

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

**Geological map of the upper Gressoney Valley, Western Italian Alps.**

**This is the author's manuscript**

*Original Citation:*

*Availability:*

This version is available <http://hdl.handle.net/2318/97283> since

*Published version:*

DOI:10.4113/jom.2011.1121

*Terms of use:*

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)



# UNIVERSITÀ DEGLI STUDI DI TORINO

***This is an author version of the contribution published on:***

*Questa è la versione dell'autore dell'opera:*

*[[Journal of maps](#), 2011, doi:10.4113/jom.2011.1121]*

*ovvero [Ivano Gasco and Marco Gattiglio, Taylor and Francis, 2011, pagg.82-102]*

***The definitive version is available at:***

*La versione definitiva è disponibile alla URL:*

*[<http://www.journalofmaps.com/>]*

# Geological map of the upper Gressoney Valley, Western Italian Alps

Ivano Gasco<sup>1\*</sup>, Marco Gattiglio<sup>1</sup>

<sup>1</sup>Dipartimento di Scienze della Terra, Università degli Studi di Torino, Via Valperga Caluso 35, I-10125 Torino, Italy

\* Corresponding Author: Phone: +39 011 6705335; Fax: +39 011 6705339; E-mail: ivano.gasco@unito.it

**Abstract.** A detailed geological mapping of the upper Gressoney Valley in the Western Italian Alps has permitted us to reconstruct the lithostratigraphy and the structural evolution of three different tectonic units: the Monte Rosa Massif and the Zermatt-Saas Zone and The Combin Zone. The studied nappes can be grouped into a Lower Tectonic Element which underwent eclogite facies metamorphism (Monte Rosa Massif and Zermatt-Saas Zone) and an Upper Tectonic Element (Combin Zone) pervasively equilibrated under greenschist facies conditions and lacking mesoscale evidences of high pressure metamorphism. The reconstruction of the lithostratigraphy and the mapping of the different generations of tectonic contacts between the different units allowed us to infer the presence of different generations of tectonic contacts separating oceanic and continental crust units.

**Keywords:** tectono-metamorphic evolution, Combin Zone, Zermatt-Saas Zone, Monte Rosa Massif, Western Italian Alps.

## 1. Introduction

The geological and tectonic maps presented in this work are the result of a PhD thesis and were surveyed during the summer seasons between 2007 and 2009. They contain information on the bedrock lithostratigraphy and on the deformation stages imprinted during the Alpine orogenic cycle.

The upper Gressoney Valley is located in the north-eastern part of the Aosta Valley region and *ca* 100 km north of the city of Torino (Fig. 1a). It exposes a geological section from the Monte Rosa Massif through the Piedmont Zone up to the Sesia-Lanzo Zone. The Monte Rosa Massif represents one of the three Internal Crystalline Massifs belonging to the Briançonnais terrain or to the European distal margin. Instead, the Sesia-Lanzo Zone is part of the Austroalpine Domain and is interpreted as the distal Adriatic margin (Avigad et al., 1993) or as an extensional allochthon within the Piedmont-Ligurian Ocean (Froitzheim et al., 1996). These continental crust units are separated by the Piedmont Zone representing the remnants of the Alpine Tethys (for a review see Dal Piaz, 1999). Along the Western Italian Alps the Piedmont Zone is separated into two main units, the Lower and the Upper one which are known as the Zermatt-Saas Zone (ZS) and the Combin Zone (CO), respectively in the southern Valais and northern Aosta Valley (Fig. 1b; Bearth, 1967; Dal Piaz, 1974; Dal Piaz and Ernst, 1978; Dal Piaz, 1999). The Zermatt-Saas and the Combin Zones are separated by a lithosphere-scale extensional shear zone, the Gressoney Shear Zone, responsible for the exhumation of eclogite facies rocks in its footwall (Reddy et al., 1999). The geological map covers an area of *ca* 8 km<sup>2</sup> sited on the right slope of the upper Gressoney Valley (Fig. 1b) up to the watershed with the Ayas Valley.

In the study area, two units originating from different palaeogeographic domains were investigated. From bottom to top and from north to south they are: the Monte Rosa Massif (Bearth, 1952; Dal Piaz, 2001 for a review) and the Piedmont Zone (Dal Piaz, 1999 for a

review). The purpose of this study was the reconstruction of the lithostratigraphy of the studied units, the unravelling of their Alpine structural evolution, the petrographic investigation of the different deformation stages and the determination of the relative age of the tectonic contacts which separates the studied units.

**Fig. 1.** a) Simplified tectonic map of the Western Italian Alps (modified after Schmid *et al.*, 2004). The black box is enlarged in b). b) Simplified geological map of the Monte Rosa Massif (MR) and surrounding units (modified after Dal Piaz and Lombardo, 1986; Steck *et al.*, 1999; Pleuger *et al.*, 2005). The location of the study area is indicated with a red box on the southern margin of the MR.

## 2. Methodology

Geological mapping was performed at the scale 1:10,000 using the topographic maps (Carta Tecnica Regionale) released by the Regione Valle d'Aosta. During the field mapping, the regional foliation (i.e. the most pervasive metamorphic surface developed in rocks) was considered as the reference for the reconstruction of the structural evolution and was termed  $S_1$ . Lithologies and structural data collected were respectively drawn and stored with the software ArcGIS 9 from which a TIFF image of the geological map was exported. This output was then imported into Canvas X to assemble the final geological map at the scale 1:10,000. The cross sections were generally drawn perpendicular to the trend of the nappe contacts and to the regional foliation resulting in four NW-SE geological sections, one trending E-W and one NE-SW. These six cross sections give a representation of the three-dimensional

arrangement of the studied units. The alignment diagram of Nevin (1949) was thoroughly used for the determination of the apparent dip of the regional foliation.

The stereo diagrams reported in the geological map are equal-area projections plotted in the lower hemisphere with the software Stereonett and represent the structural features related to the different deformation phases identified in the study area. Abbreviations are as follows: S for syn-metamorphic foliation or axial surface of folds, L for stretching lineations and A for fold axes and intersection lineations, while subscripts denote the relative deformation phase. Minerals abbreviations are given according to Kretz (1983) with the update of Bucher and Frey (2002).

### **3. Lithostratigraphy**

The lithostratigraphy of the tectonic units outcropping in the study area is described from the deepest and northern unit, i.e. Monte Rosa Massif, towards the upper and southern one represented by the Combin Zone. The middle position is occupied by the Zermatt-Saas Zone.

The Monte Rosa Massif mainly consists of medium to coarse-grained garnet micaschists with layers of meta-intrusive comprising orthogneisses and aplitic dikes. The garnet micaschists show many intercalations of metabasite boudins (Fig. 2a) which locally are arranged along layers parallel to the regional foliation  $S_1$ . The metabasites comprise well-preserved eclogites and re-equilibrated epidote-albite amphibolites. Other intercalations within the garnet micaschists are fine-grained graphite-bearing micaschists (Fig. 2b) and albite micaschists (Fig. 2c). Both albite and graphite micaschists show transitional contacts towards the garnet micaschists (Fig. 2b-c) and are considered to be stratigraphic intercalations within an heterogeneous pre-Alpine basement.

The Zermatt-Saas Zone consists of a stack of tectonic slices comprising ultrabasic and basic rocks rarely overlain by a thin stratigraphic cover. The ultramafic rocks consist of foliated serpentinites that locally contain thin layers (max 50-60 cm thick) of meta-rodingites (Fig. 2d) and boudins of eclogites, while the metabasites comprise medium to coarse-grained Mg-Al metagabbros, epidote-albite amphibolites and eclogites interpreted as Fe-Ti metagabbros or metabasalts. Eclogites form coherent bodies up to 100 m long and of boudins (20 cm to 5 m) within re-equilibrated epidote-albite amphibolites. Some tectonic slices of eclogite (Fig. 2e) are present within serpentinites or metabasites east of the Bettaforca Pass and the contact with surrounding rocks is marked by Chl + Wm + Act schists. The cover sequence is scarce in the study area and is mainly constituted by garnet calcschists interposed with impure marbles and by subordinate micaschists and greenstones (layered Ab + Chl + Act + Ep schists interpreted as submarine volcanics) preserved SSE of the Bettaforca Pass (Battforko) and NE of the Sant'Anna (Sitten) church (Fig. 2f, see also the geological map).

**Fig. 2.** Main rock types of the Monte Rosa Massif: a) eclogite boudins within the garnet-micaschists; b) stratigraphic contact between garnet-micaschists and graphite-micaschists; c) transitional contact marked by stratigraphic intercalations (black arrows) between garnet-micaschists and albite-micaschists just below the tectonic contact with the Zermatt-Saas metabasites. Main rock types of the Zermatt-Saas Zone: d) boudinaged meta-rodingites layers within the serpentinites; e) well-preserved massive eclogite mantled by Chl + Act + Wm mylonites at the contact with serpentinites; f) overturned stratigraphic contact between metabasites and its oceanic cover consisting of carbonate rich calcschists and micaschists.

According to the literature (Dal Piaz, 1999 and references therein) the Combin Zone mainly consists of calcschists, minor metabasites and serpentinites and, at its base and only in the northern Aosta Valley, is characterized by the presence of the Pancherot-Cime Bianche-Bettaforca Unit (PCB).

The PCB represents a continental sequence similar to the Frilihorn Unit which represents the cover sequence of the Mont Fort nappe (Dal Piaz, 1988; Vannay and Allemann, 1990). In the study area at the Bettaforca Pass, the lithostratigraphic sequence is identical below and above the tabular quartzites of the PCB unit (Fig 3a-b) and the contact with the Combin Zone is stratigraphic (Fig 3c) and is marked by alternating marbles, calcschists and micaschists levels locally showing a micro-conglomeratic texture (see Fig. 8e). In detail this lithostratigraphic sequence consists of quartzites, grey to white marbles with calcschists interlayers, micaschists, calcschists with grey-yellowish marbles, micaschist, and calcschists with metabasites (Fig. 3d). The mylonites which generally developed along the lithological contacts are clearly later than the lithostratigraphic sequence and are related to the Gressoney Shear Zone (Reddy *et al.*, 1999) which crops out 15-30 m structurally below the PCB Unit (Fig. 3e). Finally, we consider the PCB as the stratigraphic substratum of the Combin calcschists, as already suggested by Dal Piaz (1965).

**Fig. 3.** Main rock types of the Upper Tectonic Element in the Gressoney Valley: a-b) general view of the lithostratigraphic sequence at the Bettaforca Pass. The black box in a) is enlarged in c); c-d) detailed stratigraphic sequence of the upper stratigraphic contact between the tabular quartzites of the PCB and the calcschists of the CO; e) mylonites related to the Gressoney Shear Zone crosscutting the reversed contact between quartzites and grey marbles.



The Combin Zone is a heterogeneous metasedimentary complex showing several intercalations of different rock types (Fig. 4a). It rests stratigraphically on the PCB Unit. A detailed sketch of the lithostratigraphic sequence is shown in Fig. 4b. The Combin Zone mainly consists of calcschists which locally contain clasts of serpentinites, metabasites and marbles (Fig. 4c-d-e). In contrast, the intercalations consist of layers (up to 5 m thick) of micaceous and impure marbles, basic to intermediate meta-arenites locally with serpentinite clasts (Fig. 4f) and quartz-micaschists locally hosting metabasite clasts (Fig. 4g). The detrital origin is confirmed by the rare presence of erosional surfaces preserved at the base of the basic meta-arenite lenses in correspondence of their tapering out (Fig. 4h). The quartz-micaschists levels occur in the same structural position of the Frilhorn Series (Sartori, 1987) but clearly have an oceanic affinity since they are stratigraphically interlaid with calcschists containing mafic clasts and ultrabasic bodies. Generally, the intercalations are more abundant near the contact with the greenstones which locally consist of fine-grained tabular to massive metabasites with carbonate rich levels interpreted as meta-breccias. Also the serpentinites bodies within the Combin Zone range from massive to foliated and locally have the aspect of meta-breccias with magnetite or carbonate enriched levels (e.g. NE of Saleroforko). All of these aspects indicate that the metabasites are thick sedimentary/volcanic layers and serpentinites are detrital rather than an oceanic lithosphere. Metabasites and serpentinites become more abundant toward the top of the Combin zone away from the PCB unit located at the base of the pile.

**Fig. 4.** Main rock types of the Upper Tectonic Element in the Gressoney Valley: a) calcschists with intercalations of basic meta-arenites, impure marbles and quartz-micaschists; b) detailed lithostratigraphic sequence of the Combin Zone resting on the PCB Unit; c) calcschists with

serpentinite clasts; d) clast of metabasite in a meta-arenite level interbedded in calcschists; e) marbles clasts within calcschists; f) basic meta-arenite level with serpentinite clasts; g) contact between quartz-micaschists (grey) and metabasites (green) marked by a chlorite rich micaschist (greenish) with metabasite clasts; h) tapering out of a basic meta-arenite within calcschists showing an erosional surface marked by black arrows which indicate a reverse stratigraphic polarity. These meta-arenites are interpreted as channel fill sediments.

#### **4. Structural Data**

According to the lithostratigraphic setting described above we have grouped the studied units into two Tectonic Elements. The Lower one is composed of the Monte Rosa Massif and the Zermatt-Saas Zone which preserve eclogite facies assemblages. On the contrary, the Upper one consists of the Combin Zone with the Pancherot-Cimebianche-Bettaforca at its base, both of which do not show any eclogite facies relics and display well developed greenschist facies assemblages.

The geological cross sections reported in the map are drawn at the same scale as the outcrop map (i.e. 1:10,000 scale) without considering the quaternary deposits and show in detail the lithostratigraphy and the structural relationships between the different units.

In the study area five different deformation events have been distinguished (pre-D<sub>1</sub> to D<sub>4</sub>). D<sub>1</sub> deformation phase is strongly transpressive; therefore the pre-D<sub>1</sub> structures are only preserved at the meso- and micro-scale. The study area is dominated by a regional S<sub>1</sub> foliation concordant with the lithological boundaries, mainly dipping 10-40° towards the SW quadrant (Fig. 7a-b-e). The regional foliation developed under different metamorphic conditions (Tables 1-2) and probably at different time across the two Tectonic Elements distinguished. D<sub>2</sub>, D<sub>3</sub>, and D<sub>4</sub> in turn deform the regional foliation S<sub>1</sub> and rarely develop an axial plane

foliation indicating low to very low grade metamorphic conditions. Their relative age has been established by geometric relationships at the map scale since no meso-scale interference figure was found. Despite the regional foliation is termed  $S_1$  both in the Upper and the Lower Tectonic Elements, this does not mean that they are synchronous. The mineral assemblages related to the different deformation stages are sketched in Table 1 and 2 for the main rock types.

**Table 1.** Evolution of the mineral assemblages relative to the structural and to the metamorphic setting in the main lithologies occurring in the different tectonic units in the Upper Gressoney Valley. PCB: Pancherot Cime Bianche Bettaforca Unit.

**Table 2.** Sketch of the tectono-metamorphic evolution of the studied units in the Gressoney Valley. The grey vertical columns indicate that the units are not yet coupled.

GSZ: Gressoney Shear Zone

### ***D<sub>1</sub> structures and metamorphism in the Lower Tectonic Element***

$D_1$  is the main tectono-metamorphic stage during which almost all the metamorphic assemblages related to the HP stage were erased. The pre- $D_1$  relic in the Monte Rosa are represented by eclogite boudins within the micaschists. The eclogites preserve a pre- $S_1$  eclogite facies foliation (Fig. 5a) defined by  $Omp + Grt + Wm + Gln + Rt$ , by pre- $S_1$  foliations defined by  $Wm + Qtz + Rt$  (Fig. 6a). Pre- $S_1$  foliation in micaschists is defined by rare  $Cld$  preserved in coarse  $Grt$  (Fig. 6b). In the Zermatt-Saas Zone pre- $D_1$  relics can be found in eclogite boudins ( $Grt + Omp + Rt \pm Gln$ , Fig. 6c) ranging from some decimetres up to 100 m in length and are enclosed within re-equilibrated metabasites or within serpentinites.

In the Monte Rosa Massif  $D_1$  folds (Figs. 5b and 6a) are isoclinal to rootless and in the Zermatt-Saas  $D_1$  axes are mainly represented by intersection lineations.

The  $D_1$  structural elements ( $L_1$ ,  $A_1$ ,  $S_1$ ) plotted separately for Monte Rosa (Fig. 7a) and Zermatt-Saas (Fig. 7b) are highly scattered but show the same degree of distribution implying that the coupling between the two tectonic units pre-dates the  $D_1$  deformation stage as locally observed at the outcrop scale along their tectonic contact (outcrop coordinates: 405999 m, 5081857 m, European Datum, UTM Zone 32N). Since the following deformation events developed folds with wavelength in the order of 50-300m and since  $D_3$  and  $D_4$  have perpendicular fold axes to each other, it was not possible to define sub-areas showing the same orientation of the structural elements related to  $D_1$ . Despite this, two sub-areas were distinguished where the  $S_1$  foliation is mainly deformed by  $D_3$  and  $D_4$ , respectively.

In sub-area I (East) the  $S_1$  foliation (Fig. 7c) dips from NNW to SSE and the poles to the foliation define a NNW-SSE directed great circle which suggest the presence of folds with SSW plunging axes (thick black cross) folding the main foliation, i.e.  $D_3$ .

In sub-area II (West) the main foliation (Fig. 7d) dips 20 to 65° mainly towards the SW quadrant and is mainly deformed by  $D_4$  which shows NW-SE directed fold axes.

In both sub-areas fold axes plunge 5-35° mainly towards S to W and are sub-parallel to the stretching lineation, defined by quartz + white mica in metapelites and by amphibole in metabasites. Both stretching lineation and fold axes (Fig. 7c-d) are scattered because of their re-orientation mainly by  $D_3$ . The strong re-orientation of  $A_1$  and  $L_1$  indicates that their original orientation was at medium- to high- angle relative to  $D_3$  and  $D_4$  fold axes.

Kinematic indicators as  $\sigma$ -shaped pressure shadows around coarse garnet grains (Fig. 5c),  $\sigma$ -shaped quartz lenses in Monte Rosa metapelites and  $\sigma$ -shaped omphacite porphyroclasts in the Zermatt-Saas metabasites (Fig. 5d), are consistent with a top to S-SW sense of shear with minor top to NE or NW owing to re-orientation by  $D_3$  and  $D_4$  folds.

The parallelism between the  $S_1$  of the two units and between the  $S_1$  and the mylonitic foliation along the whole tectonic contact (Fig. 5e) suggests that these foliations should be synchronous both in the Monte Rosa and in the Zermatt-Saas. Kinematic indicators along the contact show top to S-SW shearing (Figs. 5f, 6d) and are consistent with shear sense observed away from the contact. In the Monte Rosa metapelite  $S_1$  is defined by Chl + Wm + Qtz + Grt + Ab/Olig + Rt/Ilm and the mylonitic foliation along the contact with Zermatt-Saas is defined by a similar metamorphic assemblage (Wm + Qtz + Grt + Hbl + Chl + Rt/Ilm  $\pm$  Ab, Fig. 6e). When Chl is present Bt lacks and vice-versa indicating that the two minerals probably replace each other. Moreover, the foliation in metabasites of both units is defined by metamorphic assemblages indicative of middle-P greenschist to epidote-albite amphibolite facies (subsequently referred to as medium PT conditions): Cam (blue-green) + Chl + Ab + Bt + Rt + Qtz in Monte Rosa metabasites (Fig. 6f), Cam (blue-green) + Zo + Chl + Ab + Rt + Qtz in Zermatt-Saas metabasites (Fig. 6g), and Cam (green) + Zo + Chl + Ab + Spn in Zermatt-Saas metagabbros. The tectonic contact between the two units is locally folded by meso-scale  $D_1$  folds whose axial surface is the regional foliation (Fig. 5g). These rare  $D_1$  folds along the contact deform the pre- $S_1$  eclogite facies foliation in the Zermatt-Saas Zone (Fig. 5h). Locally, eclogite boudins are preserved within ZS metabasites along the contact with the Monte Rosa Massif and are indicative that the eclogite facies assemblage was not stable during tectonic coupling. All these observations and the fact that shear sense indicators are mostly developed towards the contact between the two tectonic units suggest a direct relationship between  $D_1$  and tectonic emplacement of the two units, which is eventually related to the exhumation.

**Fig. 5.** Meso-scale structures related to  $D_1$  event: a) eclogite boudins with a well preserved pre- $S_1$  foliation enveloped within garnet micaschists of the Monte Rosa Massif; b)  $D_1$  fold

deforming a well preserved pre- $S_1$  foliation in the Monte Rosa garnet micaschists.  $A_1$  is represented by intersection lineations and is parallel to  $L_1$ ; c)  $\sigma$ -shaped pressure shadows around garnet in the Monte Rosa micaschists showing top to SSW sense of shear; d)  $\sigma$ -shaped omphacite porphyroclasts in Zermatt-Saas metabasites showing top to NW sense of shear; e) tectonic contact between Zermatt-Saas and Monte Rosa marked by parallelism between the  $S_1$  foliations; f) particular of e) (black box) showing S-C mylonites in the Monte Rosa micaschists with top to S sense of shear; g)  $D_1$  asymmetric fold near the contact with ZS, preserving a pre- $S_1$  foliation; h) pre- $S_1$  eclogite facies foliation in ZS metabasites preserved in the hinge of the  $D_1$  fold near the contact with MR.

**Fig. 6.** Representative microstructures of pre- $D_1$  and  $D_1$  event: a)  $D_1$  fold in Monte Rosa micaschists preserving a pre- $S_1$  foliation; b) Cld grains armoured and preserved within Grt in a micaschists from Monte Rosa Massif; c) coarse-grained Zermatt-Saas eclogite consisting of Grt + Omp + Rt showing a late blue-green Am growing mainly at the expense of Grt; d) S-C mylonitic micaschists along the Monte Rosa Zermatt-Saas boundary showing top to S shear sense. The sample is the same as Fig. 5f; e) mylonitic foliation in Monte Rosa micaschists defined by Chl + Wm + Qtz + Hbl. Bt is late relative to the  $S_{myl}$  and replaced Chl + Wm; f) Monte Rosa metabasite with a well-developed  $S_1$  foliation defined by Cam + Chl + Bt + Ab; g) Zermatt-Saas metabasite with a  $S_1$  regional foliation defined by Cam + Zo + Chl + Ab; h) Combin greenstone with a  $S_1$  foliation defined by Act + Chl + Ep + Ab + Spn.

**Fig. 7.** Equal area projections, lower hemisphere of the main structural features characterizing the four deformation phases identified in the upper Gressoney Valley. For discussion see text.

### ***D<sub>1</sub> structures and metamorphism in the Upper Tectonic Element***

At the Bettaforca Pass the lithostratigraphic sequence (see § 3; Fig. 3a-b) suggests the presence of an isoclinal fold with the Pancherot-Cimebianche-Bettaforca unit in its core whose axial plane surface is the S<sub>1</sub> foliation. The presence of this east-closing fold (see geological map, cross section D-D') on the E slope of Cima Bettaforca (Battberg) with the Pancherot-Cimebianche-Bettaforca Unit at its core is confirmed D<sub>1</sub> isoclinal to rootless parasitic folds in the PCB quartzites (Fig. 8a) and in calcschists. Therefore the east closure of the PCB is related to the development of the main foliation and not to a boudinage process due to the Gressoney Shear Zone.

D<sub>1</sub> folds are isoclinal and are mainly responsible for the lithological alternation of calcschists and greenstones as observed on the north-east face of the Rothore Mountain (Fig. 8b-c) and in all the study area. S<sub>1</sub> dips mainly towards SW by 10-40° and fold axes and stretching lineations are generally parallel to each other plunging SE to NW by 10-30° with some fold axes dipping S to W (Fig. 7e). The dispersion of the fold axes on the S<sub>1</sub> foliation is due to the presence of sheath folds locally observed at the outcrop scale (Fig. 8d). Kinematic indicators consist of quartzite clasts both in calcschists and micaschists and are compatible with top to SE sense of shear (Fig. 8e).

The S<sub>1</sub> foliation in metabasites of the Combin Zone is defined by a greenschist facies assemblage (Act + Chl + Ep + Ab + Spn; Fig. 6h) indicating that the regional foliation is developed in different metamorphic conditions relative to the Lower Element. In the calcschists the S<sub>1</sub> foliation is defined by Wm + Qtz + Cal + Chl + Spn while in the micaschists it is defined by Qtz + Wm + Chl + Ab + Ep.

**Fig. 8.** Meso-scale structures representing D<sub>1</sub> to D<sub>3</sub> deformation phases: a) D<sub>1</sub> fold in the PCB tabular quartzites preserving a pre-S<sub>1</sub> foliation enhanced by the presence of a thin mica rich layer; b-c) D<sub>1</sub> fold hinge (white arrow) responsible for the alternation of greenstones (grey-green rocks) and calcschists (brown-reddish rocks) on the east face of the Rothore mountain; d) anvil-shaped folds (Mies, 1993) within Combin micaschists and calcschists related to the development of sheath folds during D<sub>1</sub>; e)  $\sigma$ -shaped quartz porphyroclasts in a quartz micaschist within the CO calcschists showing top to SE sense of shear; f) D<sub>2</sub> symmetric fold in the Zermatt-Saas metabasites; g) open to close D<sub>3</sub> folds with top to SE vergence in the Zermatt-Saas metabasites locally showing overturned short limbs; h) D<sub>3</sub> open fold with top to SE vergence in the mylonites developed along the Gressoney Shear Zone.

### ***D<sub>2</sub> structures***

D<sub>2</sub> folds are rare and were only identified in the Lower Tectonic Element. These folds have tight profile and deformed the S<sub>1</sub> foliation without generating an axial plane cleavage (Fig. 8f). A clear example of these structures crops out at Ros Gaveno where the short limb (*ca* 100 m) of the structure is overturned, bringing the Monte Rosa basement over the Zermatt-Saas Zone (see cross section A-A' in geological map). D<sub>2</sub> axial surfaces are strongly scattered while the fold axes mainly plunge 15-35° towards SW (Fig. 7f) and the folds show a prevalent E-SE vergence. This D<sub>2</sub> antiform-synform couple can be related to the D<sub>2</sub> deformation phase of Pleuger *et al.* (2005) in the Upper Sesia Valley.

The relative age and the structural relationships between D<sub>2</sub> and the Gressoney Shear Zone (GSZ, Reddy *et al.*, 1999) are not clear. However, the GSZ developed after D<sub>1</sub> and is folded by D<sub>3</sub> suggesting a direct relationship with D<sub>2</sub>. Moreover, mylonites along the GSZ are parallel to the S<sub>2</sub> surface and the stretching lineations on mylonites are perpendicular to D<sub>2</sub> fold axes (Fig. 7f).



### ***D<sub>3</sub> structures***

The D<sub>3</sub> event affected both the Upper and the Lower Tectonic Elements but in different ways with the interlimb angle diminishing towards east and in the deepest unit (i.e. towards Monte Rosa Massif). In the Lower Tectonic Element D<sub>3</sub> developed meso to macro-scale folds with open to close profiles and show a prevalent SE-vergent asymmetry (Fig. 8g-h). The macro-scale folds wavelength is heterogeneous varying from 50 to 300 m. Locally, the short limb is locally overturned (west of Ros Gaveno) and the interlimb angle increases towards higher structural levels (i.e. towards the Combin Zone) (compare cross sections A-A' and D-D'). Axial surfaces dip mainly NW by a range of inclination from 35° to sub-vertical with some poles in the opposite quadrant (Fig. 7g) which are indicative of the presence of box-folds at the macro-scale. Fold axes plunge up to 45° mainly towards SW to W with some data plunging in the NE quadrant (Fig. 7g, see cross section B-B'). D<sub>3</sub> occasionally developed a new axial surface defined by the re-orientation of Wm within the Monte Rosa micaschists. According to the axial planes and fold axes orientation and to the folds style, the D<sub>3</sub> folds can be related to the Vanzone antiform (Keller *et al.*, 2005) and belong to the D<sub>5</sub> fabric domain of Babist *et al.* (2006). In the Upper Tectonic Element D<sub>3</sub> folds developed only at the macro-scale, are open in profile and the axial surfaces are sub-vertical to NW dipping with fold axes plunging SW by 10-20°.

In the study area it was not possible to observe directly a meso-scale D<sub>3</sub> deforming the GSZ, however the mylonites developed along this regional scale shear zone are deformed by D<sub>3</sub> folds (Fig. 8h). Also the structural relationships between UTE and LTE inferred from cross sections suggest that the GSZ is folded by D<sub>3</sub> open folds at the macro-scale and, instead of that, this shear zone developed before the D<sub>3</sub> event (see cross section D-D'). This hypothesis is also confirmed by Babist *et al.* (2006) who observed that the Gressoney Shear Zone is

deformed by a macro-scale top to SE open fold, in the eastern side of the Gressoney Valley (their Fig. 4o).

#### ***D<sub>4</sub> structures***

The D<sub>4</sub> deformation phase developed folds at the meso and mainly at the macro-scale with open profile and shows top to SW asymmetry. Axial planes dip towards NE to E by 35-90° with rare pole in the opposite quadrant and the fold axes are generally sub-horizontal (0-15°) and trend NW-SE (Fig. 7h). The scattering of the axial surfaces and the presence of some folds axes with intermediate inclination (max 30-35°; Fig. 7h) on the steep limbs of D<sub>3</sub> folds suggests that the orientation of D<sub>4</sub> is strongly influenced by the previous structural setting.

#### ***Structural relationships between LTE and UTE***

These two tectonic elements are separated by the Gressoney Shear Zone (Reddy *et al.*, 1999) which consists of discrete thin shear zones within a wider deformation zone up to 50 m thick (Fig. 9a). These discrete shear zones locally cut the regional foliation (Fig. 9b) and developed mainly at the interface between rocks with high competence contrast such as calcschists vs quartzites, metabasites vs serpentinites, metabasites vs calcschists and consist of mylonitic micaschists, calcschists and serpentinites. Shear sense indicators consists of dragged foliations (Fig. 9a-d),  $\sigma$ -shaped boudins Fig. 9c), and drag folds (Fig. 9d) and are all consistent with top to SE shearing. The orientation of S<sub>1</sub> in the UTE and in the LTE locally shows an angular discordance of 10-20° (Fig. 9a) supporting the hypothesis that the regional foliation developed at different time in the two tectonic elements. At the map scale, the GSZ cuts the tectonic contacts separating the different slices of oceanic crust of the Zermatt-Saas Zone suggesting that these intra-unit contacts are older than the GSZ.

**Fig. 9.** Structural features of the Gressoney shear Zone showing top to SE shear sense: a) serpentinite slice along the GSZ showing  $S_1$  foliation dragged into parallelism with younger shear zones; b)  $S_1$  foliation within Combin greenstones cut by the mylonitic foliation related to the development of the GSZ; c) carbonatic mylonites developed at the interface between PCB quartzites and CO calcschists. This shear zone at the top of the GSZ cuts  $S_1$  and envelops  $\sigma$ -shaped boudins of calcschists; d) drag fold with the short limb cut by the mylonitic foliation (red arrows).

## 5. Conclusions

The discussion of the tectono-metamorphic evolution of the study area and its linking to the evolution of the Alpine chain is beyond the scope of this paper which only describes the lithostratigraphic setting and the structural data observed during the field survey and the petrography of the main rock types.

Detailed field mapping in the Upper Gressoney Valley (NW Italian Alps) has allowed distinguishing two main Tectonic Elements according to their different structural and metamorphic evolution. In general the Lower Tectonic Element (LTE) consists of units which preserve eclogite facies metamorphic assemblages while the Upper Tectonic Element (UTE) shows no evidence of eclogitic minerals and displays well developed greenschist facies assemblages. These two Elements are separated by a ductile shear zone developed under greenschist facies conditions known as Gressoney Shear Zone (Reddy *et al.*, 1999). However, we did not find mesoscale evidences of a kilometre thick shear zone, as described by these authors, but only 30 m thick mylonites developed at the base of the Combin Zone.

The Zermatt-Saas Zone and the Monte-Rosa Massif were coupled before the development of the regional foliation and after the eclogite facies pressure peak. This is in contrast with the conclusion drawn by Lapen *et al.* (2007) who suggested tectonic coupling during eclogite facies conditions according to P-T-t data.

An interesting observation is that the calcschists complex of the Combin Zone is in stratigraphic contact with the Pancherot-Cimebianche-Bettaforca Unit and that it shows a bimodal detrital contribution both from the oceanic lithosphere and from the continental crust. Finally, at least two generations of tectonic contacts can be distinguished: the older is represented by the contact between the Monte Rosa Massif and the Zermatt-Saas Zone which developed before or contemporaneously with the D<sub>1</sub> stage responsible of the development of the regional foliation. The younger is represented by the Gressoney Shear Zone which instead developed after the D<sub>1</sub> regional stage.

Finally, detailed mapping of a problematic area across different tectonic units, proved to be an indispensable step to unravel its tectono-metamorphic evolution. Moreover, geological mapping should be considered the first step before the acquisition of PTt data and before their interpretation and extrapolation to the regional scale.

**Acknowledgments.** This work was financially supported by Ministero dell'Università e della Ricerca Scientifica e Tecnologica (M.U.R.S.T.). The review work by Jan Pleuger and Thomas Lapen is greatly appreciated and has improved the manuscript. We also acknowledge the comments and suggestions made by the map editor Heike Apps and by the editor Paolo Riccomini.

**Software**

The geological maps were drawn with the software ArcGIS 9.2 and were finally assembled with Canvas X for a better graphic output. The structural data were analyzed and plotted with Stereonett. The cross sections presented in the geological map and the photographs were compiled with Canvas X.

## References

AVIGAD, D., CHOPIN, C., GOFFÉ, B., MICHARD, A. (1993): Tectonic model for the evolution of the western Alps. *Geology*, 21, 659-662

BABIST, J., HANDY, M.R., KONRAD-SCHMOLKE, M., HAMMERSCHMIDT, K., (2006). Precollisional, multistage exhumation of subducted continental crust: the Sesia Zone, western Alps. *Tectonics*, 25. doi:10.1029/2005TC001927.

BEARTH, P., (1952). Geologie und Petrographie des Monte Rosa. *Beiträge Geologische Karte Schweiz, Neue Folge* 96, 1–94.

BEARTH, P., (1967). Die Ophiolithe der Zone von Zermatt–Saas Fee. *Beiträge Geologische Karte Schweizerische, Neue Folge* 132, 1–130.

BUCHER, K., FREY, M., (2002). *Petrogenesis of Metamorphic Rocks*. Springer-Verlag, 7th edition, p. 335-336.

DAL PIAZ, G.V., (1965). La formazione Mesozoica dei calcescisti con Pietre Verdi fra la Valsesia e la Valtournanche ed i suoi rapporti strutturali con il ricoprimento Monte Rosa e con la Zone Sesia-Lanzo. Bollettino della Società Geologica Italiana, 84, 67-104.

DAL PIAZ, G.V., (1974). Le métamorphisme alpin de haute pression et basse température dans l'évolution structurale du bassin ophiolitique alpino-appenninique. 1<sup>e</sup> Partie: Bollettino della Società Geologica Italiana, 93, 437-468, 2<sup>e</sup> Partie: Schweizerische Mineralogische und Petrographische Mitteilungen, 54, 399-424.

DAL PIAZ, G.V., (1988). Revised setting of the Piedmont Zone in the northern Aosta Valley, western Alps. *Ophioliti*, 12/2, 157-162.

DAL PIAZ, G.V., (1999). The Austroalpine-Piedmont nappe stack and the puzzle of Alpine Tethys. *Memorie di Scienze Geologiche*, 51 (1), 155-176.

DAL PIAZ, G.V., (2001). Geology of the Monte Rosa Massif: historical review and personal comments. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 81, 275-303.

DAL PIAZ, G.V., ERNST, W.G., (1978). Areal geology and petrography of eclogites and associated metabasites of the Piedmont ophiolite nappe, Breuil-St. Jacques area, Italian Western Alps. *Tectonophysics*, 51, 99-126.

DAL PIAZ G.V., LOMBARDO, B., (1986). Early\_alpine eclogite metamorphism in the Penninic Monte Rosa-Gran Paradiso basement nappes of the north-western Alps. *Geological Society of America Memoirs*, 164, 249-265.

FROITZHEIM, N., SCHMID, S.M., FREY, M. (1996): Mesozoic palaeogeography and the timing of eclogite-facies metamorphism in the Alps: a working hypothesis. *Eclogae Geologicae Helveticae*, 89, 81-110.

KELLER, L. M., HESS, M., FÜGENSCHUH, B., SCHMID, S. M., (2005). Structural and metamorphic evolution of the Camughera-Moncucco, Antrona and Monte Rosa units southwest of the Simplon line, Western Alps. *Eclogae Geologicae Helveticae*, 98, 19-49.

KRETZ, R., (1983). Symbols for rock-forming minerals. *American Mineralogist*, 68, 277-279.

LAPEN, T.J., JOHNSON, C.M, BAUMGARTNER, L.P., DAL PIAZ, G.V., SKORE, S., BEARD, B., (2007). Coupling of oceanic and continental crust during Eocene eclogite-facies metamorphism: evidence from the Monte Rosa nappe, western Alps. *Contributions to Mineralogy and Petrology*, 153, 139-157.

MIES, J.W. (1993). Structural analysis of sheath folds in the Sylacauga Marble Group, Talladega slate belt, southern Appalachians. *Journal of Structural Geology*, 15, 983-993.

NEVIN, S. M., (1949). *Principles of structural geology* (3<sup>rd</sup> ed.) Wiley, New York, 320 pp.

PLEUGER, J., FROITZHEIM, N., JANSEN, E., (2005). Folded continental and oceanic nappes on the southern side of Monte Rosa (western Alps, Italy): Anatomy of a double collision suture. *Tectonics*, 24, TC4013, doi:10.1029/2004TC001737.

REDDY, S.M., WHELEER, J., CLIFF, R.A., (1999). The geometry and timing of orogenic extension: an example from the Western Italian Alps. *Journal of Metamorphic Geology*, 17, 573-589.

SARTORI, M., (1987). Structure de la Zone du Combin entre les Diablons et le Zermatt (Valais), *Eclogae Geologicae Helvetiae*, 80, 789-814.

SCHMID, S.M., FÜGENSCHUH, B., KISSLING, E., SCHUSTER, R., (2004). Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae*, 97, 93-117.

STECK, A., BIGIOGGERO, B., DAL PIAZ, G.V., ESCHER, A., MARTINOTTI, G., MASSON H. (1999). Carte tectonique des Alpes de Suisse occidentale et des régions avoisinantes, Carte géologique spéciale 123, Service hydrologique et géologique national, Bern, Switzerland.

VANNAY, J.C., ALLEMANN, R., (1990). La Zone Piémontaise dans le Haut-Valtournanche (Val d'Aoste, Italie). *Eclogae Geologicae Helvetiae*, 83/1, 21-39.