# Tectono-stratigraphic setting and metamorphic evolution of Ligurian-Piedmont Units in the Upper Susa and Chisone Valleys (Western Alps)

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## INTRODUCTION

The Alps are a collisional belt, developed after the closure of the Alpine Tethys, opened in Jurassic times between the Adriatic and European continental paleo-margins (see Dal Piaz et al., 2003 for a review). A compelling challenge is to provide new data to constrain the lithostratigraphic setting and metamorphic evolution of various tectonic units from the Ligurian-Piedmont zone. With the intent to constrain the relative pre-collisional position and the Alpine tectono-metamorphic evolution of four tectonic units exposed in the upper Susa and Chisone valleys (Western Alps), the data here presented derive from a Ph.D. project which investigated: the Banchetta-Rognosa unit, the Albergian unit, the Lago Nero unit and the Chenaillet ophiolite.

A multidisciplinary approach was paramount to unravel the tectono-stratigraphic and tectono-metamorphic evolution of these units from the Axial sector of the Alpine belt.

The Ph.D. project was hence based on combined field survey, petrographic observations, and thermodynamic modeling. Field investigations were carried out in order to study the stratigraphic relationships and the present-day juxtaposition among different rock bodies. Petrographic observations (combined with mineral chemistry analyses) were carried out in order to define the blastesis/deformation relationships and constrain tectono-metamorphic events in the different tectonic units, correlating mesoscale and microscale data. Thermodynamic modeling allowed to reconstruct the P-T paths followed by each unit during the Alpine metamorphic evolution.

The overall intent of this work was to propose a reconstruction of the tectono-metamorphic evolution of the axial sector of the Alpine chain in the Cottian Alps, considering the new lithostratigraphic and metamorphic data. The hope is to lead to a better interpretation of the geological features and geometric relationships of four tectonic units, to unravel their syn-rift tectonic history and their following Alpine evolution.

## GEOLOGICAL SETTING OF THE STUDIED AREA

Based on geophysical investigations (Roure et al., 1996; Pfiffner et al., 1997), the Western Alps can be subdivided in three sectors: i) the inner part of the chain, the Adriatic paleo-margin representing the upper plate of the collisional system; ii) the outer part of the chain, the European paleo-margin representing the lower plate; iii) the axial sector, where units from the oceanic lithosphere, European and Adriatic crust are tectonically juxtaposed. This sector can be further subdivided (Malusà et al., 2011) in Cretaceous wedge, the Eocene Eclogite belt, and the Frontal Wedge (both made of continental- and oceanic-derived Penninic units). The axial sector is characterized by a wide range of peak Alpine metamorphism (from UHP eclogite-facies to greenschist-facies conditions) and is characterized by a double vergence, towards the inner and outer part of the chain.

The studied units belong to the Ligurian-Piedmont Zone (LPZ hereafter) cropping out in the upper Susa Valley and Chisone valleys. In their general traits, the units ascribed to the LPZ are made of widespread calcschists embedding ophiolitic bodies. Locally in the studied area, sectors of crystalline basement rocks with associated carbonate meta-sedimentary covers occur (i.e., the Ambin massif and the here discussed Banchetta-Rognosa tectonic unit).

Well known and studied since the dawn of geological studies (e.g., Barale et al., 2022; Mosca & Barale, 2022), the LPZ cropping out in the considered area can be subdivided into different units taking into account the tectono-stratigraphic records (Servizio Geologico d'Italia, 2002, 2020) an/or the structural setting and metamorphic conditions (Agard et al., 2001; Beyssac et al., 2002; Agard, 2021).

From a general point of view, the studied units fall in the blueschist-facies domain (Bousquet et al., 2008): i) the Albergian and Lago Nero units belong to the blueschist-facies units of the LPZ, mainly made of calcschists and meta-ophiolitic bodies, ii) the Banchetta-Rognosa

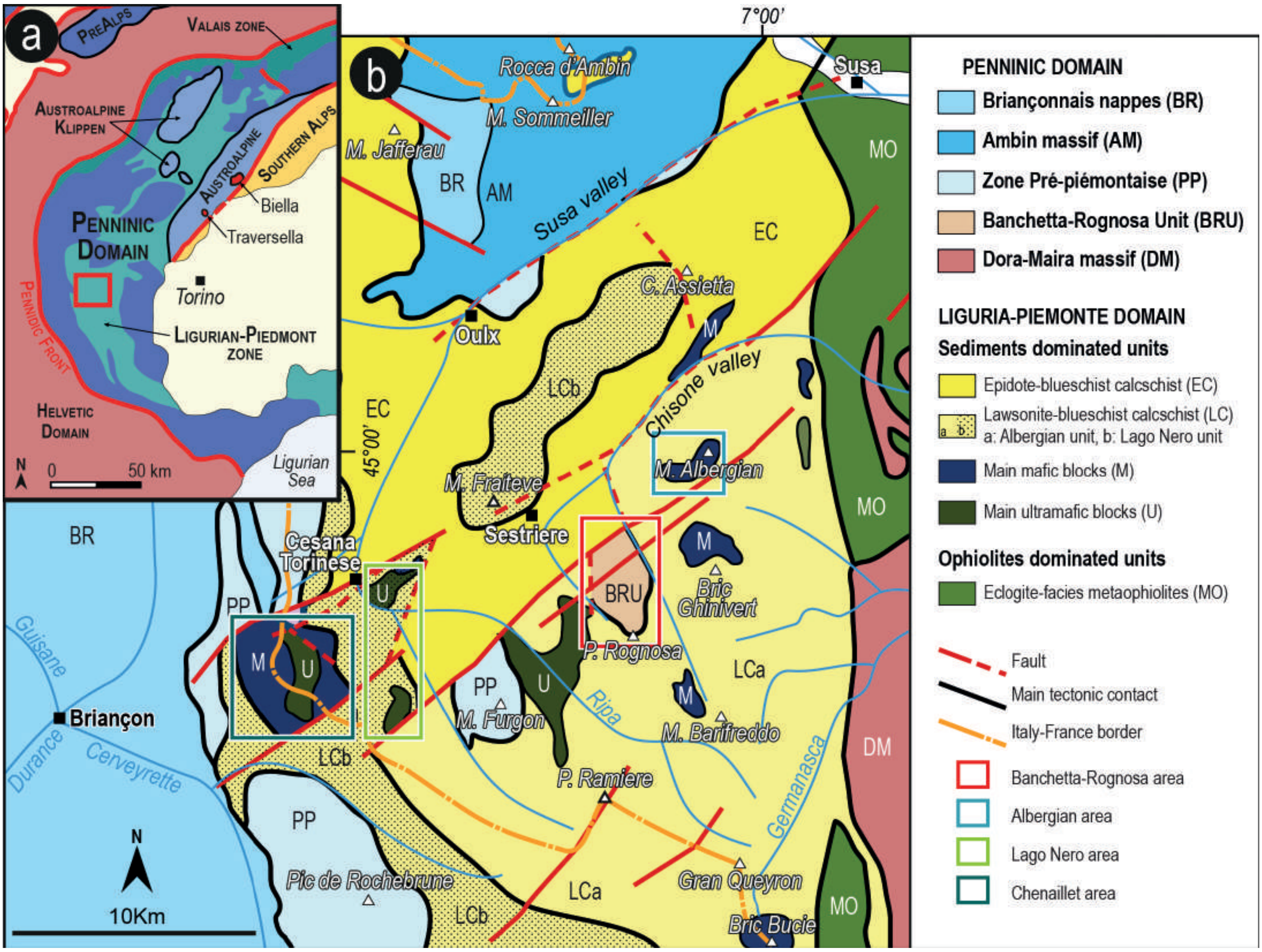


*Figure 1* ***a)*** *Simplified tectonic map of the Western Alps (redrawn and modified from Bigi* et al.*, 1990).* ***b)*** *Schematic geological map of the upper Susa and Chisone valleys (modified from Corno* et al.*, 2021b), the studied units and areas are highlighted with different colored squares.*

unit represents a tectonic unit made of both continental- and oceanic-derived rocks, recording eclogite-facies conditions (Corno et al., 2021), iii) the Chenaillet ophiolite has historically been described as a portion of oceanic lithosphere with no sedimentary cover, which escaped Alpine HP metamorphism, although this project found evidence of LT-blueschist metamorphism (Corno et al., 2023).

In last years, several authors focused on the reconstruction of pre-collisional paleo-geographic setting, by comparison with studies on modern tectonic plate boundaries and architecture of ocean floors (Mohn et al., 2012, 2014; Festa et al., 2015; Lagabrielle et al., 2015; Decarlis et al., 2017; Tartarotti et al., 2021). Similar studies are quite difficult for units forming the HP-axial sector of the Alpine belt (e.g. Beltrando et al., 2012, 2014). This study aimed to try to restore the relative positions of the four studied units with respect to the continental margins and the complex framework of the Alpine Tethys.

## THE STUDIED UNITS

### The Banchetta -Rognosa tectonic unit

The Banchetta-Rognosa tectonic unit (BRU hereafter) consists of two juxtaposed successions respectively recording the Mesozoic tectono-depositional evolution of (i) a continental margin, i.e., Monte Banchetta succession, and (ii) a neighboring oceanic sector, i.e. Punta Rognosa succession, both covered by the same post-rift sediments consisting of Upper Jurassic?-Cretaceous carbonate micaschist. Several papers by the Authors focused on the lithostratigraphy, petrography, and metamorphic evolution of the oceanic succession (Corno et al., 2019) as well as the continental one (Corno et al., 2021a, b). The result of extensive and detailed lithostratigraphic and structural field studies (supported by petrographic analyses) are reported in a 1:6,500 scale geological map (Corno et al., 2021a), which focuses also on the complex relationship between the two successions.

### *Main lithostratigraphic features of the BRU*

The oceanic succession (Corno et al., 2019), is made of serpentinized mantle overlain by syn-rift polymictic meta-breccia (with both oceanic- and continental-derived clasts) and discontinuous meta-sandstone bodies with dolostone clasts and blocks. The thick post-rift sequence is characterized by calcschist, locally embedding ophiolitic bodies.

On the other hand, the continental succession of the BRU, whose main features can be observed in the Troncea valley, is made of a crystalline basement (with minor polymetamorphic bodies), overlain by scarce levels of quartzite and a thick dolomitic sequence, followed by syn-rift carbonate-bearing quartzite, polymictic meta-breccia with quartzite and dolostone clasts within a carbonate matrix with fuchsite (Cr-bearing white mica), and black micaschist. Locally, discontinuous meta-sandstone bodies with dolostone clasts occur, quite similar to those occurring in the oceanic succession. Also, the continental succession is covered by the thick post-rift sequence made of calcschist, occurring on the oceanic succession.

### *Constrained metamorphic conditions*

For thermodynamic modeling purposes, a main focus has been given to the continental succession, better preserving the mineral assemblages useful for the isochemical phase diagram approach. However, thorough petrographic analyses have been carried out on both successions. Since conventional thermobarometry pointed to metamorphic conditions at the doorstep of the eclogite-facies field, the isochemical phase diagram approach proved to be necessary to better constrain the peak P-T conditions. Three samples, were selected on the basis of their mineral assemblages and proved to the most suitable for this kind of approach. More specifically, the HP tectono-metamoprhic evolution of the BRU was constrained based on a Cld+Ph-bearing glaucophanic schist (sample AC44), a Cld-bearing, partially retrogressed, glaucophanite (sample VT8), and a Jd-bearing gneissic micaschist. The isochemical phase diagrams were calculated in the system MnNKFMASOH (MnO-$Na_2O$-$K_2O$-FeO-MgO-$Al_2O_3$-$SiO_2$-$O_2$-$H_2O$) for samples AC44 and AC74 and in the system NKFMASOH ($Na_2O$-$K_2O$-FeO-MgO-$Al_2O_3$-$SiO_2$-$O_2$-$H_2O$) for sample VT8 (see Corno et al., 2021b for more details).

The three modeled peak P-T conditions (based on observed mineral assemblages and compositional isopleths for chloritoid and amphibole) are: i) 21-22 kbar and 450±25°C for the Cld-Ph bearing glaucophanic schist (AC44); ii) 21-22.5 kbar and 450±20°C for the Cld-bearing glaucophanite (VT8); iii) 21-23 kbar and 470±50°C for the Jd-bearing gneissic micaschist.

Hence, based on the intersection of predicted ellipses, common peak P-T conditions can be constrained at 20–23 kbar and 440–500°C (Corno et al., 2021b).

## The Albergian unit

In its general features, the Albergian unit (AU hereafter) is made of a thick succession of Cretaceous calcschist wrapping scattered blocks of oceanic lithosphere (i.e., serpentinite, meta-gabbro and metabasite), locally covered by a thin supra-ophiolitic sequence. The AU embeds the Banchetta-Rognosa tectonic unit, while being juxtaposed to the Lago Nero unit by a NE-SW high angle fault system.

### *Main lithostratigraphic features of the AU*

In order to investigate the pre-collisional evolution of the oceanic sectors sampled by the AU, this study detailed the lithostratigraphic successions exposed along the Albergian-Gran Mioul mountain ridge, located to East with respect to the village of Pragelato (upper Chisone valley).

In this area, a pluri-hm body of meta-mafic rocks (gabbro apophysis and their volcanic and volcano-sedimentary cover) is embedded by heterogenous calcschist.

In order to show the complex relationships between different lithologies, five lithostratigraphic logs from different localities have been analyzed, consisting of a clast-supported meta-breccia, dominated by metabasite clasts and blocks, with minor doleritic and gabbro clasts. In addition, rare meta-plagiogranitic clasts have been found, wrapped by the same mafic matrix. The whole meta-mafic body is covered by discontinuous levels of quarzitic meta-sandstone and and/or discontinuous levels of black micaschist, followed by a thick sequence of calcschist.

### *Constrained metamorphic conditions*

The isochemical phase diagram approach was carried out on two samples in order to constrain the peak P-T conditions: i) a Grt+Omp Mg-Al metagabbro (sample 5482) and ii) a plagiogranitic meta-breccia (sample 5681). For this latter one, due to the significant difference in bulk compositions related to different mineral assemblages and proportion, two distinct phase diagrams were calculated, one for the plagiogranitic clasts, and one for the mafic matrix. The P-T pseudosection for sample 5482 was calculated in the system MnNCFMASTH (MnO-$Na_2O$-CaO-FeO-MgO-$Al_2O_3$-$SiO_2$-$TiO_2$-$H_2O$). For sample 5681, the P-T pseudosection of the plagiogranitic clasts was calculated in the system NCKFMASTOH ($Na_2O$-CaO-$K_2O$-FeO-MgO-$Al_2O_3$-$SiO_2$-$TiO_2$-$O_2$-$H_2O$), while that for the mafic matrix was calculated in the system NCKFMASTH ($Na_2O$-CaO-$K_2O$-FeO-MgO-$Al_2O_3$-$SiO_2$-$TiO_2$-$H_2O$). For further details and the representative analyses of the mineral phases occurring in these two samples, please refer to Corno et al., 2022. Modeled peak P-T conditions (based on observed mineral assemblages and compositional isopleths for garnet, white mica, and clinopyroxene) are: i) 21±1.5 kbar and 450±30°C for the Mg-Al meta-gabbro sample 5482; ii) 18 ± 2 kbar and 410±20°C for the matrix and 21-24 kbar and T < 430°C for the meta-plagiogranitic clasts of sample 5681. Hence, based on the partial overlap of predicted ellipses, common peak P-T conditions can be constrained at 18-20 kbar and 380-420 °C (Corno et al., 2022).

## The Lago Nero unit

The Lago Nero unit (LNU hereafter) is made of oceanic lithosphere covered by a meta-sedimentary sequence similar to the ones of the non-metamorphic Ligurian units of the Apennines. The southern portion of the unit is characterized by a pretty continuous oceanic basement, from the serpentinized exhumed mantle, meta-basalts and syn- and post-rift covers. On the other hand, in the northern portion, only scattered blocks of oceanic lithosphere occur, and the vast majority of the unit is made of post- and minor syn-rift meta-sedimentary rocks.

### *Main lithostratigraphic features of the LNU*

The complex lithostratigraphy of the LNU has been studied mainly in two typical sectors, i.e. the area around the Lago Nero (orographic left, to the South with respect to Cesana T.se) and the M. Cruzore area (orographic right, to the North with respect to Cesana T.se).

In the Lago Nero section the exhumed mantle (i.e. serpentinite) is covered by meta-limestone (i.e. marble), characterized by thick pluri-decimetric bedding. This marble formation displays gradual transition to the Replatte formation (Lemoine, 1971), made of an alternance of calcschist and marble levels attributed to the Palombini shales of Cretaceous age. The Replatte formation at different lithostratigraphic levels envelopes both oceanic- and continental-derived clasts and blocks. Oceanic blocks are made of metabasite s.l. (meta-basalt, greenstone, mafic meta-breccia, meta-gabbro, etc.) and ophicarbonate rocks. Continental-derived clasts and blocks occur in smaller dimension, from centimetric to pluri-metric, and usually towards the stratigraphic lows of the Replatte formation. They are mainly made of marble and dolostone blocks, and minor clasts of crystalline basement rocks (i.e. micaschist and quartzite). The Gondran flysch follows upwards, made by an alternance of calcschist and meta-sandstone. In the area around the Cima Fournier the transition between Replatte formation and Gondran flysch is marked by grey to black schists (black shales according to Barfety et al., 1996). The Gondran flysch, up to 20 m in thickness, is mainly made of thin calcschist layers alternated with minor coarse-grained meta-sandstone layers. The following Rocher Renard complex is made by scattered blocks, up to decametric in size, embedded by dark schist. Blocks and clasts come from an oceanic lithosphere and its meta-sedimentary cover. Meta-ophiolitic blocks are made of meta-basalt, ophicarbonate rocks, serpentinite, and meta-gabbro. Blocks from the meta-sedimentary cover are made of marble and calcschist, presumably from the Replatte formation. Locally, smaller blocks and clasts of meta-chert has been observed.

The M. Cruzore section is made of serpentinite, representing a portion of exhumed mantle (Gambino et al., 2022). In addition, the oceanic crust comprises scattered meta-basalt and meta-gabbro bodies, from plurimetric to pluridecametric in size. Within the meta-mafic rocks a partial lithostratigraphic sequence can be provided, with pillow-like structures observable in the lowermost stratigraphic levels and rimmed by local hyaloclastite and variolite, while brecciated structures with variolite occur in the uppermost levels. Locally, in the upper part of this mafic sequence, where meta-mafic breccias occur, clasts of plagiogranitic compositions have been found. Scarce, decimetric meta-microconglomeratic levels occur in these meta-mafic rocks. These levels broadly represent the transition between the underlying preserved pillow meta-basalts and the overlying mafic meta-breccia (made of reworked pillow basalts). These levels display a brecciated, matrix-supported texture, with mm to pluri-mm clasts dispersed in a fine-grained matrix.

The transition between meta-mafic rocks and the first syn-rift meta-sediments is well observable on the southern slopes of the M. Cruzore. In this sector, reworked fragments of pillow meta-basalt are intercalated with thin layers of meta-chert. This level is then topped by the lower part of the meta-radiolarite formation, showing in turn thin intercalations of mafic debris. This meta-radiolarite sequence is made by two main terms: a lower part of grey and/or green quartzite, gradually fading into an upper red fine-grained meta-shale. Locally, ghosts of the original radiolarians can still be found as small round shapes forming the rocks.

### *Constrained metamorphic conditions*

Metamorphic conditions of the LNU have been constrained with the conventional thermobarometry approach, combined with microstructural observations and chemical analyses. As for the other units, mainly the mafic rocks of the LNU have been used to constrain the Alpine peak conditions. However, also the detrital bodies (meta-microconglomerate, etc.) have provided useful constrains. The peak event is defined by the Na-clinopyroxene + lawsonite ± Na-amphibole ± talc ± white mica + rutile mineral assemblage. The widespread occurrence of fresh lawsonite constrains P-T peak conditions at minimum ~17 kbar and maximum of 400-450°C. The occurrence of rare talc + acmite assemblage in metagabbro confirms this estimation (as reported by Corona et al., 2013). These conditions are in agreement with the high Si content of phengite occurring both in basic and detrital rocks (Si up to 3.70 a.p.f.u.), as suggested by the phengite barometry of Massonne & Schreyer (1987). The maximum extension of the stability field of the talc + jadeite association (as reported by Corona et al., 2013) can sensibly be influenced by $Fe^{3+}$ ratio, clinopyroxene composition and the peculiar occurrence of Na-amphibole.

## The Chenaillet ophiolite

The Chenaillet Ophiolite represents a very well-preserved portion of Ligurian-Piedmont ocean in the Western Alps. Historically, the Chenaillet Ophiolite has been known for its very low temperature - low pressure (LT-LP) Alpine metamorphism, ascribed to obduction processes. However, studies aimed at constraining the peak P-T conditions of Alpine metamorphism are virtually lacking, the general focus having been so far on its high temperature (HT) metamorphism and geochemical features.

### *Main lithostratigraphic features of the LNU*

The Chenaillet Ophiolite (CO hereafter) is made of an oceanic lithospheric succession comprising exhumed mantle, various mafic intrusives (i.e. gabbro sensu lato) and a world renown sequence of pillow basalts. Apart from scarce breccias closely related to oceanic lithosphere (Bertrand et al., 1980), post-rift Late Jurassic to Cretaceous sedimentary rocks are absent, in contrast with the neighboring oceanic units which comprise a large amount of post-rift meta-sedimentary rocks.

Mantle peridotite consists of strongly serpentinized lherzolite and harzburgite, with minor pyroxenite, dunite and wehrlite (Bertrand et al., 1980). Within the highly serpentinized mantle rocks, a thin sequence of layered troctolite and olivine-bearing gabbro less than 1 km in diameter occurs, cross-cut by diorite, dolerite, and basalt dykes. Dolerite, diorite, and basalt dykes usually occur within sheared gabbro, close to high-angle normal faults. Albitite/alkali syenite bodies occur as dikes and sills at the serpentinized peridotite-gabbro boundary throughout the massif (Chalot-Prat, 2005). The well-known volcanic sequence of the CO consists of lava flows, pillow basalts, pillow breccias, and hyaloclastites, with strong affinities with MORB (Mid-Oceanic Ridge Basalt) series.

### *Constrained metamorphic conditions*

The isochemical phase diagram approach was carried out on a gabbro sample in order to constrain the peak P-T conditions: This specific gabbro sample was selected for the thermodynamic modeling because it preserves very well the Alpine peak mineral assemblage (e.g. it contains 6% of lawsonite) and it is devoid of white mica and epidote (both <0.5%), thus allowing to simplify the system by neglecting $K_2O$ and $Fe_2O_3$. The P-T pseudosection was calculated in the system MnNCFMASTH (MnO-$Na_2O$-CaO-FeO-MgO-$Al_2O_3$-$SiO_2$-$TiO_2$-$H_2O$). For sample 5681, the P-T pseudosection of the plagiogranitic clasts was calculated in the system NCFMASTH ($Na_2O$-CaO-FeO-MgO-$Al_2O_3$-$SiO_2$-$TiO_2$-$H_2O$). The fluid saturation assumption and the effects of $Fe^{+3}$ on the stability of the observed peak mineral assemblage were investigated by calculating two P-M($H_2O$) (mol%) and two P-X($Fe_2O_3$) isochemical phase diagrams at T = 300°C and T = 350°C, available in Corno et al., 2023. For further details and the representative analyses of the mineral phases occurring in these two samples, please refer to Corno et al., 2023. The unfractionated bulk composition (i.e. the measured bulk), was used for modeling, including both the magmatic and HT-related mineral relicts (i.e. clinopyroxene and HT Ca-amphibole respectively). Modeled peak P-T conditions (based on observed mineral assemblages) constrain a minimum of 9 kbar and 350°C to a maximum of 15 kbar and 450°C, which are compatible with a geothermal gradient of 8-10°C/km.

Alpine peak P-T conditions are further constrained by the overlap with the P-T peak conditions estimated for an albitite sample (made of up to 90% of albite, omphacite, Ca-amphibole and titanite), delimited by the phase-in curves defined for the mafic system according to Harlow et al. (2015). The overlap between the peak P-T conditions inferred for the albitite and the large stability field of the gabbro assemblage predicted by thermodynamic modeling, further constrains peak Alpine metamorphism at 10-11 kbar and 340-360°C (Corno et al., 2023).

## FINAL REMARKS

The challenge of this Ph.D. project was to provide new data to constrain the positions of different Ligurian-Piedmont units within the pre-collisional paleogeographic setting as well as their Alpine tectono-metamorphic evolution.

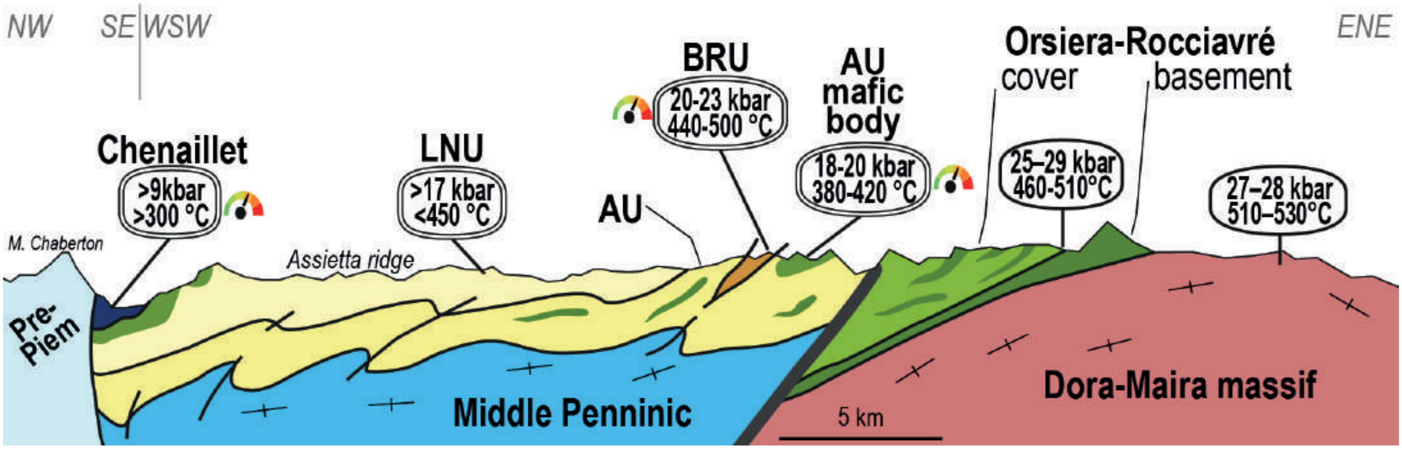


*Figure 2* *Schematized cross-section along the studied area in the upper Susa and Chisone vallyes (exaggerated vertical scale). Peak P-T estimates modeled by the Author are highlighted with small barometer icons (Chenaillet, BRU and AU mafic body). The estimations displayed for the other units are according to the most recent literature available: Manzotti* et al., *2022, for Dora-Maira massif; Ghignone* et al., *2021, for the Orsiera-Rocciavrè meta-ophiolite (i.e. Internal Piedmont Zone).*

## Paleogeographic restoration

The Banchetta-Rognosa unit (BRU) sampled a portion of the ocean-continent transition zone, were continental crust and exhumed mantle were adjacent in Mesozoic times (see Corno et al., 2019, 2021a, 2021b). Moreover, the two successions share a common tectono-metamorphic evolution since the earliest event, suggesting that they were already adjacent before (or during) the onset of subduction and Alpine deformation.

In their general features, the Lago Nero unit and the Albergian unit consist of widespread and thick sequences of calcschist, embedding meta-ophiolite bodies. The syn- to lower post-rift deposits of the LNU are characterized by a more abundant continental-derived scree in the detrital levels/bodies (with preserved K-feldspar and zircons) and a coarser grain with larger and angular clasts with respect to the fine-grained quarzitic meta-sandstones of the AU (Corno et al., 2022). These features suggest that the LNU includes continental-derived (meta-) sediments less mature than the AU ones. The meta-sediments of the LNU suffered less transportation than those of the AU and hence an original location of the Lago Nero unit closer to the continental margin can be envisaged.

The Chenaillet ophiolite (CO), as reported by many authors (see Manatschal et al., 2011; Balestro et al., 2019) sampled a portion of oceanic lithosphere, characterized by exhumed mantle, intruded by gabbroic stocks and overlain by basaltic lavas.

Based on these observations, it can be inferred as a major and general conclusion that the LPZ units exposed in the upper Susa and Chisone valleys include different sectors (i.e. units) of the Alpine Tethys, sampled during subduction, and originally occurring in structural highs or in the hanging-wall of detachment faults. These rock bodies were uprooted from the oceanic lithosphere and currently occur embedded in the widespread post-rift meta-sediments within the meta-sedimentary dominated units of the Ligurian-Piedmont zone.

## Tectono-metamorphic evolution

The Alpine metamorphic evolution of the units exposed in the investigated area of the Western Alps has been investigated using for the first time the isochemical phase diagram approach.

In particular, the constrained Alpine metamorphic peak conditions are (Fig. 2):

- 20-23 kbar and 440-500°C for the Banchetta-Rognosa unit;
- 18-20 kbar and 380-420°C for the Albergian-Gran Mioul body of the Albergian unit;
- > 9 kbar and >300°C for the Chenaillet ophiolite.

Hence, it is worth stressing that:

- the BRU could represent one of the westernmost eclogitic unit of the Western Alps. This assumption derives from comparison of the peak metamorphic conditions of the BRU with respect to the ones of other eclogitic units on the Middle Penninic known in literature (see Corno et al., 2021b; Fig. 3);

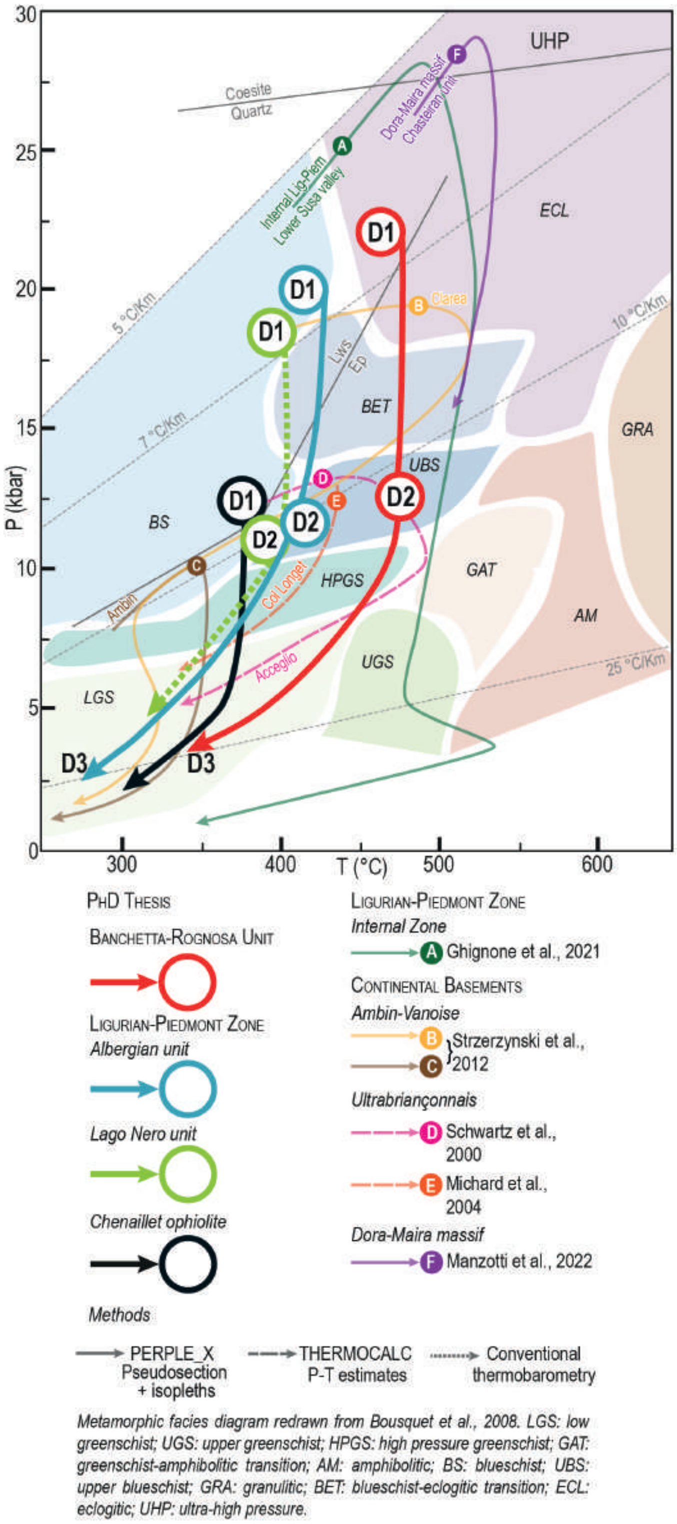


*Figure 3* *Compilation of P-T paths of different units of the Western Alps, for comparison with the studied units from the upper Susa and Chisone valleys. Studied units (Banchetta-Rognosa unit, Albergian unit, Lago Nero unit, and Chenaillet ophiolite) are reported with thicker lines. Peak conditions were constrained with the isochemical phase diagram approach, while the retrograde exhumation part of the path was qualitatively inferred in the basis of mineral assemblages. Different line patterns indicate different thermobarometric methods, as reported in the legend. Lws-Ep reaction is from Poli & Schmidt (1995), modified below 10 kbar for the modeled bulk compositions.*

- the general westward decrease in metamorphic peaks is abruptly interrupted by the eclogitic BRU, tectonically embedded within the lawsonite-blueschist AU (Fig. 2). The present emplacement of the BRU within the (slightly) lower grade AU can be tentatively explained taking into account a trans-tensional tectonic regime during exhumation;
- in the blueschist-facies AU and LNU the good and widespread preservation of fresh lawsonite can be related to favorable Ca-rich bulk compositions and fast exhumation processes;
- the new and surprising data on the Alpine metamorphic evolution of the Chenaillet ophiolite (previously considered as anchi- or non-metamorphic) invoke for subduction related processes. Therefore, the Chenaillet ophiolite must be considered in the description of the general westward decreasing of Alpine peak metamorphic conditions (Fig. 2,3).
- this latter assumption brings with it the consequence that the geothermal gradient along the subduction channel, in this sector of the Western Alps (8°C/km according to Agard, 2021), could be revised and lowered to 6-7°C/km (Fig. 3).

## REFERENCES


Agard, P., Jolivet, L., & Goffe, B. (2001): Tectonometamorphic evolution of the Schistes Lustres Complex; implications for the exhumation of HP and UHP rocks in the Western Alps. *B. Soc. Geol. Fr.*, **172(5)**, 617-636.

Agard, P. (2021): Subduction of oceanic lithosphere in the Alps: Selective and archetypal from (slow-spreading) oceans. *Earth Sci. Rev.*, 103517.

Balestro, G., Festa, A., & Dilek, Y. (2019): Structural architecture of the Western Alpine Ophiolites, and the Jurassic seafloor spreading tectonics of the Alpine Tethys. *J. Geol. Soc.*, **176(5)**, 913-930.

Barale, L., Console, F., Corno, A., Frasca, G., Mosca, P., & Pantaloni, M. (2022): The geology of the Western Alps through the field notebooks of Secondo Franchi (1859-1932). *Ital. J. Geosci.*, **141(1)**, 120-143.

Barfety, J. C., Lemoine, M., Graciansky, P. C. (de), Tricart, P., & Mercier, D. (1996): Notice explicative, carte géologique de la France (1/50 000), feuille Briançon (823). *Bureau de Recherche Géologiques et Minières*, Orléans.

Beltrando, M., Frasca, G., Compagnoni, R., & Vitale-Brovarone, A. (2012): The Valaisan controversy revisited: Multi-stage folding of a Mesozoic hyper-extended margin in the Petit St. Bernard pass area (Western Alps). *Tectonophysics*, **579**, 17-36.

Beltrando, M., Manatschal, G., Mohn, G., Dal Piaz, G. V., Vitale Brovarone, A., & Masini, E. (2014): Recognizing remnants of magma-poor rifted margins in high-pressure orogenic belts: The Alpine case study. *Earth Sci. Rev.*, **131**, 88-115.

Bertrand, J., Steen, D. M., Tinkler, C., & Vuagnat, M. (1980): The melange zone of the col du Chenaillet (Montgenèvre ophiolite, Hautes-Alpes, France). *Arch. Sci.*, **33(2-3)**, 117-138.

Beyssac, O., Rouzaud, J. N., Goffé, B., Brunet, F., & Chopin, C. (2002): Graphitization in a high-pressure, low-temperature metamorphic gradient: a Raman microspectroscopy and HRTEM study. *Contrib. to Mineral. Petrol.*, **143**, 19–31.

Bigi, G., Castellarin, A., Coli, M., Dal Piaz, G. V., Sartori, R., Scandone, P., & Vai, G.B. (1990): Structural Model of Italy scale 1:500.000, sheet 1. C.N.R., Progetto Finalizzato Geodinamica, SELCA Firenze.

Bousquet, R., Oberhänsli, R., Goffé, B., Wiederkehr, M., Koller, F., Schmid, S. M., Schuster, R., Engi, M., Berger, A., & Martinotti, G. (2008): Metamorphism of metasediments at the scale of an orogen: a key to the Tertiary geodynamic evolution of the Alps. *Geol. Soc. London*, **298(1)**, 393-411.

Chalot-Prat, F. (2005): An undeformed ophiolite in the Alps: Field and geochemical evidence for a link between volcanism and shallow plate tectonic processes. *Geol. Soc. Am. Spec. Pap.*, **388**, 751.

Corno, A., Mosca, P., Borghi, A., & Gattiglio, M. (2019): Lithostratigraphy and petrography of the Monte Banchetta-Punta Rognosa oceanic succession (Troncea and Chisonetto Valleys, Western Alps). *Ofioliti*, **44(2)**, 83-95.

Corno, A., Mosca, P., Gattiglio, M., & Borghi, A. (2021a):-Geological map of the Monte Banchetta – Punta Rognosa area (Troncea valley, Western Alps). *J. Maps*, **17(2)**, 150-160.

Corno, A., Groppo, C., Mosca, P., Borghi, & Gattiglio, M. (2021b): Eclogitic metamorphism in the Alpine far-west: petrological constraints on the Banchetta-Rognosa tectonic unit. *Swiss J. Geosci.*, 114:16.

Corno, A., Mosca, P., Groppo, C., Borghi, A., & Gattiglio, M. (2022): More widespread than supposed: preserved lawsonite in the blueschist-facies ophiolitic bodies from the Albergian unit (Liguria-Piemonte zone, Western Alps). *Ofioliti*, **47(2)**, 137-154.

Corno, A., Groppo, C., Borghi, A., Mosca, P., & Gattiglio, M. (2023): To be or not to be Alpine: New petrological constraints on the metamorphism of the Chenaillet Ophiolite (Western Alps). *J. Metamorph. Geol.*, 1-21.

Corona, J.C., Jenkins, D. M., & Holland, T.J.B. (2013): Constraints on the upper pressure stability of blueschist facies metamorphism along the reaction: glaucophane = talc + 2 jadeite in the $Na_2O$-$MgO$-$Al_2O_3$-$SiO_2$-$H_2O$ system. *Am. J. Sci.*, **313**, 967-995.

Dal Piaz, G. V., Bistacchi, A., & Massironi, M. (2003): Geological outline of the Alps. *Episodes J. Int. Geosci.*, **26(3)**, 175-180.

Decarlis, A., Beltrando, M., Manatschal, G., Ferrando, S., & Carosi, R. (2017): Architecture of the distal Piedmont-Ligurian rifted margin in NW Italy: Hints for a flip of the rift system polarity. *Tectonics*, **36(11)**, 2388-2406.

Festa, A., Balestro, G., Dilek, Y., & Tartarotti, P. (2015): A Jurassic oceanic core complex in the high-pressure Monviso ophiolite (western Alps, NW Italy). *Lithosphere*, **7(6)**, 646-652.

Gambino, F., Agostoni, A., Barale, L., Bonetto, S., Borghi, A., Corno, A., & Mosca, P. (2022): Il Verde Cesana: una storica pietra ornamentale delle Alpi Occidentali. *In*: Bove, A., Masciocco, L., Sassone, P. Geologia Ambientale in Piemonte e Valle d'Aosta. Monografie di Geologia Ambientale. *Edizioni SIGEA*, 124-128.

Ghignone, S., Borghi, A., Balestro, G., Castelli, D., Gattiglio, M., & Groppo, C. (2021): HP tectono-metamorphic evolution of the Internal Piedmont Zone in Susa Valley (Western Alps): New petrologic insight from garnet+ chloritoid-bearing micaschists and Fe–Ti metagabbro. *J. Metamorp. Geol.*, **39(2)**, 391-416.

Harlow, G. E., Tsujimori, T., Sorensen, S. S. (2015): Jadeitites and Plate Tectonics. *Annu. Rev. Earth Planet Sci.*, **43**, 105–138.

Lagabrielle, Y., Brovarone, A. V., Ildefonse, B. (2015): Fossil oceanic core complexes recognized in the blueschist metaophiolites of Western Alps and Corsica. *Earth Sci. Rev.*, **141**, 1-26.

Malusà, M. G., Faccenna, C., Garzanti, E., Polino, R. (2011): Divergence in subduction zones and exhumation of high pressure rocks (Eocene Western Alps). *Earth Planet. Sci. Lett.*, **310(1-2)**, 21-32.

Manatschal, G., Sauter, D., Karpoff, A. M., Masini, E., Mohn, G., Lagabrielle, Y. (2011): The Chenaillet ophiolite in the French/Italian Alps: An ancient analogue for an oceanic core complex? *Lithos*, **124(3-4)**, 169–184.

Manzotti, P., Schiavi, F., Nosenzo, F., Pitra, P., & Ballèvre, M. (2022): A journey towards the forbidden zone: a new, cold, UHP unit in the Dora-Maira Massif (Western Alps). *Contrib. to Mineral. Petrol.*, **177(6)**, 59.

Massonne, H. J. & Schreyer, W. (1987): Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite and quartz. *Contrib. to Mineral. Petrol.*, **96**, 212-224.

Mohn, G., Manatschal, G., Beltrando, M., Masini, E., & Kusznir, N. (2012): Necking of continental crust in magma-poor rifted margins: Evidence from the fossil Alpine Tethys margins. *Tectonics*, **31**, TC1012.

Mohn, G., Manatschal, G., Beltrando, M., & Haupert, I. (2014): The role of rift-inherited hyper-extension in Alpine-type orogens. *Terra Nova*, **26**, 347-353.

Mosca P. & Barale L. (2022): Geological explorations in the Italian-French cross-border areas (Western Alps) from 19th to early 20th century. *Rend. Online Soc. Geol. It.*, **57**, 2-16.

Pfiffner, O.A., Lehner, P., Heitzmann, P., Mueller, St., & Steck, A. (1997): Deep structure of the Swiss Alps. Birkhäuser Verlag, Basel, 380 p.

Poli, S. & Schmidt, M.W. (1995): $H_2O$ transport and realase in subsuction zones: Experiemental constraints on basaltic and andesitic systems. *J. Geophys. Res.*, **100**, 22299-22314.

Roure, F., Choukroune, P., & Polino, R. (1996): Deep seismic reflection data and new insights on the bulk geometry of mountain ranges. *C. R. Acad. Sci.* Série 2. Sciences de la terre et des planètes, **322(5)**, 345-359.

SERVIZIO GEOLOGICO D'ITALIA (2002): Carta Geologica d'Italia alla scala 1:50.0000, F. 132-152-153 Bardonecchia Regione Piemonte, Direzione Regionale dei servizi Tecnici di Prevenzione. Litografia Geda, Nichelino. Torino.

SERVIZIO GEOLOGICO D'ITALIA (2020): Carta Geologica d'Italia alla scala 1:50.0000, F. 171 Cesana. http://www.isprambiente.gov.it/Media/carg/171_CESANA_TORINESE/Foglio.html.

Tartarotti, P., Martin, S., Festa, A., & Balestro, G. (2021): Metasediments Covering Ophiolites in the HP Internal Belt of the Western Alps: Review of Tectono-Stratigraphic Successions and Constraints for the Alpine Evolution. *Minerals*, **11(4)**, 411.