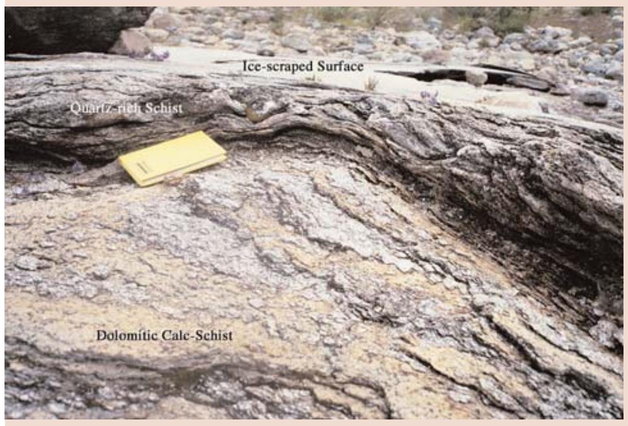


Fig. 27 - *Calc-schist is located in the structurally highest regions of the* UHP *unit, occurring as dolomitic and mica-rich layers, often observed within boudin-like isoclinal infolds. Calc-schist is the dominant lithology in the Combin Zone and it is possible that the calc-schist within the* UHP *unit comprises slices of Combin calc-schist deformed against the* UHP *unit during earlier stages of the operation of the shear zone. FOV ~1.4 metres.*

Fig. 28 - *The structurally lower levels of the quartz-rich metasediments of the* UHP *Unit (in the section near the dam wall) have fine, mafic-rich layers at the base of the sediment beds. Metabasic eclogitic boudins also commonly occur within these metasediments. The sense of shear on the boudins rendered more complex by later shortening. FOV ~80 cm.*

Fig. 29 - *Typical character of the quartz-rich metasediments. The main variation that can occur is in the inclusion, character and abundance of garnet. Note in this sample that the intensity of shear increases towards the top and that the abundance of garnet decreases with the increase in intensity of shearing. FOV ~9 cm.*

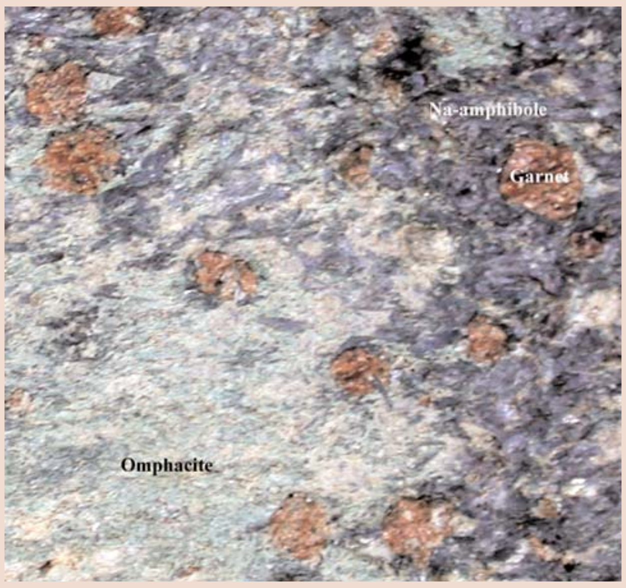


Fig. 30 - *This eclogite from near the dam wall has been almost completely converted to blueschist facies metamorphic minerals (garnet porphyroblasts, glaucophane laths, zoisite plus phengite). Such rocks provide clear evidence of separate episodes of mineral growth, first under eclogite facies conditions, and later under blueschist facies conditions. Petrographic examinations reveal that a period of deformation occurred after each mineral growth event. The garnet porphyroblasts have grown under static metamorphic conditions. FOV ~3 cm.*

Fig. 31 - *Small-scale boudins of eclogitic assemblages are preserved within a pervasively blueschist fabric, providing evidence of its earlier metamorphic history. The fabric formed in a HP shear zone. S-C bands commonly occur throughout the outcrop. FOV ~6 cm.*

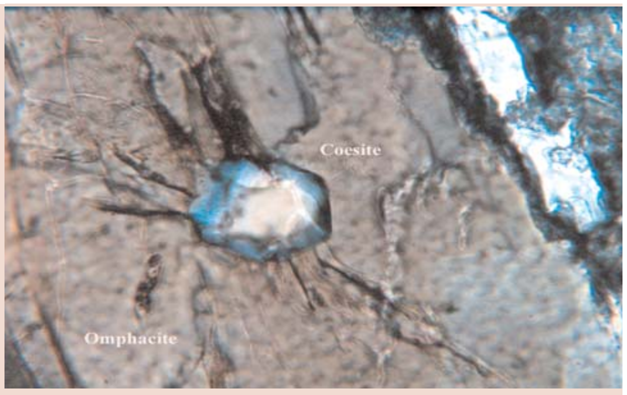


Fig. 32 - *The* UHP *unit at Lago di Cignana has been found to be a coesite-bearing unit. Both the metasediments and metabasic rocks have been found to represent* UHP *metamorphic conditions. This photomicrograph shows a coesite grain within an omphacitic pyroxene. FOV ~200 μm.*

Fig. 33 - *The garnet porphyroblasts within the quartz-rich metasediments have often retrogressed to chlorite. The centre of larger garnet porphyroblasts is often preserved. FOV ~6 cm.*

Fig. 34 - *Mn-rich, quartz-rich metasediments occur in several locations in the UHP Unit. This site is located in the outcrop in the centre of the car park, adjacent to the dam. Another site is found on the southern side of the dam wall. These could be metamorphosed manganiferous cherts. FOV ~4 cm.*

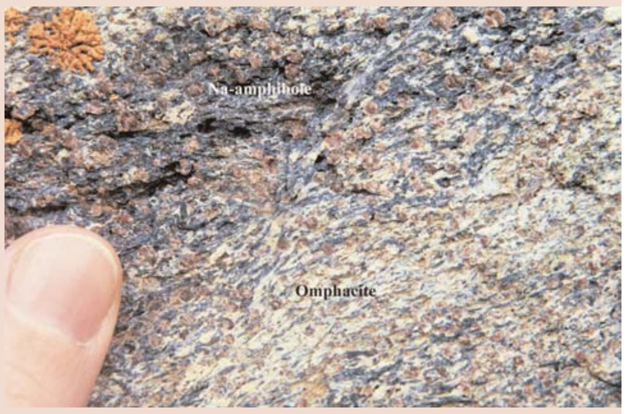


Fig. 35 - *There is a significant variation in the metabasic rocks of the UHP Unit. Distinct outcrops with omphacite + garnet assemblage, or Na-amphibole + garnet regions occur. The overprinting blueschist assemblage is more commonly observed. Variations in deformational style can give these rocks quite different appearances. FOV ~8 cm.*

Fig. 36 - *The metabasic eclogites of the UHP Unit sometimes show strong fabrics in omphacite; the one shown here has a single fabric and overprinting shear bands. Two generations of garnets can also be observed. FOV ~4 cm.*

CHARACTER OF THE MOVEMENT DIRECTION OF THE COMBIN SHEAR ZONE AND EXHUMATION OF UHP ROCKS

The character and relative timing of the exhumation of the UHP rocks at Lago di Cignana can be determined by structural analysis and geochronology of the Combin Shear Zone and Matterhorn Detachment. Movement indicators across the Combin Shear Zone are complex, with regions preserving multiple stages of overprinting while other regions are structurally simpler, due to either the pervasive overprinting of intense younger events and/or a lack of reactivation of some regions during younger deformational events.

The dominant movement sense and complexity of fabric development within the UHP unit differs to that observed in the overlying Combin Shear Zone and the underlying Zermatt Saas Zone. This is due to the UHP unit being formed at greater depths with a different exhumation history, at least in the initial stages of exhumation compared to the adjacent tectonic slices.

The oldest fabric discernible in the UHP unit is defined by eclogite facies minerals: however, sense of movement of this event cannot be positively defined at Lago di Cignana. It is also difficult to know if the UHP event is associated with this early fabric or whether this is an overprinting eclogite facies fabric. Tectonic juxtaposition of the "HP" slices from the Zermatt-Saas Zone against the "UHP" slices is most likely to have occurred during this eclogite facies event. The tectonic regime at this point in the history cannot be constrained, but fabrics are intense and later recumbently folded, and this geometry might reflect a switch from overall crustal extension to overall crustal shortening, for example.

This sheared early fabric is overprinted by multiple generations of S-C bands, all of which are suggested to represent extensional regimes. The older S-C bands show a top-to-the-east sense of movement but this is overprinted by a larger-scale and more dominantly developed S-C bands with top-to-the west sense of movement. These younger dominant S-C bands often appear as conjugate, the timing may or may not be synchronous.

The dominant movement direction in the UHP unit is in eclogite/blueschist facies with a top to the west-north-west to north-west direction. Fabrics formed in this event cut and overprint the earlier formed tectonic contact between the Zermatt-Saas and Combin Zone. Boudins and foliation boudinage with recrystallisation during deformation characteristically developed at this time.

A switch in movement direction is then observed with a south-east sense of shear. This is a less significant event formed at greenschist facies conditions, often associated with garnet growth. This is the final stage of ductile exhumation observed across the Combin Shear Zone.

Regional-scale structural analysis suggests the existence of a large-scale shear zone, based on variation of strain intensity (cf. REDDY *et alii* 2003). The geometry of this shear zone, now folded on the lithospheric scale (Fig. 3) suggests at least initially that shear sense was east-south-east directed. The pattern of later overprinting suggests a combination of tectonic mode switches and/or intense stretching and crustal-scale boudinage during the later history of exhumation (Fig. 6).

CONCLUSIONS

A narrow slice of rock that has undergone UHP conditions is exposed on the southern shore of the Lago di Cignana (Figs. 5 and 7), in the Valtournenche, in NW Italy. This sliver of rock has undergone a complex exhumation history and is now located interleaved between the upper structural boundary of the Zermatt-Saas Zone and the lower structural boundary of the Combin Zone. The maximum metamorphic grade recorded by the Zermatt-Saas Zone is high-pressure (HP) eclogite facies, whereas the now dominantly greenschist facies Combin Zone may locally contain medium-pressure (MP) blueschist facies relicts.

In detail, the UHP slice is structurally located in the lower boundary of a km-scale shear zone containing sheared and retrogressed rocks from the Combin Zone. Nevertheless, in the underlying UHP tectonic slice relict, UHP minerals and their fabric and microstructures are preserved. The UHP slice is a nest of boudins within boudins, and comprises metasediments and metabasic rocks. Locally, the UHP slice is overlain by a single tectonic slice of highly sheared Zermatt-Saas eclogitic metagabbro. This has been transected by the Matterhorn Detachment, so that locally the UHP slice may be in direct contact with the Combin Shear Zone. The UHP slice is preserved as a thin tectonic slice because the locus of the later extensional structures has not precisely followed the trajectory of older thrusts. Fabrics and mineralogy reveal that the Combin Shear Zone has operated through blueschist facies conditions until greenschist facies metamorphic conditions were reached. Intense fabrics are developed, commensurate with large shear strains associated with significant horizontal relative displacement.

The structural geology of the area suggests a history of large-scale overthrusting, during which the UHP rocks were emplaced over the HP rocks of the Zermatt-Saas Zone. Tectonic inversion subsequent to the period of HP metamorphism led to the Alpine orogen being subjected to large-scale (roughly NW-SE-directed), horizontal stretching. This led to the formation of orogen-scale, extensional shear zones, of which the Matterhorn Detachment could be one of the most important manifestations. The Matterhorn Detachment and its precursor, the extensional Combin Shear Zone, appear to be responsible for the exhumation of the UHP slice and of the HP rocks of the Zermatt-Saas Zone.

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