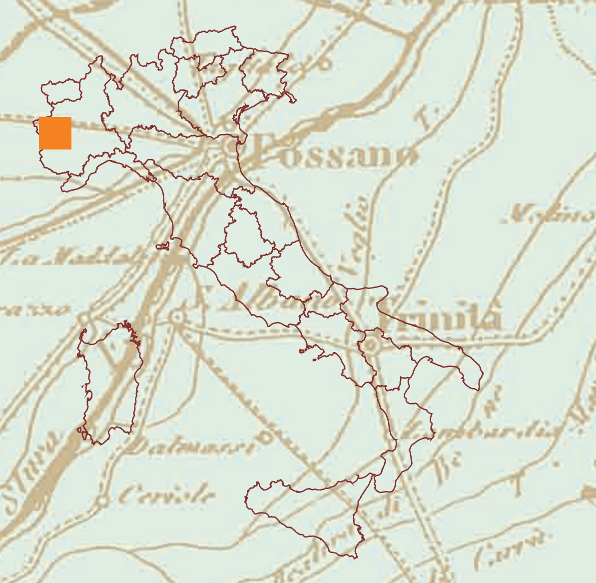

Mapping of Alpine rocks characterised by “HP” to “UHP” metamorphic overprint in the Southern Dora-Maira Massif (Western Alps)

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ABSTRACT

In the southern part of the penninic Dora-Maira massif, Italian Cottian Alps, a pile of tectonic units is exposed, which consists of Variscan continental crust very similar lithologically, but characterised by different Alpine high-pressure metamorphic overprint. For example, unlike the other units showing relics of early Alpine quartz-eclogite facies (High Pressure: HP) metamorphism, the Brossasco-Isasca Unit (BIU) preserves relics of a coeval coesite eclogite-facies metamorphic overprint (Ultra High Pressure: UHP). In all units the most widespread lithologies are orthogneisses with relict metagranitoids, in which the later Alpine greenschist-facies recrystallisation has extensively obliterated the evidence of the former HP or UHP metamorphism. For such a reason, field work must be carried out together with a detailed petrographic study, aimed at recognising the relics of the most significant HP or UHP mineral assemblages. In the text are reported the field and laboratory criteria used to distinguish the BIU from the juxtaposed tectonic units.

AIMS

- To find relics of eclogite-facies minerals in an area which at first sight appears to consist entirely of greenschist-facies rocks.
- To combine information abtained from geological, structural and petrological studies, in order to distinguish tectonic units characterised by different tectonometamorphic evolution.
- To define a series of general field and laboratory criteria used to distinguish UHP from HP metamorphic rocks on all eclogite-facies metamorphic terrains.

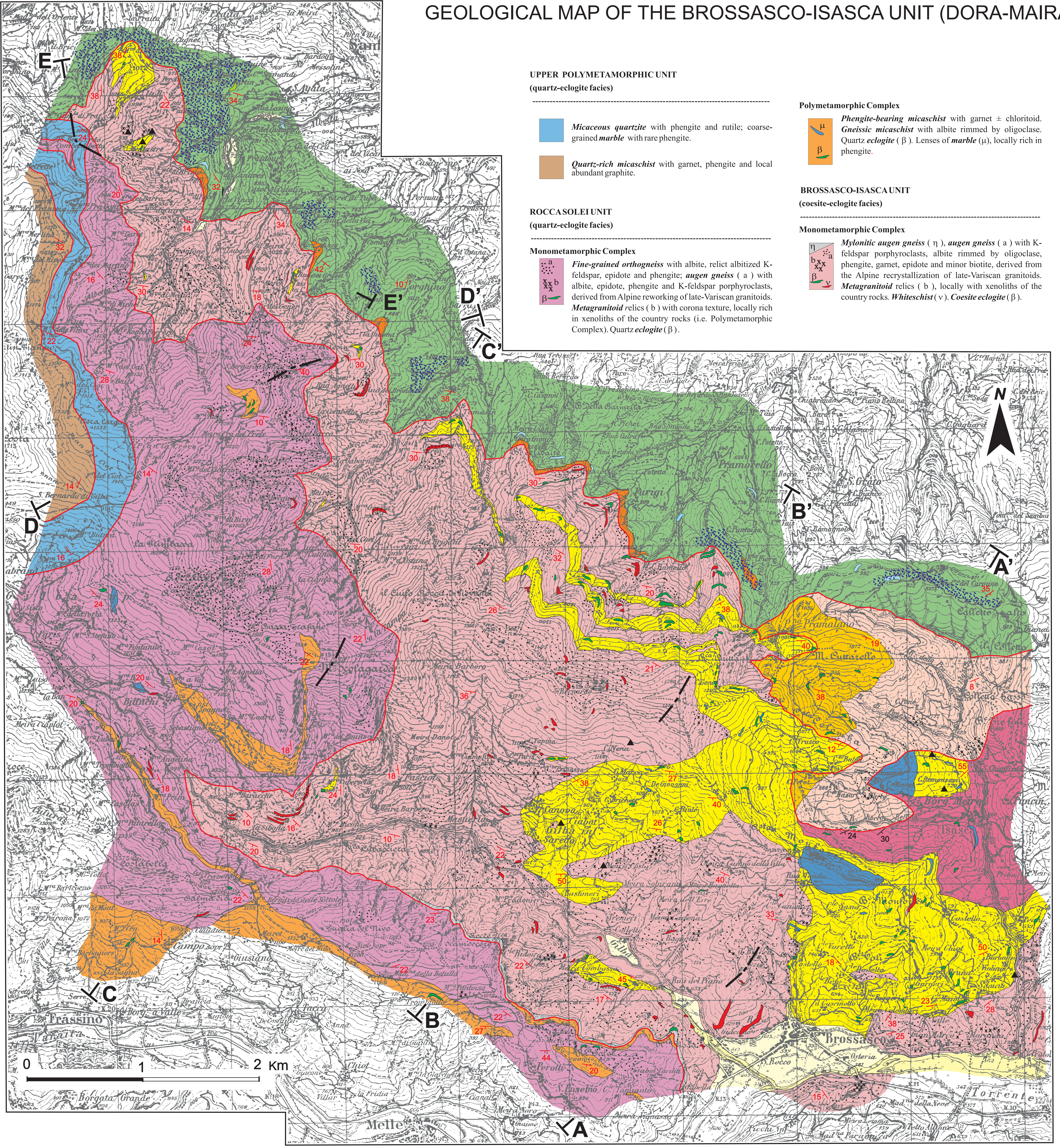
KEY WORDS

Ultrahigh-pressure metamorphism, eclogite, coesite, Brossasco-Isasca Unit, Dora Maira Massif, Western Alps.

RIASSUNTO

Nella parte meridionale del massiccio pennidico Dora-Maira (Alpi Cozie) affiora una sequenza di unità litotettoniche di crosta continentale varisica molto simili, ma con differente sovrimpronta metamorfica alpina di alta pressione. In particolare, l'Unità di Brossasco-Isasca (BIU) presenta relitti di un metamorfismo in facies eclogitica a coesite (Ultra High Pressure: UHP), mentre le unità associate presentano solo relitti di facies eclogitica a quarzo (High Pressure: HP). In tutte le unità i litotipi più diffusi sono ortogneiss con relitti di metagranitoidi, in cui la successiva riequilibrazione alpina in facies scisti verdi ha cancellato in modo pervasivo le evidenze del metamorfismo di alta pressione. Per questo motivo il lavoro di terreno deve essere svolto contestualmente ad uno studio petrografico di dettaglio, che consenta di riconoscere i relitti delle paragenesi caratteristiche del grado metamorfico. Nel testo sono indicati a scopo esemplificativo i criteri utilizzati per distinguere la BIU dalle unità tettoniche associate.

GEOLOGICAL MAP OF THE BROSSASCO-ISASCA UNIT (DORA-MAIRA MASSIF, WESTERN ALPS)



UPPER POLYMETAMORPHIC UNIT
(quartz-eclogite facies)

Micaceous quartzite with phengite and rutile; coarse-grained ***marble*** with rare phengite.

Quartz-rich micaschist with garnet, phengite and local abundant graphite.

ROCCASOLEI UNIT
(quartz-eclogite facies)

Monometamorphic Complex

Fine-grained orthogneiss with albite, relict albitized K-feldspar, epidote and phengite; ***augen gneiss*** (a) with albite, epidote, phengite and K-feldspar porphyroclasts, derived from Alpine reworking of late-Variscan granitoids. ***Metagranitoid*** relics (b) with corona texture, locally rich in xenoliths of the country rocks (i.e. Polymetamorphic Complex). Quartz ***eclogite*** (β).

Polymetamorphic Complex

Phengite-bearing micaschist with garnet ± chloritoid. ***Gneissic micaschist*** with albite rimmed by oligoclase. Quartz ***eclogite*** (β). Lenses of ***marble*** (μ), locally rich in phengite.

BROSSASCO-ISASCA UNIT
(coesite-eclogite facies)

Monometamorphic Complex

Mylonitic augen gneiss (η), ***augen gneiss*** (a) with K-feldspar porphyroclasts, albite rimmed by oligoclase, phengite, garnet, epidote and minor biotite, derived from the Alpine recrystallization of late-Variscan granitoids. ***Metagranitoid*** relics (b), locally with xenoliths of the country rocks. ***Whiteschist*** (ν). ***Coesite eclogite*** (β).

Relics of pre-Alpine intrusive contacts

In the Polymetamorphic Complex: pre-Alpine amphibolite-facies metapelite (Grt-Sil-Bt micaschist with metatects = "kinzigite": Fig. 22, 24, 25) overprinted by low-P contact metamorphism (Fig. 23). In the Monometamorphic Complex: metagranitoid (Fig. 11-14) with hornfelsic xenoliths (Fig. 31) and/or xenocrysts derived from the country rocks (cf. Figs. 27 and 28).

Polymetamorphic Complex

Garnet-phengite micaschist and ***phengitic micaschist*** with garnet and kyanite porphyroblasts ± jadeite and coesite relics. ***Marble,*** locally dolomitic, ***impure marble*** with garnet, clinopyroxene (diopside and omphacite), phengite, talc, epidote, microcline. Coesite ***eclogite*** (β) with accessory rutile ± amphibole ± phengite ± zoisite ± kyanite.

Garnet-phengite ***orthogneiss***, locally grading to augen gneiss, with relics of pre-Alpine fabric underlined by biotite. The gneiss contains lenses of ***marble*** (μ) and coesite ***eclogite*** (β).

SAN CHIAFFREDO UNIT
(quartz-eclogite facies)

Monometamorphic Complex

Fine-grained orthogneiss with albite, epidote and phengite, ***augen gneiss*** (a) with albite rimmed by oligoclase, epidote, phengite, rutile and K-feldspar porphyroclasts, derived from Alpine reworking of late-Variscan granitoids. Relics of ***metagranitoid*** with corona texture (b), ***meta-aplite*** and ***metapegmatite***. Quartz ***eclogite*** (β).

Polymetamorphic Complex

Garnet micaschist with chloritoid, zoisite/epidote and rutile. ***Micaschist*** with albite and two generations of garnet. Quartz ***eclogite*** (β).

PINEROLO UNIT
(epidote-blueschist facies)

Fine-grained gneiss with albite porphyroblasts, epidote, phengite, rare garnet and dusty graphite (τ); ***gneissic micaschist*** with phengite, garnet, albite/oligoclase, blue-green amphibole ± biotite, and rare clinozoisite.

Micaschist with phengite, garnet, clinozoisite, minor albite /oligoclase ± biotite, locally rich in dusty graphite (τ).

Fine-grained gneiss with K-feldspar, albite, phengite, zoisite/clinozoisite; ***quartz-rich micaschist*** with phengite, garnet, chloritoid, clinozoisite, and dusty graphite (τ).

QUATERNARY DEPOSITS

Recent fluvial deposits, undifferentiated

Reworked fluvial deposits

SYMBOL EXPLANATION

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28 main Alpine foliation (dip in degrees)

main Alpine tectonic contacts

A A' trace of geological cross-section

Fig. 1 - *Geological map of Southern Dora-Maira Massif, supported by careful petrographic studies. Compare with Fig. 26. The geological survey has been performed by Roberto Compagnoni, Chiara Groppo, Takao Hirajima & Robertino Turello.*

INTRODUCTION

The most relevant problem concerning the geological mapping of high pressure (HP) and ultra high pressure (UHP) metamorphic rocks is the scarcity of fresh eclogite-facies minerals, which are generally extensively converted to low-pressure (LP) greenschist- to amphibolite-facies mineral assemblages during exhumation (Fig. 28). For this reason, in most, and especially felsic, lithologies key HP to UHP minerals are preserved only as inclusions in less significant but more resistant minerals, such as garnet (Fig. 17). However, a few lithologies - eclogites first of all, these being more competent and less reactive to deformation and metamorphic recrystallisation - are better preserved and still show mineral relics of the peak P and T conditions (Fig. 7). As a consequence of this difference in the kinetic response of lithologies to retrogression during exhumation, for decades the presence of eclogite boudins within large volumes of felsic rocks of continental crust origin (ortho- and para-gneisses) - now showing LP mineral assemblages (Fig. 1) - contributed to the controversy as to the "in situ" (formed in the present geological setting) vs. "exotic" (formed

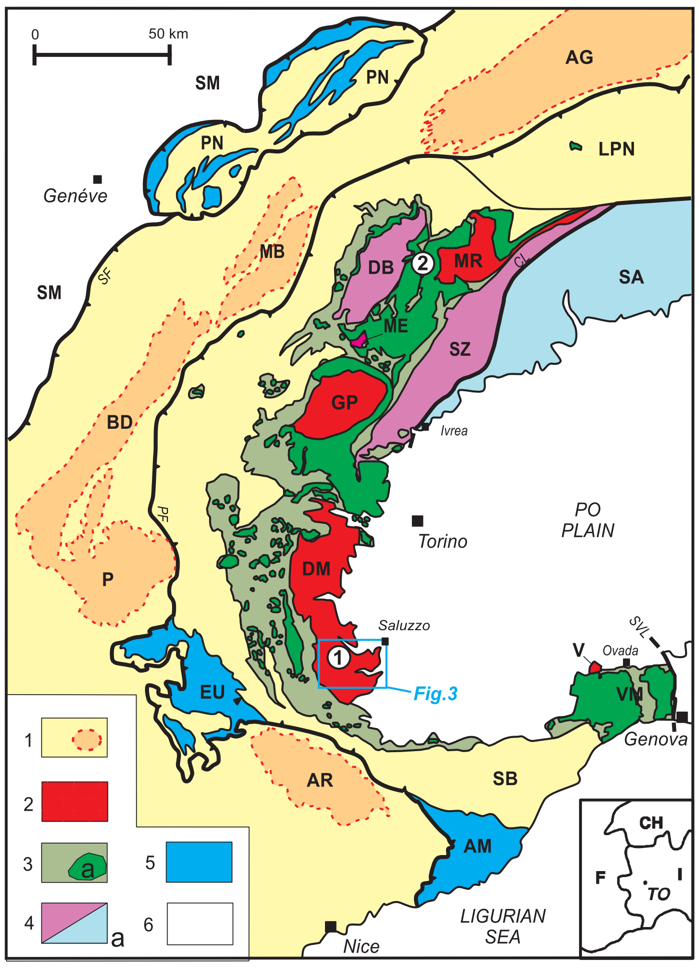


Fig. 2 - *Simplified structural sketch map of the Western Alps.* 1: *Helvetic Domain, external Penninic Domain and Prealpine decollement nappe system* (PN). *The dashed line contours the External Crystalline Massifs of the Helvetic Domain* (AR: *Argentera;* P: *Pelvoux;* BD: *Belledonne;* MB: *Mont Blanc - 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;* V: *Valosio).* 3: *Piemonte Zone* (VM: *Voltri Massif);* a) *main meta-ophiolite bodies.* 4: *Austroalpine Domain* (DB: *Dent Blanche nappe;* ME: *Monte Emilius nappe;* SZ: *Sesia Zone);* 4a) *Southalpine Domain* (SA: *Southern Alps).* 5: *Helminthoid Flysch nappes* (EU: *Embrunais-Ubaye,* AM: *Maritime Alps,* PN). 6: *Swiss Molasse* (SM), *Po Plain Molasse and Piemontese-Ligurian Tertiary basin.* CL: *Canavese line;* SVL: *Sestri-Voltaggio line;* SF: *Subalpine frontal thrust;* PF: *Penninic frontal thrust. In the inset, the borders between France* (F), *Italy* (I) *and Switzerland* (CH) *are shown.*
Location of the Ultrahigh-Pressure Metamorphic Units: (1) Brossasco-Isasca Unit of southern Dora-Maira Massif; (2) Lago di Cignana Unit, Piemonte Zone, upper Valtournenche, Aosta Valley.

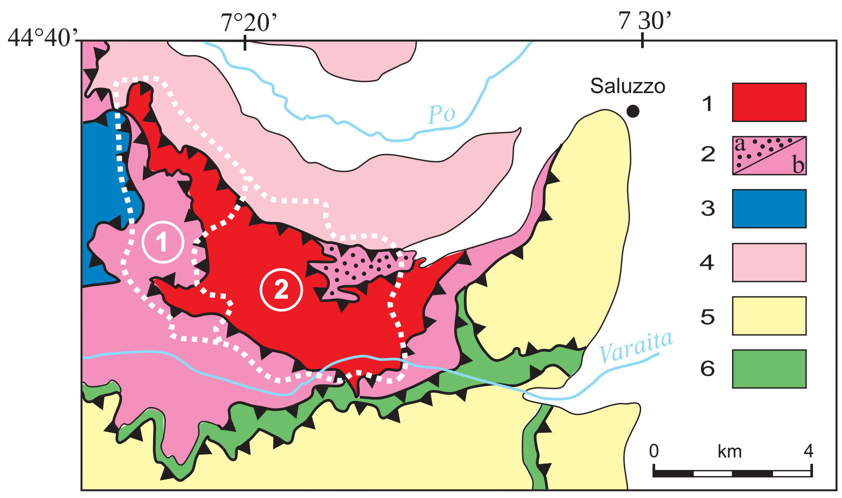
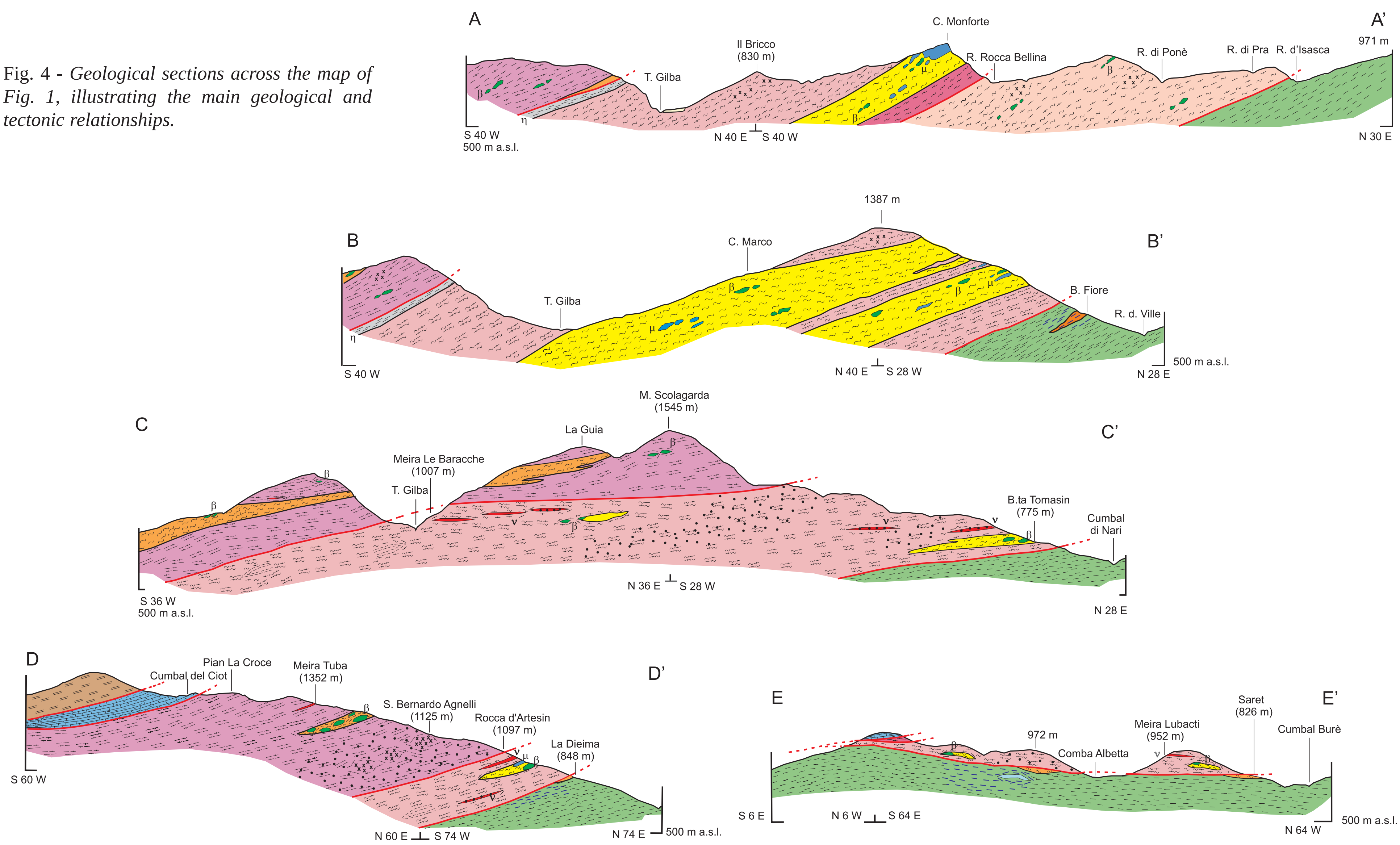


Fig. 3 - Dora-Maira Massif
(1) *Coesite-eclogite facies continental Brossasco-Isasca Unit;*
(2) *Quartz-eclogite facies continental San Chiaffredo* (a) *and Rocca Solei* (b) *Units;*
(3) *Quartz-eclogite facies Upper Polymetamorphic Unit;*
(4) *Epidote-blueschist facies Pinerolo Unit;*
(5) *Quartz-eclogite facies Dronero-Sampeyre Unit.*
Piemonte Zone
(6) *Lawsonite-blueschist facies oceanic metasediments ("calcschists").*
White dotted lines and circled numbers show mapped areas and respective surveyors: 1) Chiara Groppo; 2) Roberto Compagnoni, Takao Hirajima, Franco Rolfo, Robertino Turello.

Fig. 4 - *Geological sections across the map of Fig. 1, illustrating the main geological and tectonic relationships.*



elsewhere and tectonically introduced into the present country felsic rocks) origin of the eclogite. In the absence of eclogite boudins, it is very difficult to even identify the former presence of a HP metamorphic recrystallisation, and field work must necessarily be supported and complemented by careful petrographic studies. For this reason, a selected set of diagnostic, thin-section microphotographs integrate the field analysis (Figs. 5 - 25).

GEOLOGICAL SETTING

The Dora-Maira Massif (DMM) belongs to the Penninic domain of the Western Alps (Fig. 2). The DMM, the Monte Rosa and Gran Paradiso nappes, are the Internal Crystalline Massifs which consist of Variscan continental crust intruded by large bodies of late- to post-Variscan granitoids. The Internal Crystalline Massifs are structural highs, which are exposed because of the erosion of the overlying ocean-derived Piemonte Zone.

GEOLOGICAL AND LITHOLOGICAL SETTING OF THE AREA STUDIED

The area is located in the southern part of the DMM (Fig. 3), covers about 60 km^2 and is exposed between the lower Po Valley and the lower Varaita Valley (Fig. 1). It mainly consists of continent-derived tectonic units showing very similar lithological associations, but different early Alpine HP to UHP metamorphic overprints (HENRY, 1990; COMPAGNONI *et alii*, 1994). These tectonometamorphic units are locally separated by thin bands of Mesozoic calcschist and meta-ophiolite from the ocean-derived Piemonte Zone (Fig. 3).
By combining information obtained from geological and petrological studies (Figs. 1 and 4), the following five tectonometamorphic units have been distinguished in the area considered:

I) the BROSSASCO-ISASCA UNIT (BIU): a portion of pre-Alpine continental crust, consisting mainly of a Variscan amphibolite-facies metamorphic basement (now micaschist, impure marble, orthogneiss, eclogite) intruded by late-Variscan granitoids (now augen gneiss grading to metagranite and whiteschist). During the Alpine orogeny, this ensemble experienced an earlier coesite-eclogite facies metamorphism (T=730°C, P>35 kbar), and a later pervasive greenschist facies re-crystallisation (COMPAGNONI & ROLFO, 2003 with references therein);

II) the SAN CHIAFFREDO UNIT: a portion of pre-Alpine continental crust, consisting mainly of a Variscan amphibolite-facies metamorphic basement (now micaschist and eclogite) intruded by late-Variscan granitoids (now fine-grained orthogneiss and augen gneiss grading to metagranitoid, meta-aplite). During the Alpine orogeny this ensemble experienced an earlier quartz-eclogite facies metamorphism (T~550°C, P=15 kbar), and a later pervasive greenschist-facies re-crystallisation;

III) the ROCCA SOLEI UNIT: a portion of pre-Alpine continental crust, consisting mainly of a Variscan amphibolite facies metamorphic basement (now micaschist, micaceous gneiss, marble, eclogite) intruded by late-Variscan granitoids (now fine-grained orthogneiss and

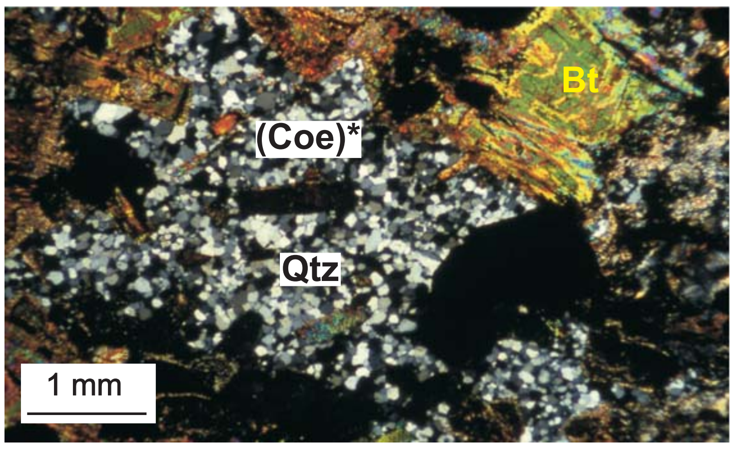


Fig. 5 - *Metagranitoid. Note the fine-grained granoblastic aggregate of quartz, statically derived from inversion of coesite which replaced the igneous quartz during* UHPM. UHP *Brossasco-Isasca Unit. Sample* DM 496 (**). XPL (***). *Mineral abbreviations* (****) *are reported on the next page.*

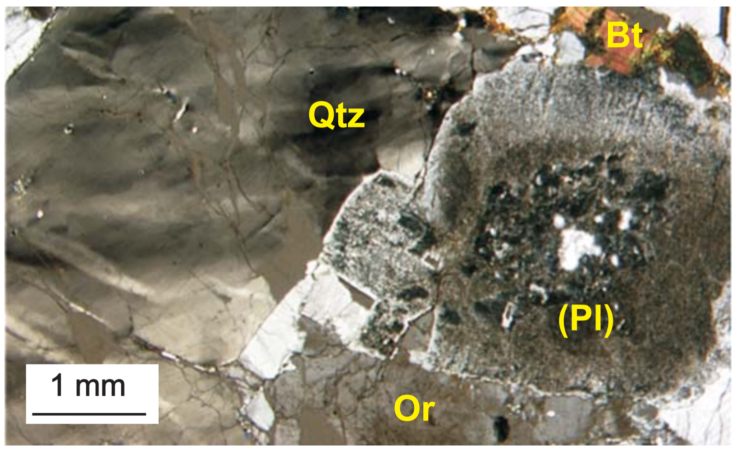


Fig. 6 - *Metagranite. Note, in the left portion of the microphotograph, a single grain of igneous quartz, with wavy extinction due to incipient deformation, which indicates that the rock did not experience pressures higher than the quartz upper stability boundary (Fig. 28).* HP *Rocca Solei Unit. Sample* DM 1513. XPL *(compare with quartz of Fig. 5).*

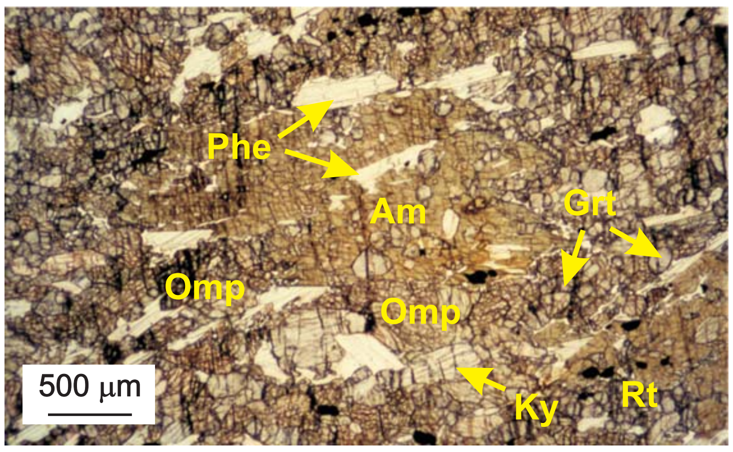


Fig. 7 - *Fine-grained quartz (after* UHP *peak coesite)-amphibole-phengite eclogite with a foliation defined by preferred orientation of phengite. Note a retrograde amphibole porphyroblast (barroisitic core and taramitic rim) in the centre, overgrowing the* UHPM *foliation.* UHP *Brossasco-Isasca Unit. Sample* DM716. PPL.

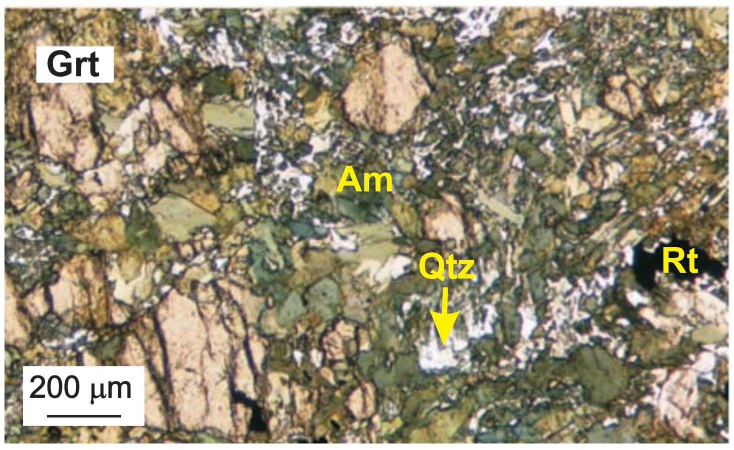


Fig. 8 - *Quartz-eclogite with retrograde edenitic to pargasitic amphibole, developed at the expense of garnet and omphacite.* HP *Rocca Solei Unit. Sample* DM1497. PPL.

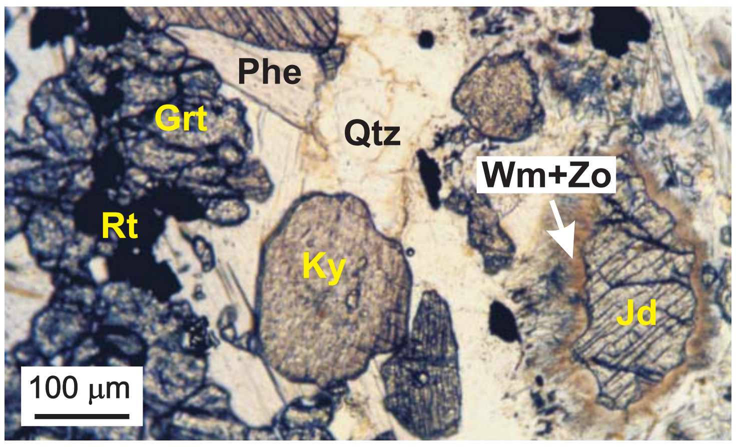


Fig. 9 - *Metapelite consisting of quartz (after* UHP *peak coesite), garnet, kyanite, jadeite, phengite and accessory rutile. The kyanite-jadeite assemblage indicates that the rock experienced pressures higher than the paragonite upper stability.* UHP *Brossasco-Isasca Unit. Sample* DM689. PPL.

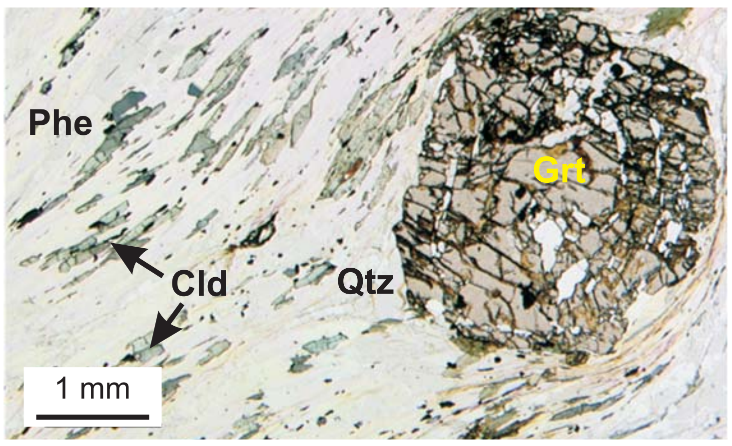


Fig. 10 - *Metapelite consisting of quartz, phengite, chloritoid and garnet porphyroblasts. The presence of chloritoid + quartz points to* LT *conditions and indicates that the rock did not experience* UHPM *conditions, because of the reaction* Cld + Qtz = Alm + Ky + H_2O *(see Fig. 28).* HP *Rocca Solei Unit. Sample* DM1504. PPL.

Fig. 11 - *Relict, late-Variscan porphyritic metagranite. On hand specimen, the only evidence of the* UHP *metamorphic overprint is a very rough foliation (roughly N-S), and the sugary appearance of the original igneous quartz, now consisting of a granoblastic polygonal aggregate of metamorphic quartz, derived from inversion from former coesite (cf. Figs. 5 and 14). Monometamorphic Complex,* UHP *Brossasco-Isasca Unit. The coin is 20 mm across.*

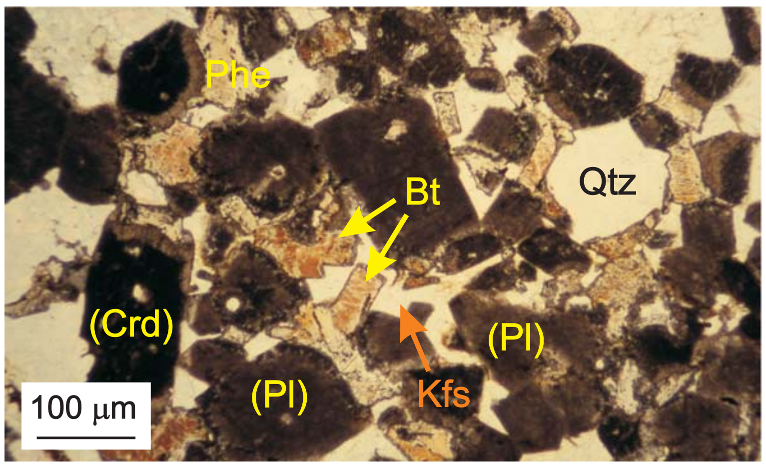


Fig. 12 - *Metagranitoid collected near the contact with the country metamorphic basement (granitoid marginal facies). Euhedral crystals of former igneous plagioclase (now a very-fine grained aggregate of jadeite + zoisite ± kyanite), cordierite (now a very fine-grained aggregate of kyanite + garnet ± biotite), and biotite (partly replaced by phengite) are set in a matrix of granoblastic polygonal quartz derived from inversion from* UHPM *coesite.* UHP *Brossasco-Isasca Unit. Sample* DM 1116. PPL.

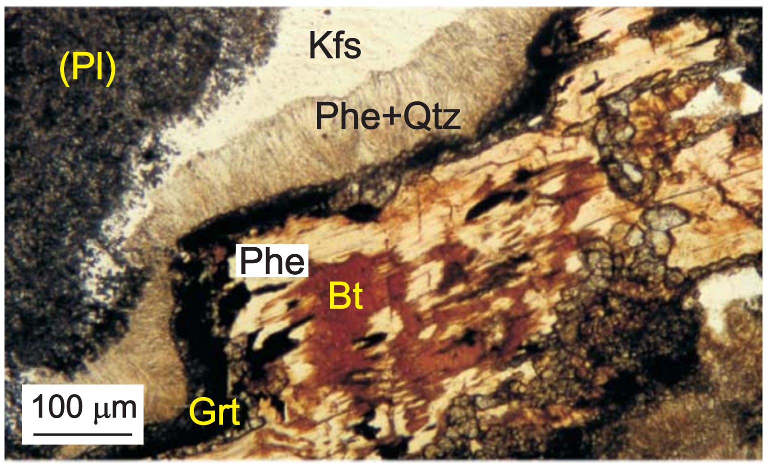


Fig. 13 - *Detail of a metagranite, showing the transformation of an igneous biotite, partly into a re-equilibrated Mg-enriched biotite and partly into phengite. The biotite domain is surrounded by a first continuous garnet corona and a second corona against K-feldspar, which consists of a very fine-grained dactylitic intergrowth of phengite and quartz.* UHP *Brossasco-Isasca Unit. Sample* DM1086. PPL.

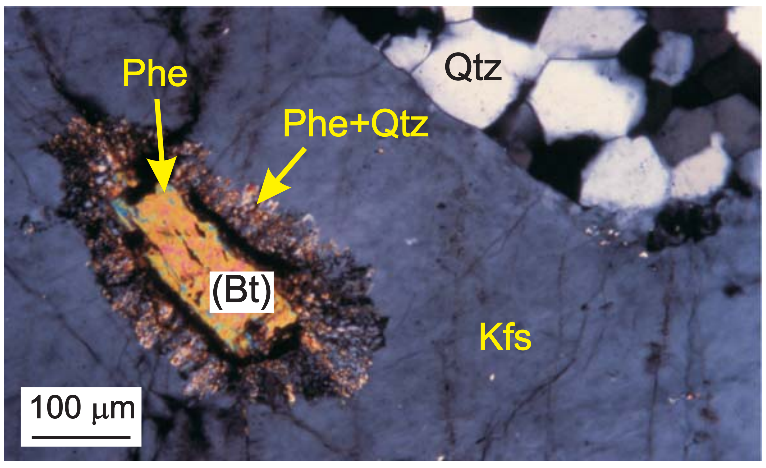


Fig. 14 - *Detail of a metagranite, showing an igneous biotite included in a K-feldspar which is pseudomorphically replaced by a single phengite crystal and surrounded by a thin garnet corona and a dactylitic phengite + quartz intergrowth. In the upper right is a granoblastic polygonal quartz aggregate from former peak coesite, developed after primary euhedral igneous quartz.* UHP *Brossasco-Isasca Unit. Sample* DM 60. XPL.

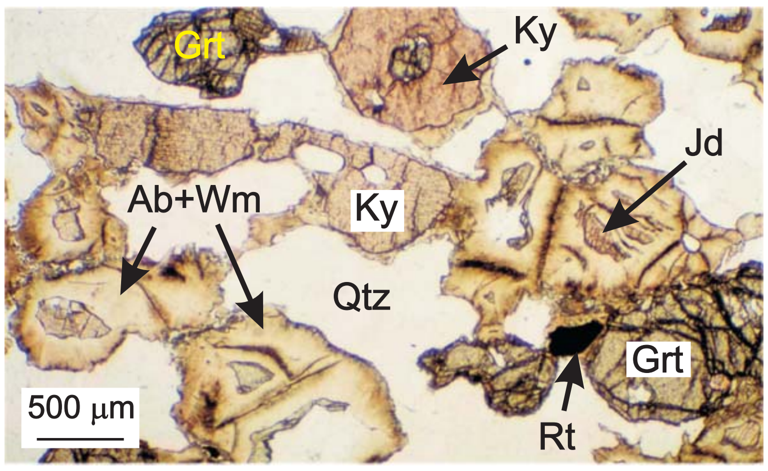


Fig. 15 - *Garnet - jadeite - kyanite - quartz / (coesite) granofels. The presence of the jadeite - kyanite assemblage indicates that P conditions, higher than the paragonite breakdown, have been reached because of the reaction:* Pg = Jd + Ky + H_2O *(Fig. 28). In the rock matrix, jadeite is pseudo-morphically replaced by albite + white mica, and coesite by granoblastic quartz.* UHPM *Brossasco-Isasca Unit. Sample* DM442. PPL.

Fig. 16 - *Pyrope megablast, ca. 20 cm across, from the whiteschist of the Monometamorphic Complex,* UHP *Brossasco-Isasca Unit. The light pink garnet colour is due to its composition, very close to the pure pyrope end-member with very little almandine. Note that the pyrope is crowded with inclusions of kyanite, rutile, etc.*

(*) *Bracketed minerals are not preserved, but their former occurrence is unambiguously inferred on the basis of the microstructure and/or composition of pseudomorphing minerals.*

(**) *Thin section numbers refer to the collection of the Department of Mineralogical and Petrological Sciences, Turin University, Italy.*

(***) PPL: *plane polarized light;* XPL: *crossed polarizers.*

(****) *Symbols for minerals:* Ab: *albite;* Alm: *almandine;* Am: *amphibole;* An: *anorthite;* And: *andalusite;* Bt: *biotite;* Cld: *chloritoid;* Coe: *coesite;* Crd: *cordierite;* Crn: *corundum;* Dmd: *diamond;* Ell: *ellenbergerite;* Gln: *glaucophane;* Gr: *graphite;* Grt: *garnet;* Jd: *jadeite;* Kfs: *K-feldspar;* Ky: *kyanite;* Lws: *lawsonite;* Ny: *nyböite;* Omp: *omphacite;* Or: *orthoclase;* Pg: *paragonite;* Phe: *phengite;* Phl: *phlogopite;* Pl: *plagioclase;* Prp: *pyrope;* Qtz: *quartz;* Rt: *rutile;* Sil: *sillimanite;* Spl: *spinel;* St: *staurolite;* Tlc: *talc;* Wm: *white mica;* Zo: *zoisite.*

augen gneiss grading to metagranitoid). During the Alpine orogeny this ensemble experienced an earlier quartz-eclogite facies metamorphism (T~550°C, P~15 kbar), and a later pervasive greenschist-facies re-crystallisation;

IV) the Upper Polymetamorphic Unit: a portion of pre-Alpine continental crust, with a Permo-Carboniferous and Permo-Triassic cover (in this area, mainly micaschist variously rich in quartz). During the Alpine orogeny this ensemble experienced an earlier quartz-eclogite facies metamorphism (T=500-550°C, P=12-20 kbar) and a later pervasive greenschist-facies re-crystallisation;

V) the Pinerolo Unit (Vialon, 1966): consisting of micaschists, locally rich in graphite, which may contain garnet and chloritoid, with interlayers of quartzite and minor paragneiss. During the Alpine orogeny, these rocks experienced an earlier epidote-blueschist-facies metamorphism (T~400°C, P~8 kbar), and a later greenschist facies re-crystallisation.

Of these five tectonometamorphic units, the most interesting is the BIU, in which Chopin (1984) reported the occurrence of coesite in continental crust for the first time. The extension of this unit, initially defined by Chopin *et alii*, (1991), was later revised by Turello (1993), Compagnoni *et alii*, (1994) and Groppo (2002).

The BIU, which is about 10x4x1 km in size, is tectonically sandwiched between the overlying Rocca Solei Unit and the underlying San Chiaffredo and Pinerolo Units (Figs. 1, 3 and 4) (Chopin *et alii*, 1991; Henry, 1990; Compagnoni *et alii*, 1994). Within the BIU, two lithostratigraphic complexes have been recognised: a "Monometamorphic Complex", mainly consisting of orthogneiss, and a "Polymetamorphic Complex" derived from Alpine tectono-metamorphic reworking of late-Variscan granitoids and of a Variscan amphibolite-facies metamorphic basement, respectively (Fig. 1).

FIELD AND LABORATORY CRITERIA USED TO DISTINGUISH UHP FROM HP METAMORPHISM IN THE ROCKS OF THE SOUTHERN DORA-MAIRA MASSIF

Most lithologies exposed in the area derive from the same pre-Alpine (most likely Variscan) con-

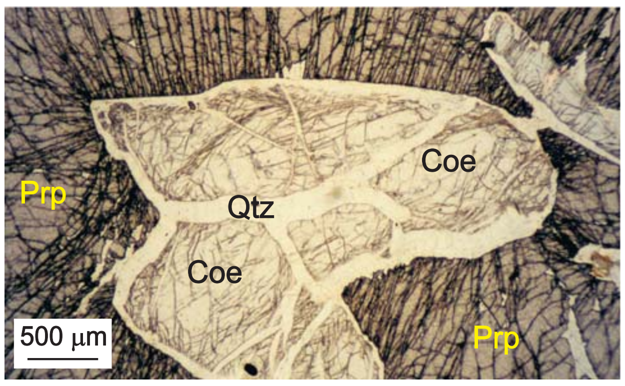


Fig. 17 - *Pyrope whiteschist. Relics of coesite, included in a pyrope porphyroblast, are partially converted to quartz along rims and fractures. Radial fractures, consequent to volume increase during the coesite to quartz inversion, are developed in the hosting pyrope. Monometamorphic Complex,* UHP *Brossasco-Isasca Unit. Sample* DM507. PPL.

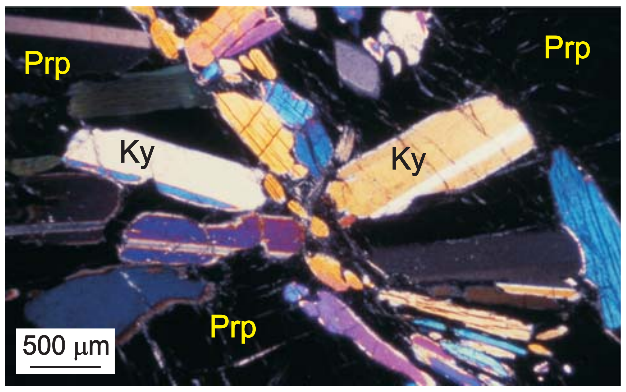


Fig. 18 - *Radial kyanite aggregate in pyrope (black) from whiteschist. Some pyropes contain more than 50 vol.% of mineral inclusions, largely kyanite.* UHP *Brossasco-Isasca Unit. Sample* DM450. XPL.

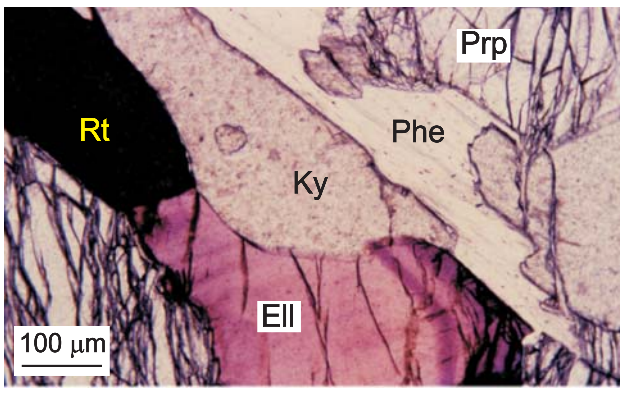


Fig. 19 - *Zoned ellenbergerite in association with kyanite, phengite, and rutile, armoured in a pyrope megablast from a whiteschist. Ellenbergerite, a new mineral so far reported only from this UHPM unit, is always preserved as inclusion.* UHP *Brossasco-Isasca Unit. Sample* DM450. PPL.

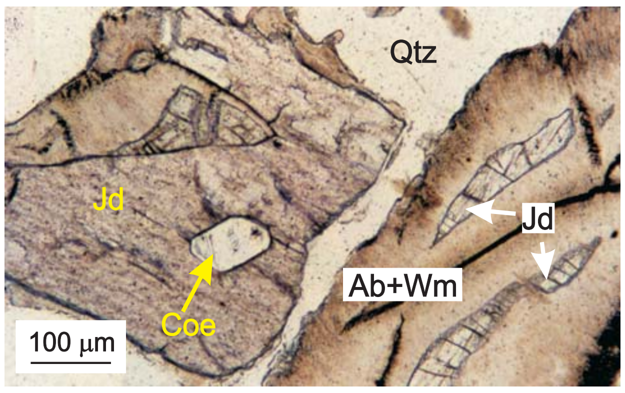


Fig. 20 - *Coesite, partly inverted to quartz, included in a jadeite from kyanite - jadeite - quartz / (coesite) granofels. Jadeite is mostly retrogressed to albite + white mica.* UHP *Brossasco-Isasca Unit. Sample* DM442. PPL.

Fig. 21 - *Marginal facies of the late-Variscan porphyritic metagranite, crowded with contact metamorphosed xenoliths of the country Variscan paraschists. Note that the xenoliths preserve a clear Variscan metamorphic foliation. Case Bastoneri, Gilba Valley.* UHP *Brossasco-Isasca Unit.*

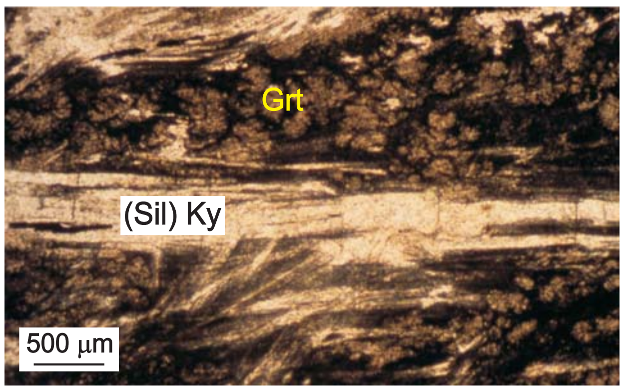


Fig. 22 - *Contact-metamorphosed Variscan amphibolite-facies paraschist. A bundle of Variscan sillimanite, pseudomorphically replaced by a* UHP *kyanite aggregate, is embedded in a dark matrix derived from late Variscan contact metamorphic cordierite, which mainly consists of fine-grained* UHP *garnet aggregates. Polymetamorphic Complex,* UHP *Brossasco-Isasca Unit. Sample* DM493. PPL.

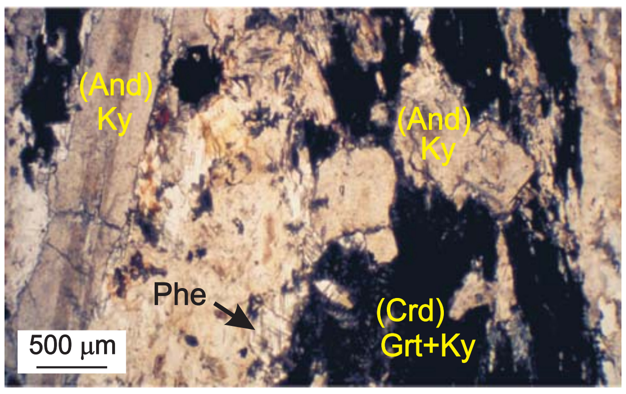


Fig. 23 - *Relict of a Variscan paraschist, showing kyanite pseudomorphs after contact-metamorphic andalusite and garnet + kyanite + white mica pseudomorphs after contact-metamorphic cordierite. Polymetamorphic Complex,* UHP *Brossasco-Isasca Unit. Sample* DM1143. PPL.

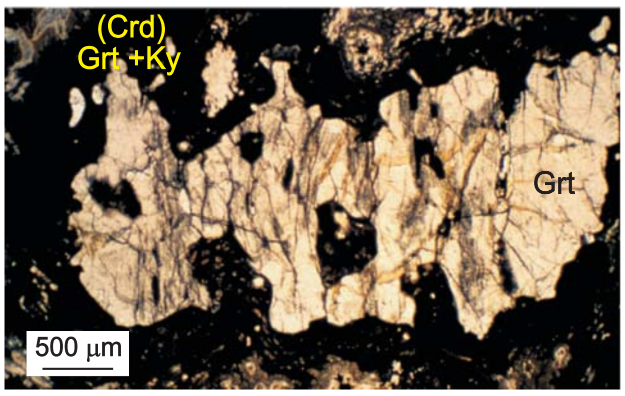


Fig. 24 - *Metapelite showing a corroded Variscan amphibolite-facies garnet, partly replaced by late-Variscan contact metamorphic cordierite, now converted to a very fine-grained aggregate (dark grey) of Alpine garnet + kyanite. Polymetamorphic Complex,* UHP *Brossasco-Isasca Unit. Sample* DM495. PPL.

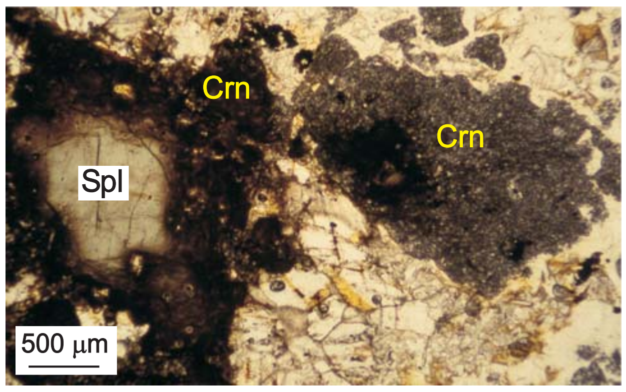


Fig. 25 - *Impure dolomitic marble which preserves Variscan green spinel, in part pseudomorphically replaced by a* UHP *corundum aggregate. Polymetamorphic Complex of the* UHP *Brossasco-Isasca Unit. Sample* DM1171. PPL.

tinental crystalline basement, which experienced different early-Alpine HP to UHP metamorphic overprint in different portions. Consequently, the main problem is to define reliable geological and petrological criteria in order to distinguish between different peak metamorphic conditions. Therefore, field work must be systematically coupled with laboratory studies. More than 800 georeferenced samples were collected, classified and examined in thin section. The most representative of these were studied by means of SEM-EDS, and mineral chemistry was used for geothermobarometric estimates, i.e. to constrain the metamorphic conditions. Since the most distinctive features were acquired during the early-Alpine overprint, special attention was paid to the distinction between HP and UHP metamorphism, the mineral relics of which are mainly preserved in small rock volumes, such as less pervasively deformed lithologies or mineral grains.

The following criteria have been used to distinguish HP from UHP metamorphic rocks:

- occurrence of coesite (or its pseudomorphs consisting of polycrystalline quartz aggregates) armoured in minerals such as garnet (pyrope and almandine rich), clinopyroxene (jadeite and omphacite), kyanite and zoisite. Coesite relics are often surrounded by peculiar radial cracks in the host mineral, resulting from the increase in volume connected to the coesite to quartz reaction (Figs. 5, 17 and 28). The finding of coesite relics in a wide spectrum of lithologies allowed to define the areal extent of the UHP metamorphism, and, consequently, to trace the tectonic contacts against the juxtaposed units;

- occurrence of pyrope (Figs. 16 and 17) compositionally close to the pure end-member (up to Prp_{98}) in the kyanite phengite pyrope - whiteschists, which are metasomatic rocks derived from former granitoids or orthogneisses (COMPAGNONI & HIRAJIMA, 2001);

- occurrence of other UHPM index minerals, such as ellenbergerite (Fig. 19), phosphoellenbergerite, or magnesiodumortierite found as inclusions armoured in pyrope (CHOPIN & FERRARIS, 2003 with references therein);

- occurrence of glaucophane, compositionally close to the pure end-member $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$, in rocks whose bulk chemistry can be represented by the NMASH system, such as the “sodic whiteschist” of Case Parigi (KIENAST *et alii*, 1991);

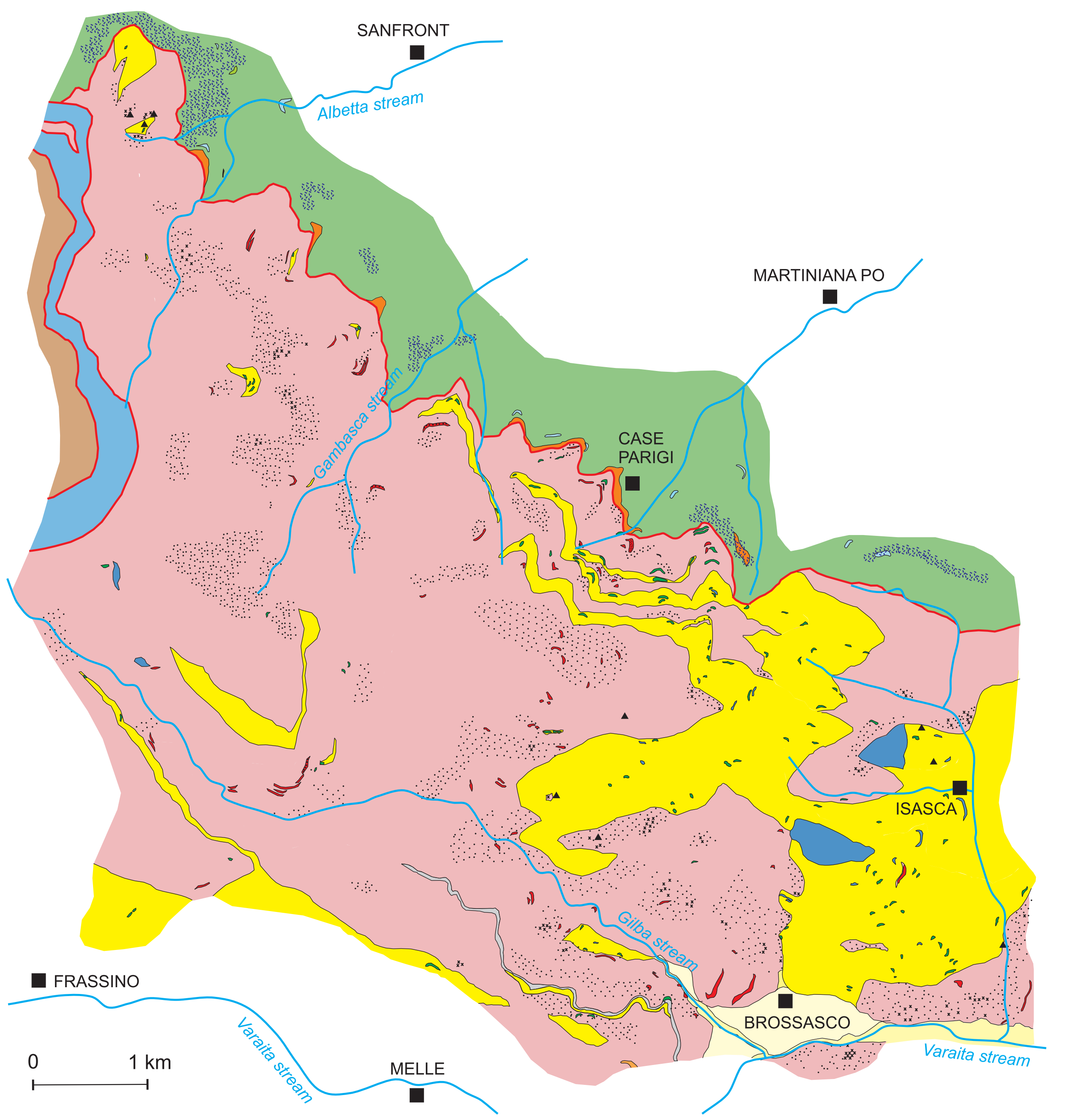


Fig. 26 - *Field geological map of Southern Dora-Maira Massif, not supported by careful petrographic studies. Compare with Fig. 1.*

- lack of relics of igneous quartz in weakly deformed metagranitoids. Unlike in the other tectonic units, the pristine magmatic quartz of the BIU metagranites (Figs. 21 and 11) is systematically replaced by peculiar granoblastic quartz aggregates (Biino & Compagnoni, 1992). These aggregates (Fig. 5) are interpreted as being derived from inversion from former coesite which replaced the original igneous quartz during the metamorphic pressure peak (Fig. 14);

- pyrope + coesite (Fig. 17) instead of the lower-P assemblage kyanite + talc in the whiteschist, because of the reaction: Ky + Tlc = Prp + Coe + H_2O (Fig. 28);

- kyanite + jadeite (Fig. 15) instead of the lower-P paragonite in the orthogneiss, because of the reaction: Pg = Ky + Jd + H_2O (Fig. 28);

- grossular-rich garnet + rutile + phengite instead of the lower-P assemblage titanite + clinozoisite in the orthogneiss (Chopin *et alii*, 1991), because of the reaction: Grs + Rt + Coe + H_2O = Ttn + Czo (Fig. 28);

- kyanite instead of paragonite in the eclogites;

- in eclogites (coesite-eclogite facies), peak temperatures of about 700-750°C, instead of 500-550°C typical of the quartz-eclogite facies of the other juxtaposed tectonic units;

- almandine + kyanite (Figs. 9 and 15) instead of the lower-T assemblage chloritoid + quartz (Fig. 10) occurring in metapelites of the adjoining tectonic units (Fig. 28);

- high-celadonite (Si > 3.50 a.p.f.u.) and low paragonite (less than 10 mol%) phengite with 3T polytype, optically uniaxial when observed under a polarising microscope;

- phengite with exsolved talc + quartz lamellae, only visible by means of TEM (Chopin & Ferraris, 2003).

The petrological study of these tectonometamorphic units, coupled with geochronologic data (Rubatto & Hermann, 2001), allows to constrain the pressure-temperature-time (P-T-t) path of the BIU Alpine evolution (Fig. 28). The study of mineral inclusions within peak UHPM minerals suggests a steep prograde path. The early Alpine UHP peak metamorphic conditions are well constrained at T = 750 ± 30°C and P = 33 ± 3 kbar, i.e. at pressures lower than the equilibrium curve diamond-graphite. The lack of diamond was confirmed by a systematic search of micro-inclusions within the UHP zircons, which revealed the presence of coesite only (Sobolev *et alii*, 1994). The post-peak metamorphic evolution was marked by a decompression from 33 to about 5 kbar, coupled with a progressive cooling from 750°C to 500-550°C, and by a new moderate heating coupled with slower decompression down to the boundary between greenschist and amphibolite facies. This second thermal peak, occurring about 30 Ma ago (Rubatto & Hermann, 2001), was followed by a slow decompression and significant cooling. It is noteworthy that, due to preservation of pre-Alpine relict minerals and microstructures, part of the pre-Alpine evolution can also be inferred. This includes a regional amphibolite-facies, most likely Variscan, metamorphic event overprinted by a contact metamorphism connected to the emplacement of the late-Variscan granitoids (Gebauer *et alii*, 1997), (Figs. 21 and 27).

CONCLUSIONS

The study has shown that the Brossasco-Isasca, the San Chiaffredo, and the Rocca Solei units consist of the same lithological associations (orthogneiss, metagranite, micaschist, marble, eclogite), derived from similar pre-Alpine, most likely Variscan, crystalline basements, which experienced different peak-P conditions during the Alpine subduction. A discriminant method of recognizing the presence of different tectonic units within this crystalline basement is the identification and characterization of the relics of the early subduction metamorphism.
Without a careful petrographic study, the resulting geological map would be as reported in Fig. 26, which is significantly different from that of Fig. 1.
In conclusion, the mapping of basements which underwent eclogite-facies metamorphism requires a systematic petrographic study, which is essential towards identifying the few and tiny relics of the eclogite-facies metamorphism, extensively obliterated by the greenschist- to amphibolite-facies overprint acquired during exhumation. In the same way as for the distinction between UHP (or coesite-eclogite facies) and HP (or quartz-eclogite facies) metamorphism, the criteria suggested here may be very useful on other UHP and HP metamorphic terrains.

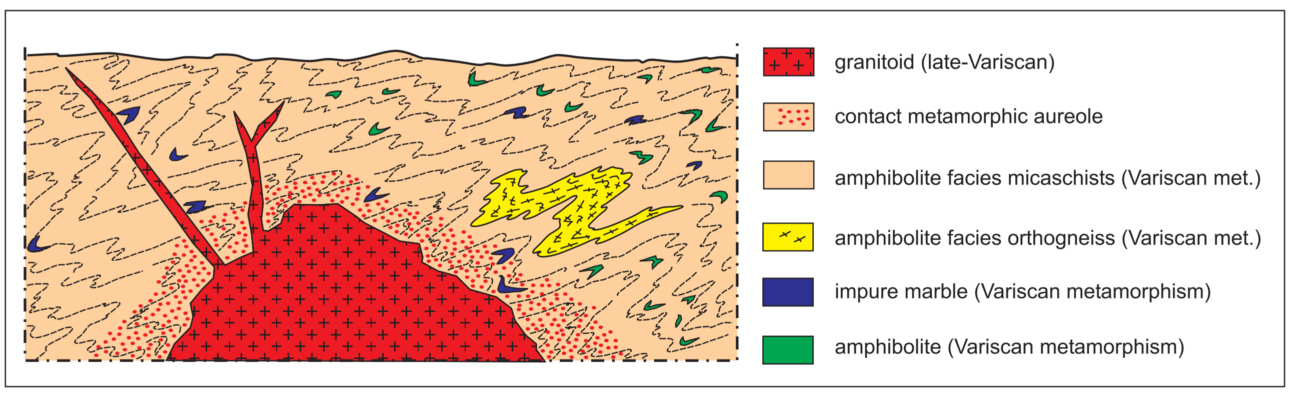


Fig. 27 - *Geological relationships between the Polymetamorphic Complex and the Monometamorphic Complex of the BIU, before the Alpine tectonic and metamorphic reworking, as inferred from the study of the pre-Alpine mineral and structural relics.*

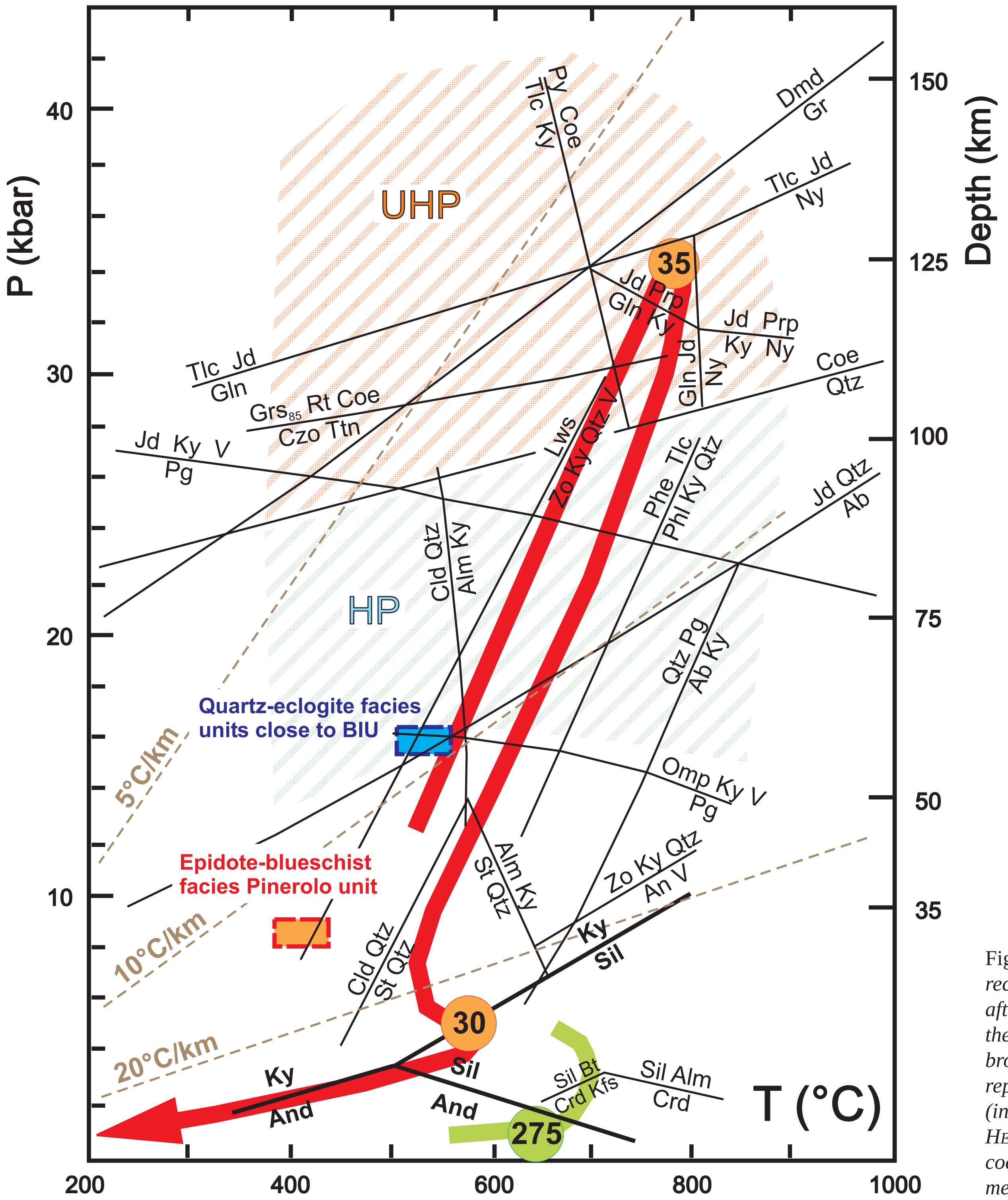


Fig. 28 - *Simplified petrogenetic grid showing the P-T-t path recorded in the UHP rocks of the Brossasco-Isasca Unit, modified after* COMPAGNONI et alii *(1995). Peak metamorphic conditions of the surrounding tectonic units are also shown. Dashed lines in brown are geothermal gradients. Mineral abbreviations (****) are reported on page 291. Circled numbers are the metamorphic ages (in Ma) determined by* GEBAUER et alii, *(1997) and* RUBATTO *&* HERMANN *(2001) for the UHP Brossasco-Isasca Unit. The quartz-coesite reaction curve divides the field of UHP from that of HP metamorphism.*

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