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32nd INTERNATIONAL
GEOLOGICAL CONGRESS

THE SUBDUCTED TETHYS IN THE AOSTA VALLEY (ITALIAN WESTERN ALPS)

Leader: S. Martin

Associate Leaders: G. Godard, G. Rebay

Pre-Congress

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The scientific content of this guide is under the total responsibility of the Authors

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Front Cover:
Cervino/matterhorn

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Introduction

The five-day excursion "The subducted Tethys in the Aosta valley (Italian western Alps)" presents an overview of the eclogitized ophiolites of the Zermatt-Saas unit, focusing on the relationships and metamorphic features of different lithologies (serpentinite, metagabbro and metabasalt, Mn-rich quartzite, hydrothermal sulphide deposits and metasediments). These rocks underwent high- to ultrahigh-pressure metamorphism during subduction of the Tethyan ocean, and developed peculiar high-pressure peak to decompressional assemblages according to their composition.

First, in order to acquire a general view of the main Alpine nappes and their lithologies, we will cross the Tethys ocean suture (the Zermatt-Saas and Combin units of the ophiolitic Piedmont Zone) from the former European passive continental margin (now represented by the Monte Rosa nappe) to the Adria (Africa) continental margin (Sesia-Lanzo and Dent Blanche nappes). We will then visit some of the most typical outcrops of Alpine geology in the NW Alps: (i) the Saint-Marcel Fe-Cu hydrothermal sulphide deposits; (ii) the famous Praborna Mn mine with its unique high-pressure minerals; (iii) the Cignana coesite site and the Crepin metagabbro (Valtournanche). Attention will be especially focussed on the eclogitized ophiolites and hydrothermal oceanic deposits. In addition, historical aspects, Alpine views and regional setting will be taken in consideration. The field trip will be concluded with the breathtaking view from Plateau Rosa, south of Cervino (Matterhorn), where we will be able to summarise the regional relationships of the collisional nappe stack and the ophiolitic suture (remnants of the "lost Tethyan ocean"), and will have the opportunity to enjoy some last eclogite outcrops.

First day: Meeting on the 15th August 2004 at the railway station of Novara, from where we will leave at 13:00 for Gressoney (arrival time at 15:00). From there, we will take a cableway up to Passo dei Salati (2950 m; panorama). After a short walk across the contact between the Monte Rosa and Zermatt-Saas units (i.e., the European plate and Tethys ocean, respectively), we will reach Rifugio Città di Vigevano (2864 m) for dinner.

Second day: One group will visit the Zermatt-Saas meta-ophiolites and the underlying Monte Rosa basement, up to Rifugio Città di Mantova (3500 m), whereas the second group will come across the Zermatt-Saas meta-ophiolites towards the overlying Sesia-Lanzo unit (i.e., Adria microplate), down to Lago Gabiet (2342 m). Take away lunch to be eaten on the way. Return to Gressoney valley by cableway. Bus to Lillianes (eclogite-facies rocks of the Sesia-Lanzo unit), and then to Collegio Gervasone at Châtillon (dinner and discussion).

Third day: Departure for the Saint-Marcel valley, by minibus. Walk to the Servette Fe-Cu mine, with a visit of the ancient foundry and slag heaps, and then on to the Praborna Mn mine (high-pressure metamorphism of hydrothermal oceanic deposits). Return through the abandoned mine village of Chuc and the unusual Cu hydroxide deposit in the river at Acqua verde. Take away lunch; dinner at Gervasone (Châtillon).

Fourth day: Departure by minibus for Cignana (coesite-bearing occurrence in the Zermatt-Saas meta-ophiolites). Walk from Lago di Cignana (2158 m) down to the eclogitized oceanic metagabbros of Crepin (1577 m). Take away lunch; dinner at Gervasone (Châtillon).

Fifth day: Departure for Cervinia by bus and then by cableway up to Plateau Rosa, for a breathtaking view of the Cervino (Matterhorn) peak and the Africa/Europe collisional zone. On 19th August in the afternoon, travel to Florence by bus.

Weather can be from warm to quite cold (near or below 0°C). Bring warm, waterproof clothes and mountain shoes; walks will be on marked paths in an alpine environment (up to 3500 m); altitude changes of up to 900 m per day.

Regional geologic setting

On the northern side of the Aosta valley, the Alpine collisional wedge (the Penninic-Austroalpine nappe stack) is characterized, from bottom to top, by: (i) the eclogite-facies Monte Rosa nappe (the European continental margin), (ii) the eclogitic Zermatt-Saas meta-ophiolite, overlain in turn by (iii) a few eclogitic Austroalpine slices (outliers) and/or a Permian-Mesozoic decollement cover unit of debatable continental origin (the Pancherot-Cime Bianche unit), (iv) the blueschist-facies Combin meta-ophiolite, and (v) the capping upper Austroalpine units (Adria/Africa continental margin), consisting of the eclogite-facies Sesia-Lanzo inlier and blueschist-facies Dent Blanche-Mont Mary-Pillonet klippen (outliers)

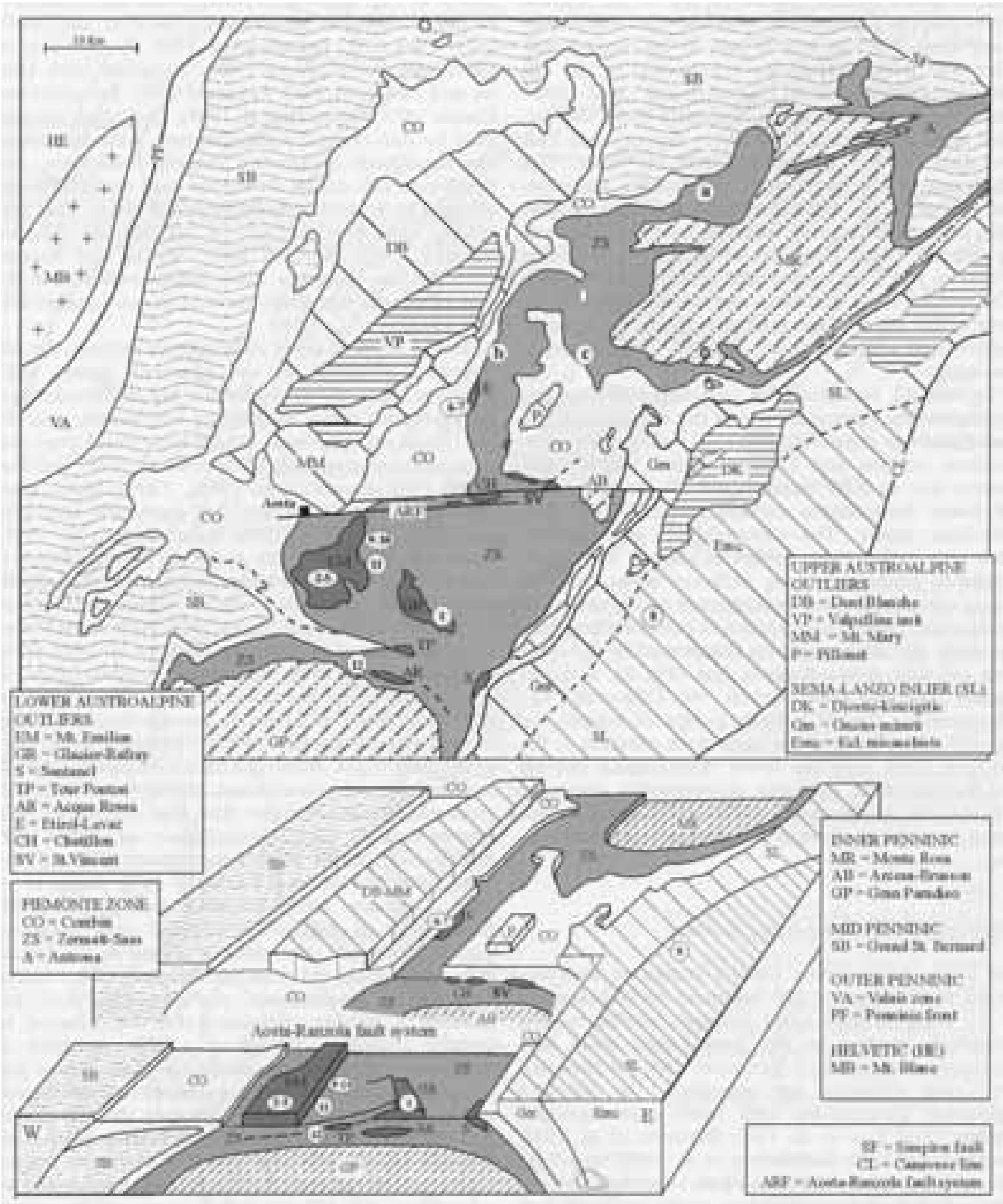

Figure 1 - Tectonic map and block-diagram of the Aosta valley and surrounding areas, NW Alps.
Grey colour: ophiolitic units, white colour: basement units.
Legend: A=Antigorio, AB=Arcesa-Brusson slice, An= Antrona meta-ophiolites, AR=Aosta-Ranzola line, B=Berisal, CH= Chatillon slice, CMB=Cossago-Mergozzo-Brissago line, CR= Cremosina line, E= M. Emilius, EL= Etirol-Levaz, GR= Glacier-Rafray, FR=Fobello-Rimella unit, LA, LS= Simplon line, LC= Canavese line, MM= Mont Mary, GP= Gran Paradiso, SL= Sesia-Lanzo, IIDK= II Diorite-kinzigitic zone,LS= Simplon line, ML= Monte Leone, MR= Monte Rosa, Pi=Pillonet, SB= Gran San Bernardo nappe, S= Santanel, SC= Sion-Courmajeur, SL= Sesia-Lanzo, TP=Tour Ponton, VP= Valpelline unit, ZP=Piedmont zone.

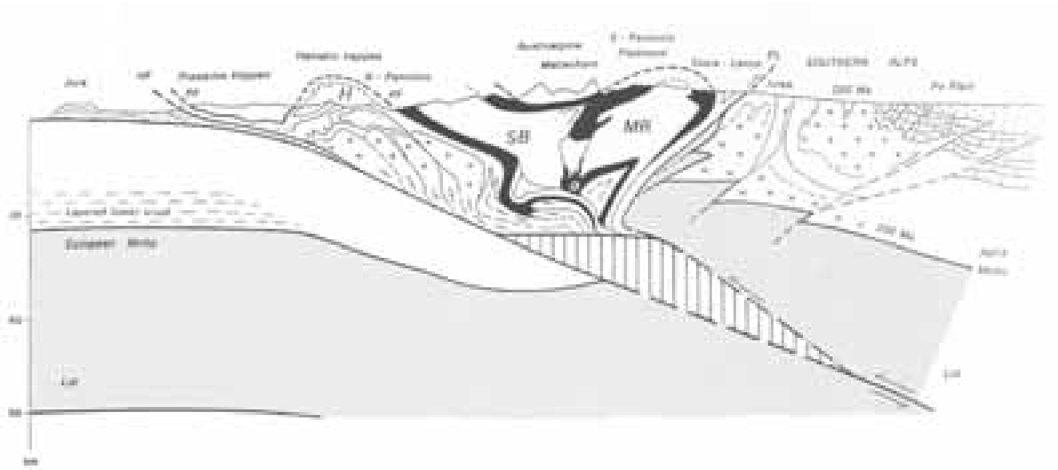

Figure 2 - Cross section and lithospheric interpretation of the Western Alps, after Canepa et al., 1999. PL=Periadriatic Line; PF=Penninic frontal thrust; ophiolitic units are in black; MR= Monte Rosa nappe; SB=Grand St. Bernard system; H=Helvetic zone; HF=Helvetic frontal thrust.

(Ballèvre et al., 1986; Bigi et al., 1990; Dal Piaz, 1999; Dal Piaz et al., 2001).

In this introduction, we present the features of the main nappe systems to be visited during the excursion, namely the Monte Rosa nappe (inner Penninic domain, i.e., European continental crust), the Zermatt-Saas and Combin meta-ophiolites (i.e., the Tethys ocean), and, finally, the Sesia-Lanzo and Dent Blanche nappes (Austroalpine domain, i.e., the Adria microplate).

The European continental crust (Monte Rosa unit)

The Monte Rosa nappe lies at the junction between the Central and the Western Alps. In terms of tectonic position, it is situated at a level corresponding to the Suretta nappe, to the east, and to the Gran Paradiso and Dora Maira nappes, to the southwest. In Argand's view, Monte Rosa forms the fifth recumbent fold-nappe of the Penninic system (Lugeon & Argand, 1905; see Dal Piaz, 2001a, for a historical review), which likely derived from the European margin. The Penninic domain includes several stacked nappes (Figure. 2): (i) the upper Monte Rosa [MR], Gran Paradiso and Dora Maira nappes; (ii) the mid nappe of the Grand Saint-Bernard [SB]; (iii) the lower Lepontine nappes of the Ossola-Ticino; (iv) the Valais domain (lower/outer Penninic), composed of flysch and minor meta-ophiolites (*e.g.,* Ballèvre & Merle, 1993; Dal Piaz *et al.*, 2001).

The Monte Rosa nappe may be subdivided into three main units derived from these pre-Alpine protoliths: (i) a pre-granitic basement composed of a Variscan, high-grade, gneissic complex; (ii) Upper Carboniferous and/or Lower Permian granite-granodiorite plutons; (iii) remnants of Permian-Mesozoic sedimentary cover and the composite Furgg zone (Bearth, 1956).

The pre-granitic basement is composed of paragneiss, micaschists, migmatite and interlayered metabasites (Bearth, 1952; Dal Piaz, 1966, 1971; see references in Dal Piaz, 2001a, and Engi *et al.*, 2001), which have undergone high-T low-P metamorphic conditions during the Variscan orogeny, producing K-feldspar and cordierite-bearing migmatite and pegmatite (*e.g.,* Engi *et al.*, 2001). They were sharply intruded by Upper Carboniferous granodiorites and Permian granites (Hunziker, 1970; Liati *et al.*, 2001; Scherrer *et al.*, 2001). The whole Variscan basement was deformed and metamorphosed during Alpine orogeny, under eclogite-facies high-P conditions (typically 500°C and 1.6 GPa: Chopin & Monié, 1984; Dal Piaz & Lombardo, 1986). Recently, Le Bayon *et al.* (2001) obtained a pressure estimate as high as 2.3 GPa for some whiteschists from an Alpine shear zone of the Ayas valley. According to recent radiometric determinations, the eclogite-facies peak of the Monte Rosa unit is nearly contemporaneous to the peak of the Zermatt-Saas eclogites and coesite-bearing metasediments (Middle Eocene: Rubatto *et al.*, 1998; Rubatto & Gebauer, 1999; Pawlig & Baumgartner, 2001). Finally, a mesoalpine (Late Eocene-Early Oligocene: 38-35 Ma) overprint from greenschist- to amphibolite-facies metamorphic conditions affected the whole Monte Rosa nappe (Bearth, 1958).

The Furgg zone has been defined as a high-strain zone with a heterogeneous association of paragneiss, leucocratic gneiss and melanocratic rocks, derived from Permian granitoids and/or volcanic rocks, Cambrian metagabbros (Liati *et al.*, 2001), mafic boudins in marbles (presumably derived from Mesozoic rocks intruded by basic dykes) (*e.g.,* Bearth, 1954; Keller & Schmid, 2001). For a few authors, this zone might represent the cover of the Monte Rosa basement, whereas others interpret it as a tectonic melange (see review in Dal Piaz, 2001b, p. 295). Initially observed and mapped by Bearth at the northern border of the massif, it was subsequently identified southwards, as well as at various structural levels of the nappe, closely associated to and folded together with the polymetamorphic basement (Dal Piaz, 2001a). The eclogitic to retrogressed mafic boudins, occurring on the southern Italian side of the Monte Rosa basement, are representative of Variscan or older mafic granulites or amphibolites, derived in turn from continental tholeiitic basalts (Ferrando *et al.*, 2002).

The subduction-related early Alpine foliation (S1), discontinuously recorded and marked by eclogite- or blueschist-facies mineral assemblages, was followed by a S2 foliation developed during the Monte Rosa exhumation-related shearing, accompanied by retrogression (Wheeler & Butler, 1993). These two foliations were further folded by large folding during the mesoalpine event (*e.g.,* the Vanzone antiform and Antrona synform).

The Zermatt-Saas meta-ophiolite unit

The meta-ophiolites of the composite Piedmont Nappe extend along the entire arc of the Western Alps up to the Central Alps (Bigi *et al.*, 1990). They form numerous metamorphic units, which are scattered at different structural levels of the Alpine nappe pile, from the uppermost Platta-Arosa unit (Central Alps) to the lowest and outermost Versoyen unit (in the Western Alps).

Argand (1916) attributed these meta-ophiolites to the Penninic domain. Since the development of the plate tectonics, they are considered as derived from the oceanic lithosphere of the Liguro-Piedmont branch of the Tethys that opened in the Middle-Late Jurassic between the passive continental margins of Europe and Adria (Africa) (see historical review *in* Dal Piaz, 2001b). This oceanic lithosphere was sliced and dismembered during the plate margin convergence that led to the subduction of the oceanic and continental crusts under the Adriatic margin and to their partial exhumation. The occurrence of either a single Piedmont ocean or two separated oceanic branches (South-Penninic / Piedmont and North-Penninic / Valais basins) has been envisaged since the first work of Sturani (1973) to the last contribution of Rubatto *et al.* (1998), who tried to date both oceans.

On the basis of the metamorphic evolution of these meta-ophiolites, Dal Piaz (1965, 1974), Bearth (1967) and Kienast (1973) distinguished two main units, namely the Combin (blueschist-facies) and Zermatt-Saas (mainly eclogite-facies) units. This discrimination has been accepted by many authors (*e.g.,* Elter, 1971), who also used lithostratigraphic and structural criteria to distinguish between these two units. Here, we only emphasize the features of the lower Zermatt-Saas meta-ophiolites, whereas those of the upper Combin unit are described in a section below.

The rocks of the Zermatt-Saas unit are predominantly serpentinite from locally preserved mantle peridotite, abundant ophicalcitic breccias, minor metagabbro with magmatic mineral or textural relics (*e.g.,* Allalin, Mellichen, Crepin), metabasalts with N-MORB affinity (Dal Piaz *et al.*, 1979b; Dal Piaz *et al.*, 1981; Beccaluva *et al.*, 1984; Pfeiffer *et al.*, 1989) and metasediments derived from the internal part of the Tethyan ocean (*e.g.,* Bearth, 1967; Ernst & Dal Piaz, 1978).

The meta-ophiolites that were originally closer to oceanic hydrothermal out-flow zones show occurrences of Fe-Cu sulphide and Mn ore deposits (*e.g.,* Dal Piaz & Omenetto, 1978). The former are located within metabasalts, the latter in siliceous sediments (metacherts). The most important Cu-Fe sulphide deposits are within high-pressure metabasalts with strong oceanic alteration (garnet glaucophanite, chloriteschists and talcschists) in the Zermatt-Saas unit. They are located in the southern Aosta valley, noticeably at Saint-Marcel (see Stops 3.4 and 3.5 below) and Champ-de-Praz, but also in the Täsch area (Zermatt-Saas, Switzerland: Widmer *et al.*, 2000). The Mn deposits occur mainly as metamorphosed boudinaged quartzites rich in braunite, piemontite, spessartine (Castello, 1981). At Praborna (Saint-Marcel; see Stop 3.7 below), which is by far the most important and famous occurrence, the ore deposit includes very peculiar Mn-bearing silicates (*e.g.,* Martin-Vernizzi, 1982; Martin & Kienast, 1987; Mozgawa, 1988). This deposit is thought to derive from an oceanic hydrothermal system, or accumulation of Mn-rich oceanic nodules and "umbers", as evidenced by high Sb, Sr and Ba contents (Perseil, 1988; Perseil & Smith, 1995; Tumiati, personal communication).

The effect of oceanic hydrothermalism and alteration on the basic rocks is also evidenced by abnormal contents of various elements (Na, OH, Mg, Ca) (Beccaluva *et al.*, 1984; Barnicoat & Bowtell, 1995; Martin & Cortiana, 2001) and the scattering of δO^{18} values (Cartwright & Barnicoat, 1999).

The subduction and exhumation history of the Zermatt-Saas unit is marked by such prograde relics as pseudomorphs after lawsonite, eclogite-facies assemblages and decompressional retrogression. The Zermatt-Saas rocks that crop out north of the Aosta-Ranzola fault (*i.e.,* in the northern part of the Aosta valley), gave the highest P-T estimates for the peak metamorphism (*e.g.,* Meyer, 1983; van der Klauw *et al.*, 1997; Reinecke, 1998), with values as high as 2.7-2.9 GPa and 600-630°C for the coesite-bearing metasediments of Cignana (Reinecke, 1998; see Stop 4.2), whereas metabasites from the southern part yielded relatively lower P-T conditions (*e.g.,* Mottana, 1986; Martin & Tartarotti, 1989), typically 2.0±0.3 GPa and 550±50°C (Servette: Martin *et al.*, 2004; see Stop 3.4).

The formation of the Zermatt-Saas oceanic crust is attributed to the Jurassic (164-153 Ma: Rubatto *et al.*, 1998). Geochronology yielded a range of ages between 52 and 43 Ma (Eocene) for its subduction metamorphism, depending on the technique used (Botwell *et al*., 1994; Barnicoat *et al.*, 1993; Rubatto *et al.*, 1998; Mayer *et al.*, 1999; Dal Piaz *et al.*, 2001). The different results may correspond to different steps of the P-T path between the peak conditions and the retrogression below 500°C.

The structure of the Zermatt-Saas meta-ophiolite in the Saint-Marcel valley and Monte Avic massif is generally characterized by a N-S-trending lineation parallel to the axes of isoclinal folds, and related to a D2 deformation phase that occurred under eclogite facies (Tartarotti, 1988; Martin *et al.*, 2004). Relics of an earlier prograde deformation (D1) have been recognised only in the core of garnet crystals. The D2 foliation is further folded by a D3 deformation phase with axes still oriented N-S. An E-W-trending D4 regional tectonic phase developed under the greenschist facies (*e.g.,* Elter, 1960; Ballèvre, 1988). South dipping fault planes belonging to the Aosta-Ranzola normal fault system (Bistacchi & Massironi, 2000), locally reactivated as N-vergent thrusts, represent the last deformation episode, D5 (Martin & Tartarotti, 1989).

The intermediate continental slices

On the northern side of the Aosta valley, the ophiolitic Zermatt-Saas (below) and Combin (above) units are discontinuously separated by a thin slice of a Permo-Mesozoic sedimentary sequence (Pancherot-Cime Bianche: Dal Piaz, 1999, and refs. therein). This slice is composed of albite-bearing quartzitic schists (Permian), conglomerate (Verrucano), tabular quartzite (Lower Triassic), limestone and dolostone (Middle-Upper Triassic), polygenic sedimentary breccias (Jurassic rift) and calcschists (Cretaceous?), which have been interpreted as being deposited on a thinned continental margin or on an extensional allochthon (Mt. Emilius?) trapped inside the ocean (Dal Piaz, 1999, and references therein). These extra-oceanic sediments were metamorphosed during the Alpine events, but they still conserve some fossils (Kienast, personal communication).

Moreover, some slices of cover-free eclogite-facies continental crust are known along the tectonic contact and metamorphic gap between the Zermatt-Saas and Combin meta-ophiolites, in the lowered northern hangingwall of the Aosta-Ranzola normal fault system (Bistacchi *et al.*, 2001). The most important are the Etirol-Levaz (Kienast, 1983; Ballèvre *et al.*, 1986), Châtillon, and Saint-Vincent slices. They are also known as lower Austroalpine outliers (eclogitic) because they are located at a structural level that is lower than both that of the Sesia-Lanzo inlier and the Dent Blanche-Mont Mary-Pillonet upper-Austroalpine outliers that override the Combin unit.

In the southern footwall of the Aosta-Ranzola fault system, the Combin unit has been eroded and the preserved top units are represented by numerous eclogite-facies lower-Austroalpine outliers (or intermediate basement slices), which occur over (Mt. Emilius) or inside (Glacier-Rafray, Tour Ponton, Acque Rosse) the Zermatt-Saas meta-ophiolite. There, only the Santanel slice seems to lie between the Zermatt-Saas and Combin units.

These intermediate or lower Austroalpine continental slivers are mainly made up of pre-Alpine high-grade paragneiss, marbles, granitoids and continental gabbro bodies (Mt. Emilius, Etirol-Levaz), which have undergone an eclogite-facies metamorphism and greenschist-facies retrogression (see Dal Piaz, 1999; Dal Piaz *et al.*, 2001). Kienast (1983) and Ballèvre *et al.* (1986) obtained an estimate of 550°C and 1.6-1.7 GPa for the peak metamorphism of the Etirol-Levaz slice. Although the metamorphic history of these basement slivers is more-or-less comparable to that of the Sesia-Lanzo Zone (see below), the age of their high-P metamorphism (40-49 Ma: Dal Piaz *et al.*, 2001) is 20-25 Ma younger than that in the Sesia-Lanzo domain, but roughly the same as the Zermatt-Saas meta-ophiolite.

The Combin meta-ophiolite unit

The Combin unit consists of calcschists, impure marble, quartzitic schists and mafic to ultramafic meta-ophiolites. It displays a pervasive greenschist-facies overprint and preserves some epidote-blueschist-facies relics, without traces of the eclogite-facies assemblages that, in contrast, are common in the underlying Zermatt-Saas unit. An oceanic hydrothermalism is documented by whole rock geochemistry and the presence of Mn-rich metacherts and disseminated ore deposits (Cu-Fe-oxides, sulphides and tourmaline) (Dal Piaz *et al.*, 1979a; Castello, 1981; Martin & Cortiana, 2001). The P-T conditions for the development of the blueschist-facies paragenesis have been estimated at 0.5-0.7 GPa and 350-400°C (Sperlich, 1988; Martin & Cortiana, 2001).

A crystallisation or cooling age of 43.0±0.3 Ma was obtained for a Combin sodic amphibole from Grand Tournalin by the $^{40}Ar/^{39}Ar$ total fusion technique (Martin & Cortiana, 2001). Cooling ages below 400°C are very scattered, ranging from 49 to 30 Ma (Delaloye & Desmons, 1976; Ayrton *et al.*, 1982). These ages are quite similar to those of the Zermatt-Saas unit.

The Adria continental crust
(Sesia-Lanzo and Dent Blanche nappes)

The Austroalpine domain is represented, in the Aosta Valley, by two first-rank units, namely (i) the Sesia-Lanzo internal zone, a 90-km-long and 25-km wide belt bounded to the east by the Canavese fault, and (ii) numerous external slices of continental crust traditionally grouped as the Dent Blanche nappe (Argand, 1916; Stutz & Masson, 1938; Compagnoni *et al.*, 1977). Since the development of the theory of plate tectonics, these units have been widely interpreted as slices of the Adria microplate or African promontory.

The Sesia-Lanzo zone mainly consists of (i) the internal *Micascisti eclogitici* complex (Stella, 1894; Franchi, 1900, 1902), (ii) the external greenschist-facies *Gneiss minuti* complex (Gastaldi, 1871-1874) and (iii) some *klippen* of the Adria lower crust (*e.g., II zona Dioritico-Kinzigitica*).

The Dent Blanche nappe (*s.l.*) is subdivided into two main groups of units which are characterized by a contrasting subduction metamorphism and a different structural position: (i) the blueschist-facies Dent Blanche (*s.s.*), Mont Mary and Pillonet thrust units (Diehl *et al.*, 1952; Ayrton *et al.*, 1982; Dal Piaz & Martin, 1988; Canepa *et al.*, 1990; Dal Piaz *et al.*, 2001), which, like the Sesia-Lanzo zone, override the entire ophiolitic Piedmont Zone and therefore may be reported as upper Austroalpine outliers (Dal Piaz, 1999); (ii) the eclogite-facies lower Austroalpine outliers, represented by the Mt. Emilius, Glacier-Rafray, Etirol-Levaz and other similar units, and located between the Combin and Zermatt-Saas units, or inside the latter (Ballèvre *et al.*, 1986: Ballèvre & Merle, 1993; Dal Piaz, 1999).

The pre-Alpine Adriatic crust was mainly composed of felsic and mafic granulites (*e.g.,* Nicot, 1977; Lardeaux & Spalla, 1991), kinzigitic gneisses (*e.g.,* Diehl *et al.*, 1952; Canepa *et al.*, 1990), a few slices of serpentinized mantle peridotite (*e.g.*, Cesare *et al.*, 1989), marbles, abundant Upper Paleozoic granitoids (*e.g.,* Arolla) and gabbros (*e.g.,* the base of the Cervino/Matterhorn: Dal Piaz *et al.*, 1977). A Mesozoic sedimentary cover, composed of quartzite, marble, dolostone, sedimentary breccia, conglomerate, etc. is locally preserved in the Dent Blanche-Mont Mary system (Roisan zone, Mont Dolin) and has been metamorphosed together with the basement (Ayrton *et al.*, 1982; Canepa *et al.*, 1990). Similarly, a metamorphosed sedimentary cover has been described in the Sesia-Lanzo zone (Venturini, 1995).

During the Alpine orogeny, the high-grade metamorphic and igneous basement was metamorphosed in eclogite-facies (the Sesia-Lanzo and lower Austroalpine outliers) or blueschist-facies (the upper Austroalpine outliers: Dent Blanche, Mont Mary, Pillonet) conditions, giving rise, respectively, to *micascisti eclogitici* (*auct*.) and chloritoid-bearing micaschists (Dent Blanche: Kienast & Nicot, 1971), and then phengite-jadeite orthogneiss and Na-amphibole mafic boudins (Pillonet: Dal Piaz, 1976). As for the leucocratic granitoids that intruded the Adria basement during the Early Permian, they were transformed into *Gneiss minuti* (Sesia-Lanzo) and *Gneiss Arolla* (Dent Blanche *s.l.*).

The metagranitoid and metapelites of the Sesia-Lanzo zone are of particular interest, because they have preserved rather well the eclogite-facies paragenesis. The *micascisti eclogitici*, first defined and studied by Stella (1894) and Franchi (1900,

1902), are coarse-grained micaschists, with quartz, phengite, paragonite, large garnet crystals, omphacite, glaucophane, chloritoid and rutile (*e.g.*, Lillianes, see Stop 2.7). Some granites gave rise to the famous eclogite-facies rocks, with jadeite, quartz, phengite, and garnet (*e.g.*, Monte Mucrone: Compagnoni & Maffeo, 1973; Compagnoni *et al.*, 1977; Oberhänsli *et al.*, 1982, 1985; Rubbo *et al.*, 1999).
In the Dent Blanche nappe, the blueschist-facies P-T conditions were estimated at 400-550°C and 0.7-0.8 GPa (Kienast & Nicot, 1971; Cortiana *et al.*, 1998), whereas higher P-T-values have been obtained for the Sesia-Lanzo eclogite-facies rocks (*e.g.*, 550±50°C and 1.4-2.1 GPa: Oberhänsli *et al.*, 1985; Inger *et al.*, 1996; Tropper *et al.*, 1999).
The peculiarity of the Sesia-Lanzo nappe and of the upper Austroalpine outliers is the relatively old age of their high-P metamorphism, which is dated as Late Cretaceous (110±13 Ma, Jäger *et al.*, 1990; 69.2±2.7 Ma, Duchêne *et al.*, 1997; 65±5 Ma, Rubatto *et al.*, 1998). A similar age was obtained for the Pillonet klippe (75-73 Ma: Cortiana *et al.*, 1998). These ages have been interpreted as the crystallization age of the eclogite-facies paragenesis at a depth of 50-100 km.
In the Sesia-Lanzo zone, Gosso (1977) and Gosso *et al.* (1979) identified four Alpine deformation phases (D1-D4), on the basis of field interference structures and microstructures. The D1 phase was coeval to the eclogite-facies event and produced an almost complete transposition, whereas D2-D4 are post-nappe deformation phases, which occurred at different steps of the retrogression or during the late mesoalpine greenschist-facies overprint.
The tectonic contact between the Austroalpine domain (*i.e.*, the Sesia-Lanzo and Dent Blanche nappes) over the Piedmont meta-ophiolites (*i.e.*, the Zermatt-Saas and Combin units) is locally outlined by Permian gabbro bodies (*e.g.*, Dal Piaz *et al.*, 1977; Zanella, 1992) that were strongly deformed under blueschist or greenschist-facies conditions during accretion or exhumation (*e.g.*, Monte Pinter, Monte Tantané, Cervino/Matterhorn, and Moussallion). Therefore, it seems that the thrust plane reworked pre-existing normal shear zones of the Adria crust, along which the gabbro bodies had been exhumed and laterally juxtaposed to coeval shallower intrusions (Dal Piaz, 1993). In contrast with the Monte Rosa/Zermatt-Saas contact, which is folded, the Dent Blanche/Combin contact is generally straight and regular.

Field trip itinerary

DAY 1

"Contact between Europe (the Monte Rosa unit) and the Tethys ocean (the Zermatt-Saas meta-ophiolites)"

From the meeting point at the Novara railway station, we leave at 13:00 for Val di Gressoney, where we will take a cableway up to Passo dei Salati (N 45° 52.617'; E 7° 52.069'; alt. 2936 m). If we arrive early, we shall go uphill from the top of the cableway towards Stolemberg Peak.

Stop 1.1:

Tectonic contact between Monte Rosa gneiss and Zermatt-Saas ophiolite, at the klippe of Punta Stolemberg (N 45° 52.762'; E 7° 51.936'; alt. 3068 m)

The Stolemberg peak is a beautiful example of a klippe of Zermatt-Saas ophiolitic metabasalts resting on the Monte Rosa basement. On the slopes of the peak, we first observe typical Monte Rosa micaschists, with Alpine imprint and some white aplitic gneiss. At a platform (N 45° 52.698'; E 7° 51.983'; alt. 3043 m), some metabasic lenses occur within the Monte Rosa gneisses, which display an almost horizontal fabric (foliation 012/11). A little further on, going uphill, we observe the contact between the Monte Rosa gneiss and the Zermatt-Saas meta-ophiolites (N 45° 52.762'; E 7° 51.936'; alt. 3068 m). Large amphibole, talc and chlorite reaction rims develop between gneiss and serpentinite (the pathway can be slippery). The Stolemberg meta-ophiolites mainly consist of banded albite-bearing amphibolite, with garnet relics, deriving from former eclogite. Some eclogite relics, which escaped subsequent retrogression, consist of omphacite, garnet and amphibole.
We walk along the contact. As this one is folded, we come across different lenses of Monte Rosa gneiss and meta-ophiolite. We thus find several repetitions of the two units.

Stop 1.2:

Panoramic viewpoint (N 45° 52.934; E 7° 51.874)

We reach a point (N 45° 52.934; E 7° 51.874), from where we have a sweeping view, but the path becomes difficult (very steep and with ropes), so we stop here.
Looking towards the south, we see closest to us Corno Rosso and Lago Gabiet, which belong to the Combin ophiolitic unit, and, in the distance, a ridge with the

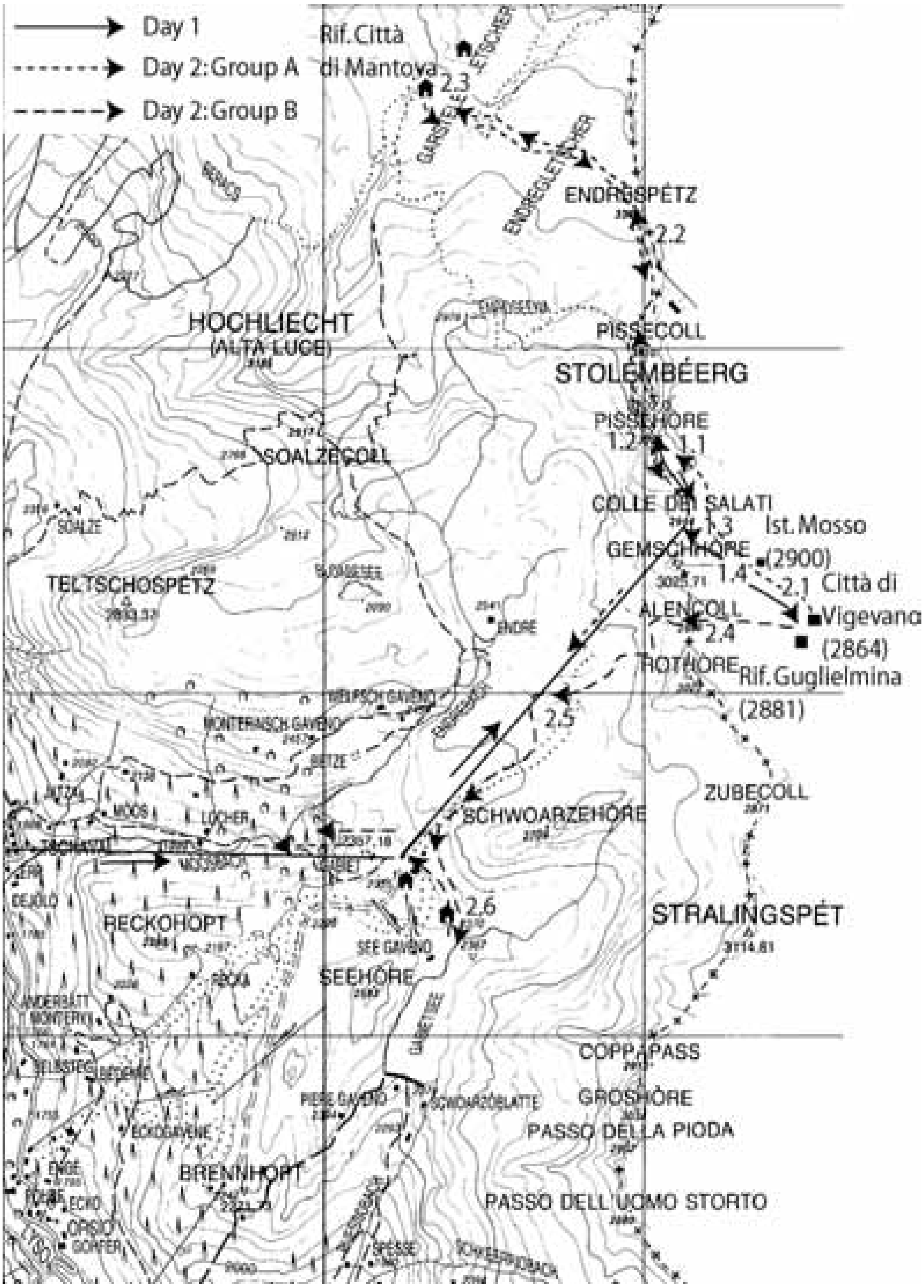

Figure 3 - Itinerary of days 1 and 2. Note that the paths for different groups are traced with different symbols.

Figure 4 - Folded contact between the Monte Rosa Basement and Zermatt Saas ophiolites at Mt. Stolemberg.

Straling and Corno Bianco peaks which belong to the overlying Sesia-Lanzo zone (*Gneiss minuti*). The folded contact between the Sesia-Lanzo gneiss and the meta-ophiolites is visible on the western side of the Gressoney valley, from Monte Pinter (to the south) to Testa Grigia and Monte Rothorn. Further north, the Combin unit occurs between Passo del Rothorn and Passo Bettaforca, where there is the tectonic contact between the Combin and Zermatt-Saas meta-ophiolites. The latter unit crops out on the southern slopes of the Monte Rosa massif. North of a line going from Monte Rosso to Lago Bleu, all the snowy peaks of Monte Rosa consist of Penninic gneiss.

At the base of the cliff, at about 300 m in the direction of N240, one can see the ruins of an old gold mine (19^{th}-20^{th} centuries; Lorenzini, 1998, p. 157-158). Quartz sulphide gold-bearing veins are quite abundant in the Monte Rosa massif (*e.g.,* Curti, 1987; Lattanzi, 1990; Pettke *et al.*, 1999), noticeably near Alagna (Val Sesia), where they have been mined for centuries. The ore is related to the mesoalpine hydrothermal activity (Stella, 1943).

We return downhill. After passing the top of the cableway, we descend a few metres and leave the path, moving some tens of metres to our right, below Corno Camoscio.

Stop 1.3:

<u>The contact between Monte Rosa gneisses and Zermatt-Saas ophiolites</u> at Corno Camoscio (N 45° 52.481'; E 7° 52.136'; alt. 2952 m)

At the base of Corno Camoscio, which consists mainly of serpentinite, we can observe again the

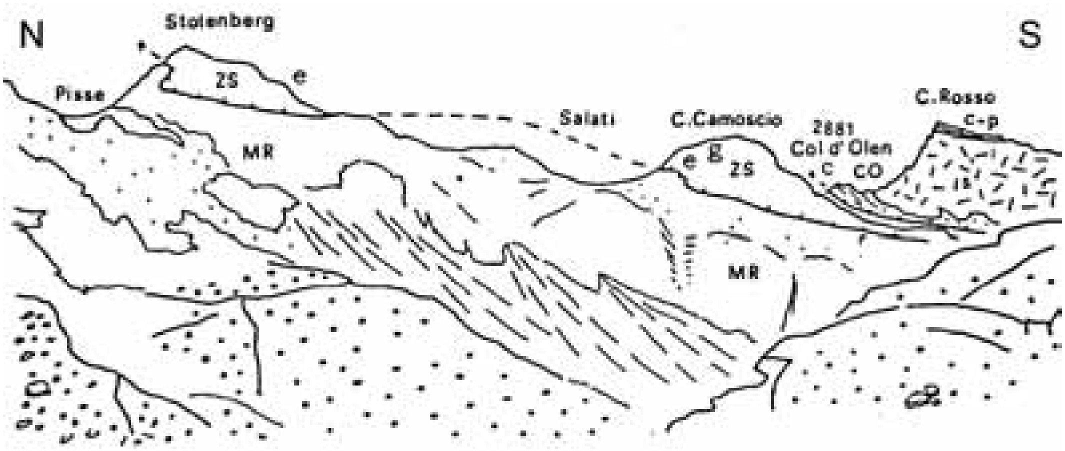

Figure 5 - Stolemberg-Col d'Olen section. The south-dipping tectonic contact between the Monte Rosa basement and the Zermatt- Saas meta-ophiolites is represented. The Monte Rosa-Zermatt Saas infolding is not evidenced. Legend: MR= Monte Rosa, ZS= Zermatt-Saas, Co=Combin, e=eclogite, g= metgabbro, c=calcschists, s= serpentinite.

Figure 6 - M. Pinter-Testa Grigia-M. Rothorn- ridge on the right side of the Gressoney valley. The ridge is characterized by the infolding of calcschists and prasinite (Combin meta-ophiolites) and by Gneiss Minuti (the Sesia-Lanzo unit). North of Mt. Bettaforca, at Colle Bettaforca, the Combin meta-ophiolites are in tectonic contact with the underlying eclogite–facies Zermatt-Saas meta-ophiolites. For legend, see the previous figures. CO = Combin, SL = Sesia-Lanzo, ZS = Zermatt-Saas.

folded contact of Monte Rosa gneiss and metabasites belonging to the Zermatt-Saas ophiolites. The Monte Rosa gneisses consist here of banded rocks, with leucocratic quartz+feldspar-rich layers alternating with mafic layers (5 cm thick) that are boudinaged and variously folded. Some debris of these gneisses shows pseudotachylites. A few metres up, at the contact between the Monte Rosa and Zermatt-Saas units (N 45° 52.481'; E 7° 52.136'; alt. 2952 m), we observe garnet+chloritoid micaschists and abundant tremolitite. This latter rock is typical, together with chloritite and tremolite + talc + epidote ± garnet rocks, of the reaction rims that developed between micaschists (or gneiss) and serpentinite. Further uphill, one can see the mylonitic gabbro and serpentinite of Corno Camoscio.

Go downhill and return along the pathway that leads to Rifugio Città di Vigevano.

Stop 1.4:

<u>Monte Rosa folded garnet micaschists and gneiss</u> near Istituto Mosso (N 45° 52.469'; E 7° 52.308'; alt. 2902 m)

Where the pathway passes near Istituto Mosso, leave the path to reach an outcrop that is a few metres to the left (N 45° 52.469'; E 7° 52.308'; alt. 2902 m). A 2-m-high section shows typical Monte Rosa gneisses, consisting of 3-to-20-cm-thick alternating layers of quartz+feldspar-enriched rocks (leucosome) and mica-rich rocks (former melanosome). Note the large garnet crystals (up to 2 cm in diameter) that are wrapped in the pre-Alpine foliation and the disharmony of folds, due to the contrasted behaviour of the various layers. On the right, a boudin (1x3 m) of metabasite is folded within gneisses.

Inaugurated by Queen Margherita in 1907 and managed by the Torino University, the Istituto Mosso is devoted to scientific research in the fields of physiology at high altitudes, meteorology, glaciology and geology. It was recently completely destroyed by a fire, but is now under reconstruction.

Figure 7 - Alternating layers of quartz+feldspar-enriched rocks (leucosome) and mica-rich rocks (melanosome). Axes of the asymmetric folds are oriented 280/12.

Return to the pathway and go downhill, crossing again some Monte Rosa gneiss and ophiolitic slices. For dinner, reach Rifugio Città di Vigevano (N 45°

52.251'; E 7° 52.413'; alt. 2865 m), built in 1914, where we will illustrate the next day's excursions.

DAY 2

"Crossing the Tethys ocean, from Europe (Monte Rosa) to Adria (Sesia-Lanzo zone)"

The second day is devoted to a section across various Alpine tectonic slices, traversing the Europe plate (Monte Rosa unit), the Tethys ocean (Zermatt-Saas ophiolites), up to the Adria microplate (the Sesia-Lanzo zone). Two itineraries are proposed, depending on the physical capabilities of the participants.

A first group (Group A) of fit people with mountain experience can go uphill to Punta Indren and then to Rifugio Città di Mantova to observe the pre-Alpine Monte Rosa migmatitic basement that was subsequently eclogitized during Alpine metamorphism. This is recommended for people with a good knowledge of the mountain, as it demands severe physical efforts, having to cross a glacier and to climb a hill (via ferrata). Alpine equipment is mandatory (strong boots with creepers, alpine clothes).

A second group (Group B) will follow an itinerary that starts from the Monte Rosa unit and crosses the Zermatt-Saas ophiolite unit up to Lake Gabiet, where the upper contact of the meta-ophiolites with the Sesia-Lanzo unit can be seen.

The two groups will join in the valley, at Gressoney, and then visit continental eclogitized rocks of the Adria microplate (Lillianes; the Sesia-Lanzo unit).

Groups A and B

Stop 2.1:

Metabasic dyke in serpentinite, north of Rifugio Città di Vigevano (N 45° 52.321'; E 7° 52.371'; alt. 2861 m)

The mountains that can be seen to the east of the refuge, on the other side of the Sesia valley (Monte Tagliaferro, Cima Carnera, and Cima delle Croci), show a jagged profile due to regional foliation and faults. They belong to the Combin ophiolite (Tagliaferro) and overlying Sesia-Lanzo unit (*Gneiss minuti* and *II Dioritico-kinzigitico klippen*).

Around the refuge we can again observe the main lithologies of the Zermatt-Saas and Monte Rosa units. The Monte Rosa garnet-bearing micaschists, with chloritoid ± kyanite, are folded by rounded folds.

A few tens of metres north of the Rifugio Città di Vigevano, serpentinite of the Zermatt-Saas unit is visible near a small lake. Looking towards Corno Camoscio, a 3-m-high ridge is visible (N 45° 52.321'; E 7° 52.371'; alt. 2861 m). It is mainly made of foliated serpentinite and shows a 50-cm-thick dyke of metabasite, slightly rodingitised, and consisting of dark-green amphibole, Ca-rich garnet and epidote. The transposed dyke, is foliated, almost horizontal and slightly boudinaged. A 2-cm-thick rim of chloritite occurs between the dyke and the enclosing serpentinite. The latter displays a number of brownish rounded spots that were preferentially dissolved by weathering and are made of carbonates.

Figure 8 - Foliated serpentinites and a 50-thick transposed dyke of a slightly rodingitised metabasite (Zermatt-Saas meta-ophiolites).

Group A

Stop 2.2:

the Monte Rosa basement at Punta Indren (N 45° 53.01'; E 7° 51.89'; alt. 3109)

From Rifugio Città di Vigevano, we turn back towards Punta Stolemberg. Passing through Stop 1.2 from yesterday, we descend the roped slope of Punta Stolemberg and, walking along the northern contact of the ophiolitic klippe with Monte Rosa gneiss, we reach Col delle Pisse (N 45° 53.01'; E 7° 51.89'; alt. 3109), where numerous lenses (boudins) of metabasite from pre-Variscan protoliths are found in the Monte Rosa basement.

From that point we will cross typical Monte Rosa gneiss, with garnet-rich micaschists and leucocratic gneiss. These rocks contain cm-to-m-sized boudins of a very fine-grained eclogite with blue-amphibole blasts overgrowing the fine-grained matrix. In thin section, phengite, rutile, quartz, omphacite and numerous microcrystalline atoll-shaped garnet crystals, whose core is filled with quartz or phengite, are observed. The blue amphibole (crossite and/or glaucophane) has grown lately, according to a sliding reaction (omphacite + garnet + quartz + H_2O = glaucophane) that has consumed quartz and omphacite but preserved some garnet, occurring as corroded crystals in the amphibole blasts. Surprisingly enough, these rocks are identical to the Champtoceaux and Malpica-Tuy eclogites that are known in the Variscan belt (*e.g.*, Godard *et al.*, 1981; Godard, 1988). As their Variscan equivalent, these peculiar Monte Rosa eclogites are thought to represent pre-Variscan mafic sills of continental tholeiitic affinity (Ferrando *et al.*, 2002; Dal Piaz, 2001) intruded in the Monte Rosa continental crust, and subsequently boudinaged and eclogitized with the latter during the Tertiary subduction. Their origin is different from that of the nearby Stolemberg eclogite (Stop 1.2) which results from eclogite-facies metamorphism of ophiolitic normal MORB (*e.g.*, Beccaluva *et al.*, 1984).

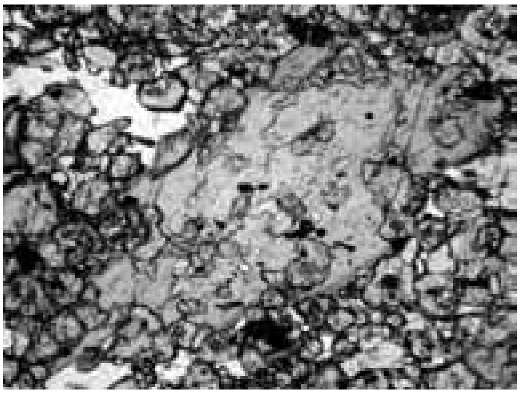

Figure 9 - Fine-grained eclogite (garnet + omphacite + quartz), with blue-amphibole blast overgrowing the matrix and enclosing some garnet crystals. Plane-polarized light, base of the photo corresponds to 1 mm.

Climbing to Punta Indren, note the beautiful, typical garnet-bearing micaschists. From Punta Indren, we cross the Indren glacier and climb up the rocky ridge made of Monte Rosa gneiss and migmatite to reach Rifugio Città di Mantova.

Figure 10 - Nebulitic structures, leucosomes and melanosomes in eclogitized migmatite near Rifugio Città di Mantova. The black patches are pseudomorph after cordierite. Lens cap = 3 cm.

Stop 2.3:
<u>Eclogitized migmatites</u> at Rifugio Città di Mantova

NW of the Rifugio, outcrops show migmatitic paragneiss with transposed leucocratic dykes. Migmatisation is obvious due to the common occurrence of leucosomes, melanosomes and nebulitic structures. In some places, migmatite encloses cm-sized dark spots that are pseudomorphs after cordierite.

These rocks show petrological evidence for two distinct metamorphic stages. An early paragenesis, typical of high-T low-P conditions and coincident with migmatisation, consists of biotite + quartz + plagioclase + garnet ± cordierite ± K-feldspar + ilmenite.

During a second stage, the rocks underwent a high-P metamorphism that is indicated by several metamorphic reactions:

Biotite + plagioclase = garnet + phengite + quartz + rutile [coronas occasionally visible with a magnifying lens];

Biotite = garnet + phengite + rutile [biotite pseudomorph; Figure. 13];

Ilmenite + plagioclase = garnet + rutile + quartz [coronas around ilmenite; Figure. 14].

Cordierite = garnet + micas + kyanite ± quartz [cordierite pseudomorph; Figure. 15];

These reactions, which produced garnet, rutile, and phengite at the expense of biotite, ilmenite and plagioclase, are typical of a high-P eclogite-facies metamorphism. During such a metamorphism,

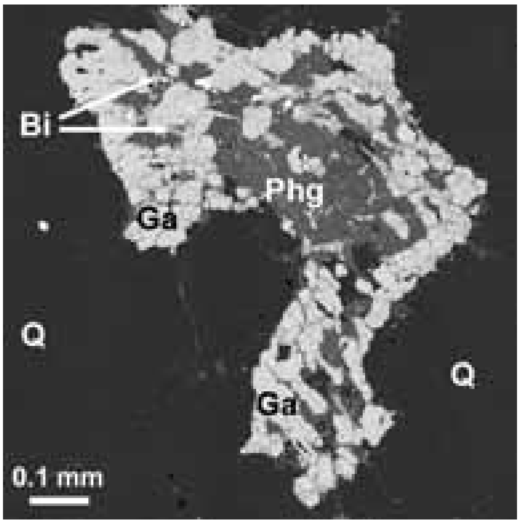

Figure 11 - Eclogitized migmatite at Rifugio Città di Mantova: Pseudomorph after biotite. Biotite (Bi: remnants) isolated in a matrix of quartz (Q) has been replaced by an assemblage of garnet (Ga), phengite (Phg) and rutile (white inclusions in phengite). Back-scattered electron image.

plagioclase in metapelitic rocks is ordinarily replaced by cryptocrystalline aggregates of jadeite + quartz (+ kyanite + zoisite), which in turn are retrogressed into polycrystalline albite or oligoclase during decompression (*e.g.,* Tropper *et al.*, 1999; Bruno *et al.*, 2001). As for the Monte Rosa migmatites, the initial plagioclase was replaced by cryptocrystalline albite that contains rodlets of kyanite, zoisite and phengitic muscovite (Figure. 15). Although jadeite has not been observed yet, it is likely that this plagioclase recrystallisation was due to the albite-to-jadeite transition followed by the reverse reaction during retrogression.

The two metamorphic stages belong to two distinct orogenic cycles, namely pre-Permian (pre-granitic high-T cordierite-bearing migmatites) and Alpine (eclogite-facies coronas and pseudomorphs after cordierite). This metamorphic history is characteristic of the whole Monte Rosa basement, which represents a slice of the Variscan European continental crust that underwent subduction and subsequent eclogite-facies metamorphism during Alpine convergence.

Group A returns to Passo dei Salati to take the cableway to Gressoney.

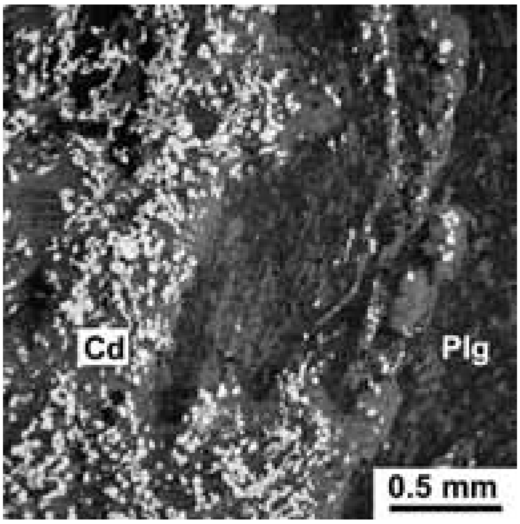

Figure 13 - Eclogitized migmatite at Rifugio Città di Mantova: Pseudomorph after cordierite. Plg: pseudomorph after plagioclase, mainly made of albite, possibly after jadeite (dark grey); Cd: Cordierite pseudomorph made of garnet (light grey), micas (grey), kyanite and minor quartz (dark grey). Back-scattered electron image.

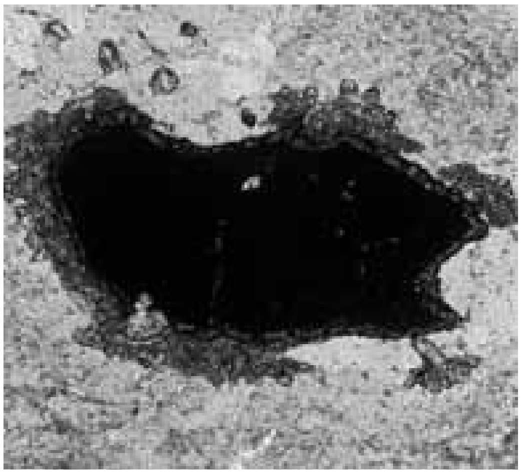

Figure 12 - Eclogitized migmatite of Rifugio Città di Mantova: high-pressure corona between ilmenite and plagioclase. Garnet and quartz grew at the expense of plagioclase, whereas a thin rutile corona occurs on the ilmenite side. Note that the corona is interrupted at contacts with quartz. Plane-polarized light.

Figure 14 - Large garnet porphyroclasts in garnet-chloritoid bearing "calcschists" at Col d'Olen. Lens cap diameter is 3 cm.

<u>Group B</u>

Stop 2.4:

The <u>contact between Zermatt-Saas and Combin meta-ophiolites</u> at Col d'Olen (N 45° 52.229'; E 7° 52.129'; alt. 2885 m)

Group B reaches the neighbouring Albergo Guglielmina, built in 1878 (N 45° 52.235'; E 7° 52.353'; alt. 2869 m), where we take the pathway that goes up to Col d'Olen.

Col d'Olen (N 45° 52.229'; E 7° 52.129'; alt. 2885 m) is located at the tectonic contact between the retrograded greenschist-facies metabasites and serpentinite of the Zermatt-Saas unit on the right (*i.e.,* Corno Camoscio to the north), and serpentinites of the Combin unit on the left (*i.e.,* Corno Rosso to the south). The contact is outlined by cataclastic or folded calcschists with prasinite bands and thin quartzites. Although irregular, the contact dips towards the SSE at an angle of about 25°.

Following the ridge a few metres southwards, give a look at the calcschists. Some layers contain large garnet porphyroclasts (up to 2 cm in diameter) and chloritoid. A little further along the ridge, lenses of listvenite (altered carbonate-bearing serpentinite) are observable in the calcschists.

Stop 2.5:

<u>Zermatt-Saas and Combin meta-ophiolites</u> on the pathway towards Gabiet (e.g., N 45° 52.25'; E 7° 51.76'; alt. 2800 m)

Descending the path from Col d'Olen, we observe rather complex associations of serpentinite, tremolitite, calcschists, and rodingite from the Zermatt-Saas unit.

The pathway crosses a ski run, and, close to the cableway, reaches a sliced recumbent fold of the Monte Rosa pre-Triassic basement inside meta-ophiolites. Here, the basement is made of garnet-bearing micaschists with boudins of eclogite and albite-bearing amphibolite (N 45° 52.272'; E 7° 57.272'; alt. 2798 m). It may be attributed to the Furgg zone (see "Monte Rosa unit" in the "Regional geologic setting" section), which occurs along the Cima Indren-Gabiet section (Gosso *et al.*, 1979).

The contact between the Zermatt-Saas meta-ophiolite and the Monte Rosa unit is again very irregular, being deformed by the same post-nappe folds observed near Col d'Olen.

On the way down to Gabiet, we cross again the same calcschist level observed at Col d'Olen.

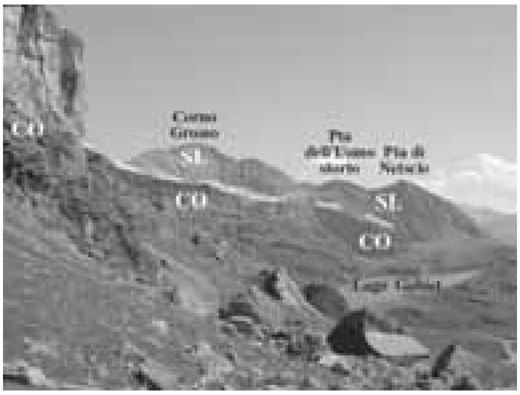

Figure 15 - View of Lago Gabiet (resting on meta-ophiolites) with Punta Straling, Corno Grosso, P.ta dell'Uomo Storto and Corno Bianco (the Sesia Lanzo zone) in the back. The ridge between the lake and the peaks is made of calcschists and serpentinites.

Looking back to the north we can see, at the base of Corno Camoscio, the folded contact between the Zermatt-Saas greenish meta-basalts and serpentinites (above) and the light-brownish Monte Rosa basement (below).

To the east Corno Rosso is made up of serpentinite capped by thin alternances of calcschists and tabular prasinite, all belonging to the Combin unit.

Stop 2.6:

Panoramic viewpoint on the upper contact between the meta-ophiolites and the Sesia-Lanzo zone, at Lago Gabiet (alt. 2367 m)

We arrive at Lago Gabiet, which was created by a gravity dam (2367 m). From here, beautiful panoramic views allow us to summarise what we have seen and to add some regional perspective. From bottom to top, we notice three elements : (i) the Combin meta-ophiolites; (ii) the contact between the Combin meta-ophiolite (below) and the Sesia-Lanzo unit (above); and, further up (iii) the albitic banded orthogneiss (*Gneiss minuti* auct.) of the Sesia-Lanzo zone (Adria continental crust, Austroalpine domain). The Combin meta-ophiolite is made up of bands of calcschists, prasinite, metagabbro and serpentinite, which crop all around Lago Gabiet. Also notice that the contact between the Combin meta-ophiolite and the Sesia-Lanzo unit passes along the slopes of Punta Straling and Corno Grosso; it is marked by its morphology and a contrast in colours. Near Punta Starling, this contact is deformed by a large-scale south-verging fold and, at Corno Rosso, it dips gently southwards.

We take the cableway at Gabiet towards Gressoney. This cableway follows the small Mos valley, where serpentinite and retrogressed eclogite (near the Mos house) from the Zermatt-Saas unit crop out.

Groups A and B

We all meet at the parking lot, and should be on the bus at 4:30 pm (remember that the cableway takes 20 min from Passo dei Salati, and 10 min from Gabiet).

We descend the Gressoney valley, passing from the meta-ophiolites to the Sesia-Lanzo zone.

Stop 2.7:

The Sesia-Lanzo unit (i.e., Adria microplate) at Lillianes (N 45° 37.985'; E 7° 50.634'; alt. 646 m)

From Gressoney the bus goes southwards along the *Val di Gressoney* for about 30 km. After the first 6 km, near Chemonal (Gressoney-Saint-Jean), we cross the tectonic contact between the Piedmont nappe (the Combin meta-ophiolite with dominant calcschists) and the Sesia-Lanzo zone (*Gneiss minuti* unit, orthogneiss without eclogite-facies relics). At Issime, 14 km south of Gressoney-Saint-Jean, we enter into the inner part of the Sesia-Lanzo zone, which is characterized by a well-preserved eclogite-facies imprint (*Micascisti eclogitici* unit). We stop a few km further to the south, at Lillianes, to observe this high-pressure unit in the Lys River.

Figure 16 - Eclogite-facies Sesia-Lanzo rocks at Lillianes. Note the dark lamprophyre dikes that crosscut all structures.

Here, we leave the bus and cross the arched medieval stone bridge over the Lys River. We descend to the western river bank to observe rocks of the Sesia-Lanzo unit (note the large erratic block consisting of beautiful eclogitic micaschists with cm-sized garnet crystals). Some metres down from the bridge an outcrop displays a whole range of eclogite-facies rocks (micaschists, gneiss, leucocratic dykes and eclogite) boudinaged and deformed together. These rocks show a polyphase metamorphic evolution, with a pre-Alpine high-grade evolution typical of a continental crust, followed by the Alpine eclogite-facies imprint. Several late-Alpine undeformed dykes of a dark ultrapotassic lamprophyre (Venturelli *et al.*,

Fig. 17 - Microphotograph of the contact between Eclogitic Micaschist (on the left, note garnet) and lamprophyric dyke (note pyroxene and biotite phenocrysts). Plane-polarized light, width of the photograph = 3 mm.

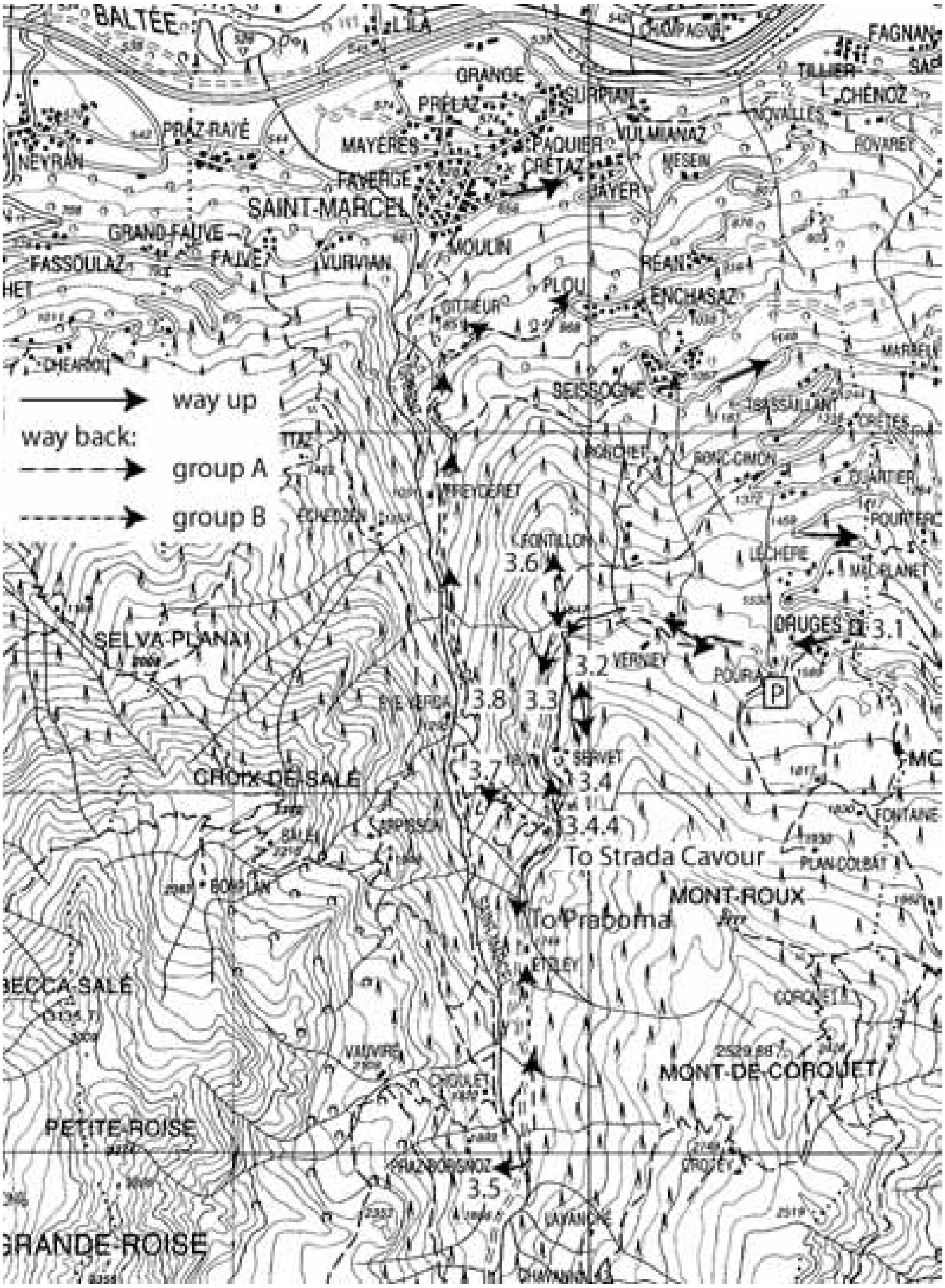

Figure 18 - Itinerary of day 3. Note that paths for different groups are traced with different lines, and that two different paths can be followed to return to the bus: read text for details.

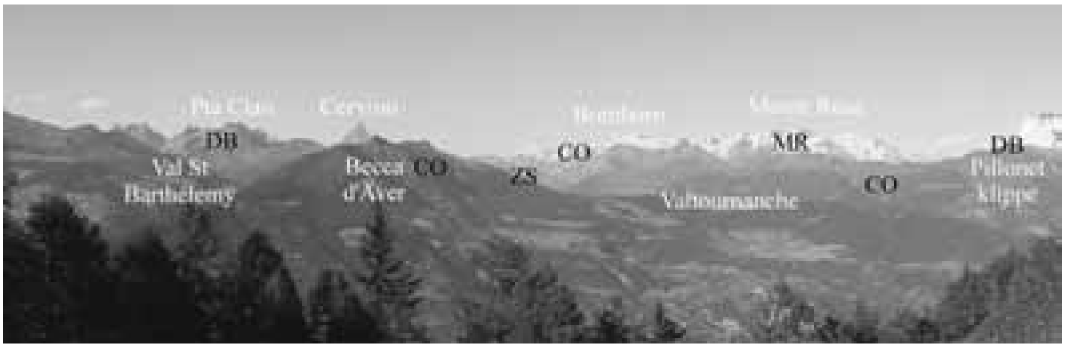

Figure 19 - Panorama from the road to Druges looking towards the North. Mountain and localities names are in white. In black the different units: DB = Dent Blanche; CO = Combin greenschist ophiolites; ZS = Zermatt-Saas eclogitized ophiolites; MRU = the Monte Rosa Unit.

1984) crosscut the high-pressure fabric. In the Western Alps, such post-metamorphic intrusions crosscut the Alpine nappe pile (Dal Piaz *et al.*, 1979b). They display Late Oligocene ages (Venturelli *et al.*, 1984; Pettke *et al.*, 1999), and were probably generated by partial melting of a metasomatised mantle, with some contamination by the Alpine crust (Dal Piaz *et al.,* 1979b; Venturelli *et al.*, 1984). Moreover, we can see in the river bed some huge loose blocks of eclogite that come from the Zermatt-Saas meta-ophiolite.

DAY 3

"Eclogitized hydrothermal deposits in ophiolites: the Servette and Praborna mines"

During this day we visit the eclogitized oceanic deposits of Saint-Marcel, namely the Fe-Cu hydrothermal sulphide deposit of Servette and the famous Praborna Mn mine, which allow observation of peculiar high-pressure lithologies and minerals. As these mines, now abandoned, had been exploited since the 17th century (Praborna) and even in Roman times (Servette), archaeological and historical aspects will also be considered (ruins, old foundry and slags). Furthermore, the trip reproduces the one followed by Horace-Bénedict de Saussure on 20th August 1792 (*Voyages dans les Alpes*, t. 4, pp. 454-460), on which occasion he described blueschists ("schorl bleuâtre") for the first time.

Stop 3.1:

Panoramic viewpoint on the road between Druges Basses and Druges Hautes (N 45° 42.469'; E 7° 28.608'; 1585 m)

We leave *Collegio Gervasone* by minibus at 8:00 am after breakfast and head to Druges (Saint-Marcel). After a 1h15 drive, on the way up, we stop at a panoramic viewpoint.

Spectacular view of (from E to W): Monte Rosa (Penninic nappe), Cervino/Matterhorn (Dent Blanche Austroalpine nappe), Grandes Jorasses and Mont Blanc (Helvetic nappe). Lower down, on the northern side of the Aosta valley, we observe the eclogite- and blueschist-facies ophiolites of the Piedmont nappe

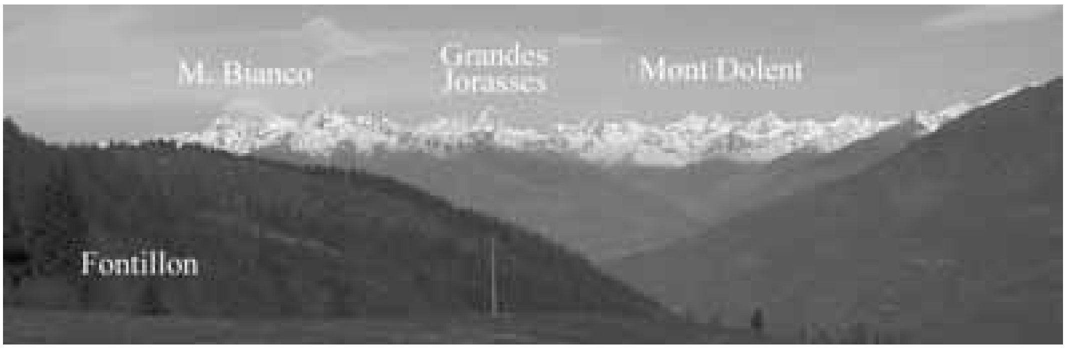

Figure 20 - Panorama from the road to Druges (continued from Fig. 19).

Figure 21 - Remains of the old foundry at Treves: a furnace structure.

and slices of continental crust attributed to the Adria margin (Châtillon, Pillonet and Mont Mary).
We reach Druges Hautes in five minutes. Here we leave the bus, and have a 30-mn walk up to the ruins of the old foundry of Treves.

Stop 3.2:

Old foundry of Treves

(N 45° 42.444'; E 7° 27.432'; alt. 1672 m)

In this foundry, copper metal was extracted from chalcopyrite ($CuFeS_2$) from the nearby Servette mine. The blast furnace was loaded by the top, through a path coming from the mine (see the pillars that supported the catwalk). Layers of mineralised stones and coal, used as fuel, were interlayered in the furnace. The process produced gas, iron-rich silicate slags and copper. Such blast furnaces have been used since the 15th century.

Stop 3.3:

Slag heap

(N 45° 42.449', E 7° 27.304', alt. 1659 m)

Near the foundry, on the southern side of the main road, we can observe huge amounts of slags deriving from the processing of Servette ore.
Two main kinds of slags are observed (Casartelli, in

Figure 22 - Huge slag heap on the path between the Treves foundry and Servette mine. In the inset, slag with fragments of charcoal (used for dating).

preparation). Some are porous and contain fragments of gangue and pieces of carbonised wood. The more abundant slags, however, look like lava.
They display an upper face with fluidal structures, internal flow channels, and a rough lower face (soil imprint).
The slags are mainly composed of fayalite, wustite, spinel, relict sulphides and interstitial glass that concentrated such residual elements as Ca, K, and Na.Weathering has produced green crusts of Cu sulphates (Casartelli, in preparation).
A preliminary dating of a piece of carbonised wood (*Picea excelsa*) enclosed in a piece of slag provided an age of 1120±40 BP (GX-29281; Mambretti, 2003). This indicates that the mine was active during the Middle Ages, far before the activity of the Treves foundry.
From the slag heap, leave the main road and take a pathway that climbs in the woods towards the ancient mine of Servette.
Along the path, some outcrops of magnetite-bearing serpentinite can be observed.
At a fork, take the left branch of the way that leads to the uppermost level of the Servette mine, which was dug in sulphide-bearing meta-ophiolites.

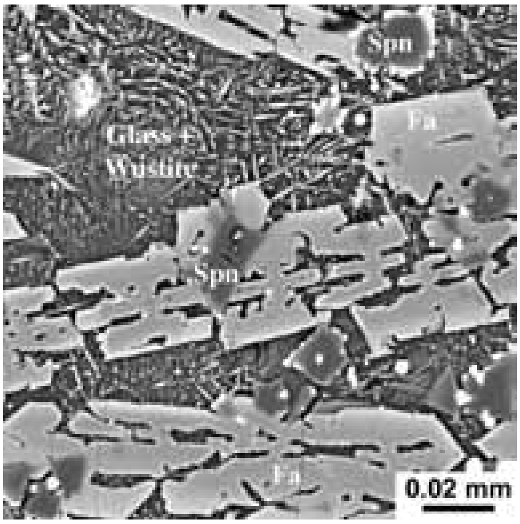

Figure 23 - Piece of slag from the ancient Servette mine. Spinel (Spn) and skeletal fayalite (Fa) grew in a liquid matrix, now made of glass (black) and skeletal wustite (grey). The small white grains are sulphides of Cu and/or Fe, whose presence indicates an incomplete oxidation. Back-scattered electron image.

Stop 3.4:

Eclogitized oceanic hydrothermal ore of the Servette mine

Introduction: The Saint-Marcel eclogite-facies meta-ophiolites, making part of the Zermatt-Saas unit, are overthrust by the Monte Emilius klippe (see "the intermediate continental slices" above). The uppermost section of these meta-ophiolites, well exposed at Servette, consists of interlayered chloriteschists, talcschists, glaucophanite, quartzite, slices of eclogite-facies metagabbro and serpentinite.
At Servette, these rocks include a Cu-Fe sulphide ore, consisting mainly of pyrite and chalcopyrite. The deposit occurs between 1717 and 1890 m in altitude. It is concentrated in two major ENE-dipping layers of 3-4 m in thickness, and some minor levels (less than 1 m) located at the boundary between chloriteschists and glaucophanite, but it is also disseminated throughout the surrounding rocks.
The Servette mine was probably exploited in the middle ages, as testified by the slag datation (1120±40 BP: see stop 3.3) and the existence of old excavations (see stop 3.4.2 below). During the 18th century, Servette was exploited by the Challant family, as recorded by Nicolis de Robilant (1786-87). However, most of the remnants actually date from the last period of exploitation (1854-1950; see Lorenzini, 1998).
The lithologies have been described in detail by Krutow-Mozgawa (1988), Martin & Tartarotti (1989) and Martin *et al.* (2004), whose work can be summarised as follows:
(a) Chloriteschists have chlorite, garnet, quartz, ±talc, ±chloritoid, ±crossite, ±paragonite and accessory sulphides, rutile, epidote, ilmenite, all aligned along the main foliation. These rocks display S1 planes (schistosity) and C-planes (shear planes), outlined by large flakes of primary chlorite, and which intersect each other at about 35°. The C-planes coincide with the main foliation of the associated glaucophanite. Garnet occurs as zoned euhedral porphyroclasts up to 1 cm in diameter, with inclusion trails (ilmenite, apatite and epidote) occurring in the core, whereas rare inclusions of rutile, crossite and chloritoid are found in the rim. Chloritoid forms cm-sized porphyroclasts elongated along the schistosity and stretched grains along the C-planes. It is often replaced by secondary chlorite. Rare blue amphibole (crossite) crystals show rims of blue-green secondary hornblende (barroisite).
(b) In talcschists, centimetric, zoned garnet crystals, characterized by a pink core and red rim, and large, dark, chloritoid porphyroclasts up to 5 cm long are

immersed in a fine-grained talc matrix. Only rutile and quartz occur as inclusions in garnet cores, whereas chloritoid and talc also occur in rims. Garnet, glaucophane, chloritoid, rutile and sulphides are irregularly disseminated in the matrix. Chloritoid shows chlorite + paragonite rims that are due to a retrograde reaction such as chloritoid + glaucophane = chlorite + paragonite. Glaucophane is rare and not retrograded.

(c) Glaucophanite is composed of glaucophane, garnet, chloritoid, epidote, paragonite and accessory phengite, rutile, magnetite and ilmenite. Glaucophane is strongly aligned in the main foliation and is microboudinaged parallel to the N-S trending lineation. Talc + magnetite ± albite and paragonite aggregates fill the stretching-related fractures and glaucophane is rimmed by blue-green secondary hornblende. Garnet crystals show different sizes. The biggest, up to 5 mm in diameter, are zoned with a core enclosing quartz and titanite. The inner rims include rutile, quartz, chloritoid, pseudomorphs after lawsonite, ilmenite and glaucophane elongated accordingly with the outside main foliation. In the outermost rims, which grew after the external foliation, inclusions are rare, as in the smaller, unzoned garnet crystals of the matrix. Prisms with a lozenge-shaped basal section are frequent in this rock. They consist of zoisite, and/or clinozoisite, paragonite, ±calcite, albite and chlorite, and are interpreted as pseudomorphs after lawsonite.

Glaucophanite in contact with talcschists is generally characterized by the absence of lawsonite, and an abundance of glaucophane and small garnet crystals, whereas the associated talcschists have abundant talc and large garnets. In these transitional rocks, chloritoid may reach 3-4 cm in length, and is generally inclusion-free.

(d) Sulphide-bearing quartzite forms thin layers. Pyrite, chalcopyrite, magnetite, garnet, cummingtonite and blue amphibole (crossite) are the major minerals, besides quartz (Martin & Tartarotti, 1989; Tartarotti & Caucia, 1993). Deerite, a rare high-pressure iron silicate ($(Fe, Mn)_6$ $(Fe, Al)_3$ Si_6O_{20} $(OH)_5$), is also found aligned along the main foliation. Sulphides may include silicates, but garnet in turn includes sulphides, cummingtonite and crossite.

(e) The ore assemblages, hosted by glaucophanite, chloriteschists, talcschists and quartzite, consist of sulphides and oxides: pyrite (FeS_2), chalcopyrite ($CuFeS_2$) with minor sphalerite (ZnS), bornite (Cu_5FeS_4), other secondary sulphides such us digenite (Cu_9S_5), pyrrotine, marcassite, mackinawite ($(Fe,Ni)_9S_8$) (Natale, 1969; Gruppo ofioliti, 1977; Castello, 1979; Castello *et al.*, 1980), native copper (Jervis, 1873), rutile, ilmenite, hematite and magnetite. Chalcopyrite generally defines "flames" in pyrite, or it borders earlier pyrite, suggesting exsolution. Occasionally, earlier pyrite has been observed inside ilmenite. Chalcopyrite and sphalerite may crystallize later as interstitial phases and fill fractures of garnet. Bornite has been observed only as small crystals inside pyrite. Ilmenite is observed both in the main foliation and in cores and rims of zoned garnet crystals. It includes rutile, exsolved ilmeno-hematite and Fe-Ti intergrowth structures, which were generated after the eclogite peak. In the matrix, ilmenite may show hematite rims.

(f) In the walls of the house, a beautiful Cr- and Mg-rich light-coloured flaser eclogite-facies metagabbro shows centimetric garnet porphyroclasts and large green Cr-rich omphacite.

(g) Micaschists and calcschists are interlayered rocks. The former may contain garnet and chloritoid, whereas the latter contain glaucophane and pseudomorphs after lawsonite.

The interlayering of glaucophanite, chloriteschists and talcschists has been interpreted as resulting from hydrothermal oceanic alteration and deformation under high-pressure metamorphic conditions of quartz-rich sediments, mafic and ultramafic materials (Martin & Tartarotti, 1989; Martin *et al.*, 2004).

The metamorphic evolution of the Servette rocks can be summarised as follows (Martin *et al.*, 2004). In quartzite, the early prograde evolution is evidenced by the presence of deerite and that of cummingtonite and crossite included in garnet. In glaucophanite, it is revealed by pseudomorphs after lawsonite and some relics of an early mineral assemblage preserved in garnet cores as inclusions of chlorite, lawsonite pseudomorphs, glaucophane, paragonite and chloritoid. In glaucophanite, the main paragenesis is characterised by the equilibrium assemblage garnet + chlorite + glaucophane + paragonite + talc. Martin *et al.* (2004) have estimated the peak metamorphic P-T conditions for the main 3 different rocks (glaucophanite, chloritschists and talcschists), as 550 ± 60°C and 2.0 ± 0.3 GPa. Finally, greenschist-facies partial retrogression is testified by several observations: garnet is partially substituted by chlorite and quartz; chloritoid and glaucophane are replaced by chlorite and paragonite.

Stop 3.4.1:

The uppermost level of the Servette mine (N 45° 42.111', E 7° 27.327', alt. 1820 m)

All the rocks and ore described above are visible along the path, occurring mainly as loose blocs in the mine debris.

Advance along a path across the debris, up to a platform where the path is interrupted (N 45° 42.054'; E 7° 27.319', alt. 1828 m). Then, go a few steps eastwards to the entrance of the uppermost gallery (N 45° 42.059'; E 7° 27.339', alt. 1829 m). The gallery was opened in glaucophanite and Mn-rich quartzite cm-to-dm-thick layers that grade into carbonate-rich micaschists. This Mn-bearing rock is rich in alurgite (pink Mn-muscovite), yellow Mn-garnet, red piemontite or/and Mn-epidotes. The main schistosity dips 20-30° towards ENE. Above the entrance (N 45°

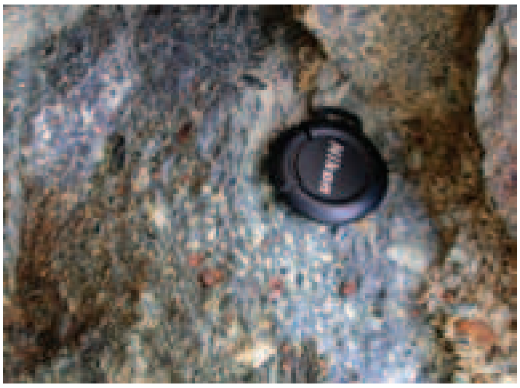

Figure 26 - Servette: glaucophanite with pseudomorphs after lawsonite, centimetric red garnet and prismatic black chloritoid. Lens cap: 3 cm

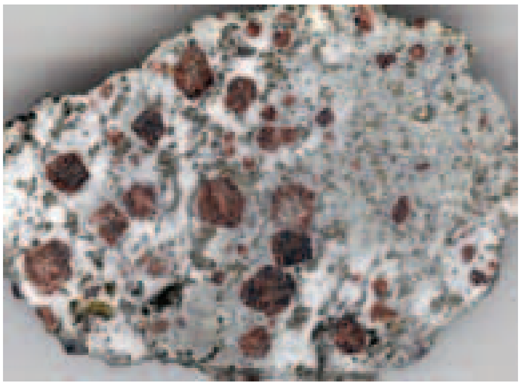

Figure 24 - Servette: mineralised quartzite. Note centimetric garnet crystals and abundant sulphides (pyrite and chalcopyrite).

Figure 27 - Servette: talcschist with large zoned garnet crystals and prismatic chloritoid. Note that small glaucophane prisms are found with talc in the matrix. Lens cap is 3 cm.

Figure 25 - Servette: rodingite consisting of red grossular-rich garnets + green diopside + epidote, in the surroundings of stop 3.4.1. Lens cap: 3 cm.

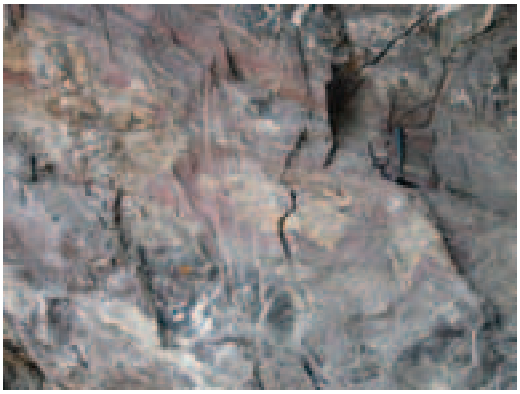

Figure 28 - Praborna: boudinaged bands of piemontite-rich (reddish) and braunite-rich (black) quartzites.

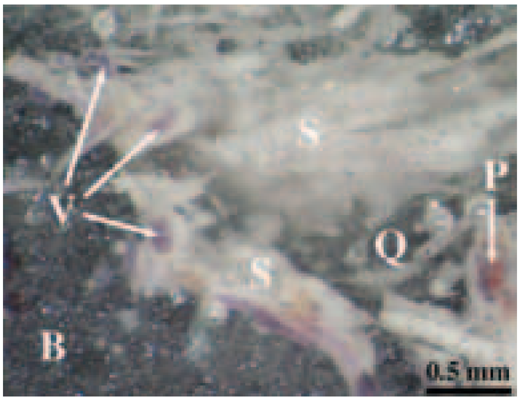

Figure 29 - Praborna: violan (V) corroded by a Cpx+albite symplectite (S), in a matrix of braunite (B) and quartz (Q), with minor reddish piemontite (P).

Figure 30 - Praborna: Cr+Fe^{3+}-clinopyroxene+garnet-rich quartzite band in braunite-rich quartzite.

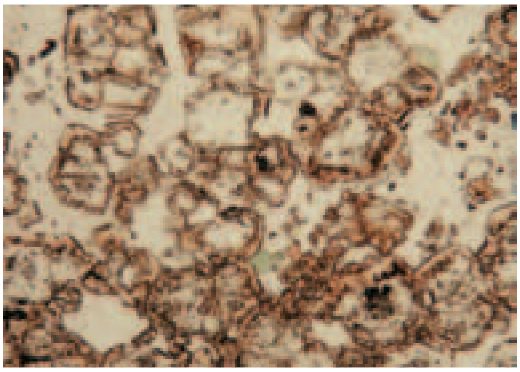

Fig. 31 - Praborna: garnet-bearing Mn-rich quartzite. Garnet rim is spessartine-rich. Plane-polarized light.

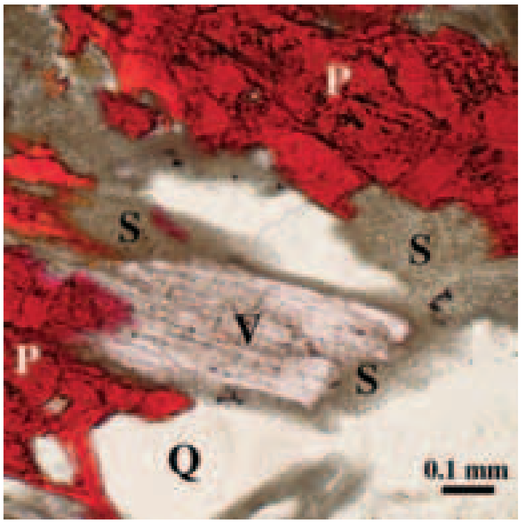

Figure 32 - Praborna; rock with piemontite (P), quartz (Q) and violan (V) partly transformed into a Cpx+albite symplectite (S) during retrogression. Plane-polarized light.

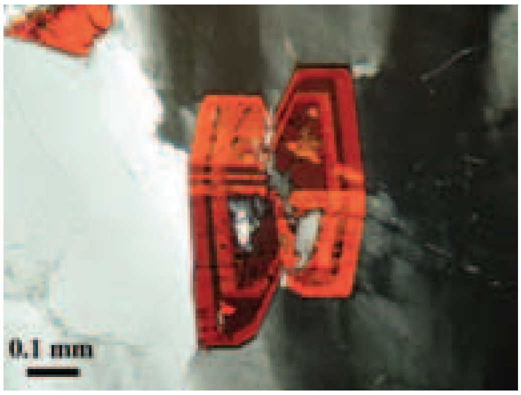

Figure 33 - Praborna: piemontite crystals in quartzite. The zoned piemontite displays mechanical twins that have a peculiar relationships with the subgrains of the host quartz. Cross-polarized light.

Figure 34 - Green fountain (Acqua Verde): blue gel covering the stones of the river.

Figure 35 - Crepin: completely eclogitized gabbro. Pyroxene is green, plagioclase white, olivine (transformed to talc) is brownish. Note coronitic rims developed between the different microdomains.

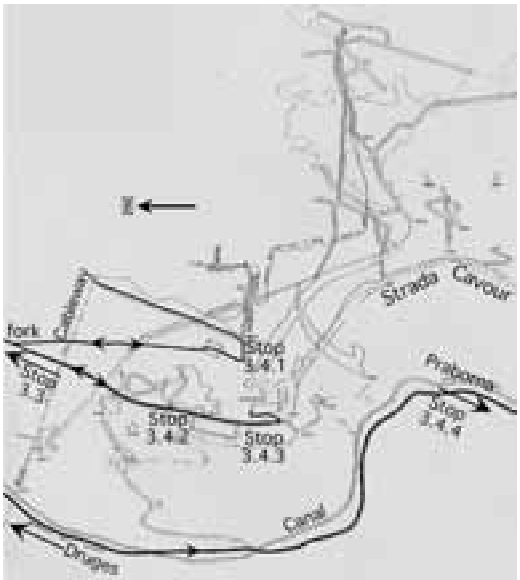

Figure 36 - Map of the Servette mine after Castello (1979).

42.061'; E 7° 27.338'), a rodingite (grossular-rich garnet + diopside + epidote) formed by metasomatism at the expense of a metagabbro, at the contact with an overlying serpentinite slice. This one separates the Servette sequence from the overlying Mont Roux rock complex, which is made up of retrogressed metagabbro, prasinite and minor serpentinite.
At the northern extremity of the uppermost level of the mine (N 45° 42.112'; E 7° 27.361'; 1820 m), one can see what used to be the upper terminal of the cableway towards the Chuc mine village and factory (see stop 3.7).

Stop 3.4.2:

The old mine (N 45° 42.066'; E 7° 27.280', alt. 1792 m)

Return to the fork (Figure. 37) and take the right branch of the path heading downhill, which leads to a 7-8m long cleft opened in the wall but partly hidden by debris. This cavity results from the excavation of

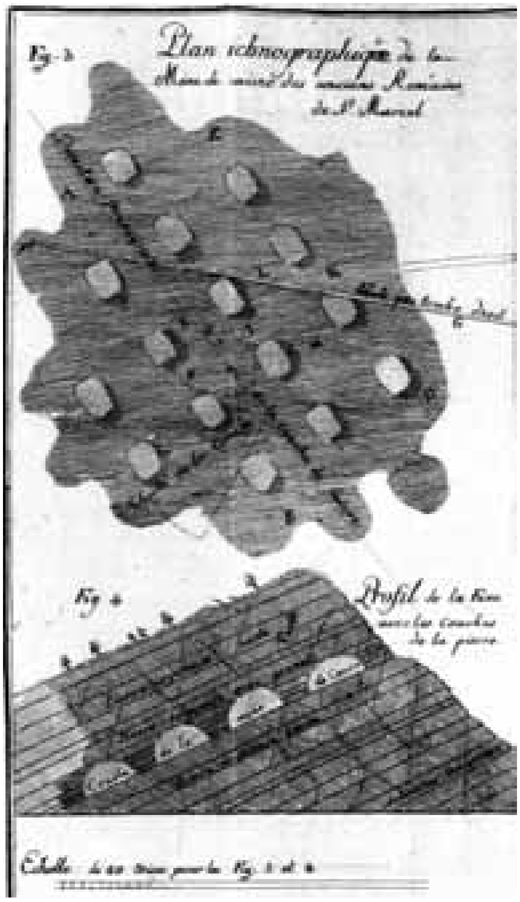

Figure 37 - Map and section of the Servette mine after the work of Robilant (1786-87). "Fig. 3 - Map plan of the copper mine of ancient Romans in St. Marcel"; "Fig. 4 - Profile of the cave with the beds of the stone".

a sulphide-rich layer. Because of the old-fashioned technique used, which has preserved part of the ore as pillars, this work was attributed, without much proof, to Roman, or even pre-Roman (*i.e.,* Celtic), times by Nicolis de Robilant (1786-87), as well as by several authors after him. Actually, the mine was mainly exploited during the 18th century and in the period from 1854 to 1950 (Lorenzini, 1998).

Stop 3.4.3:
The modern mine
(N 45° 42.053'; E 7° 27.297', alt. 1800 m)

Continue a few metres southwards, up to the ruined mine house, which dates from the last period of exploitation (1854-1950). On the walls of the house, we can see a good summary of all the Servette lithologies (see "Stops 3.4, Introduction"). Below the mine house, several remnants of the exploitation are still visible: powder magazine, gallery entrances, and tailings (Lorenzini, 1998; Zinetti, 2002). However, this part of the mine is quite dangerous, and we recommend you reach the main road downhill by going back to stop 3.3.

Stop 3.4.4:
Slag deposit
(N 45° 41.660'; E 7° 27.134'; alt. 1734 m)

From stop 3.3, take the main road towards the South, heading to Praborna. At the intersection with the "Strada Cavour" (N 45° 41.811'; E 7° 27.252'; alt. 1738 m), an overview of the Servette mine is visible to the north. A few metres southwards, a large slag heap is visible on the western side of the path (N 45° 41.660'; E 7° 27.134'; alt. 1734 m). These slags are porous, irregular, containing pieces of carbonised wood which have given a recent age (<100 B.P.; GX-29282: Mambretti, 2003). They date from the last period of exploitation of the Servette mine.

Stop 3.5:
Praborna Mn mine
(N 45° 40.774'; E 7° 26.968', alt. 1894 m)

Where the pathway crosses the Saint-Marcel River, turn to the right heading towards the cliff. Huge and wide loose blocks of manganiferous quartzite and metagabbro occur at the foot of the hill. They were thrown from the old mine, which was excavated in the cliff at about 50 m above the meadow.

The old Praborna mine is one of the most famous Mn occurrences worldwide. It was already known by 1415 (Pelloux, 1913), and was intensively exploited by the Challant and Davise families during the 17th and 18th centuries (archives of the Aosta province, Aosta; "fonds Challant"). Braunite was used by the glassmakers of Murano, near Venice, to fade glass, thanks to the relatively high electronegativity of Mn: $Mn^{3+} + Fe^{2+}$ (coloured) = $Mn^{2+} + Fe^{3+}$ (transparent).

The ore consists of manganic quartzite, including a 4-8m-thick boudinaged layer rich in braunite ($Mn^{2+}Mn^{3+}_6SiO_{12}$). It is associated with ophiolites metamorphosed into eclogite facies. Serpentinite and metagabbros overlie the Mn ore, whereas sulphide-bearing glaucophanite, chloriteschists and micaschists underlie it.

The Praborna ore is well known for its peculiar mineralogy. It is the type locality for several rare

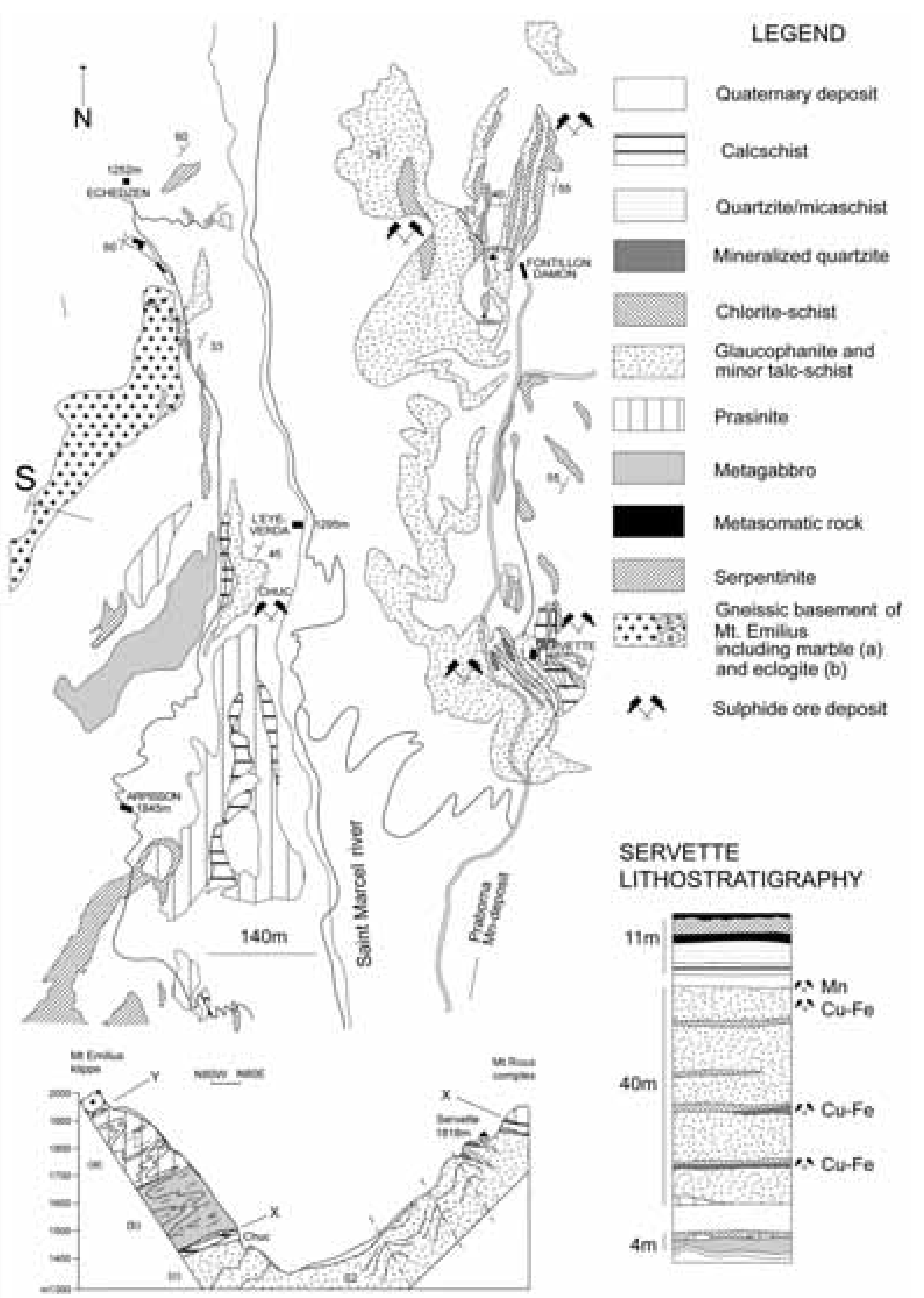

Figure 38 - Lithological map of the lower St. Marcel valley with a schematic geological section (s) and lithostratigraphy of the Servette deposit (after Martin et al., 2004).

Figure 39 - Entrance of the Praborna mine.

Mn minerals: violan, a semiprecious violet-blue Mn-bearing clinopyroxene (Breithaupt, 1838; Descloizeaux, 1862-74; Bondi *et al.*, 1978; Brown *et al.*, 1978); piemontite, the manganic epidote (Napione, 1788-89; Kenngott, 1853); alurgite, the Mn-bearing variety of muscovite (Penfield, 1893); romeite, a complex oxide of Sb, Mn and Fe (Damour, 1841; Pelloux, 1913; Brugger *et al.*, 1997); strontiomelane (Meisser *et al.*, 1999). Many

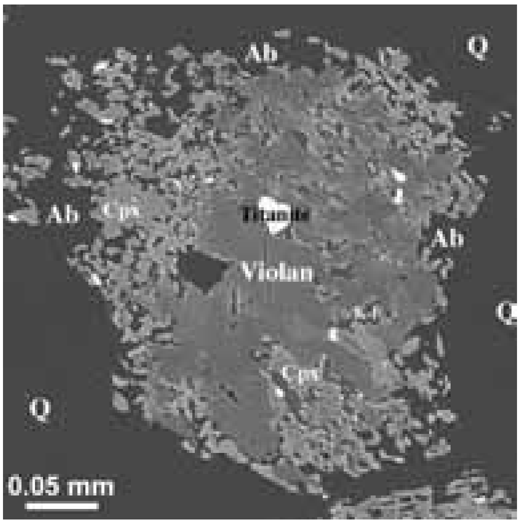

Figure 40 - Praborna: during retrogression violan (i.e. Mn-rich omphacite) was transformed at contacts with quartz (Q) to a symplectite of albite (Ab) and jadeite-free Cpx, with minor K-feldspar (K-F) [i.e. Jd s.s. in violan + Q = Ab]. Back-scattered electron image.

other manganese minerals have been observed: braunite ($Mn^{2+}Mn^{3+}_6SiO_{12}$); garnets (spessartine, blythite, calderite, etc.: Martin-Vernizzi, 1982; Abs-Wurmbach *et al.*, 1983); Mn-bearing augite, jadeite and chloromelanite; rhodonite ($Mn^{2+}_2Si_2O_6$); K-F-Mn-richterite (Martin-Vernizzi, 1982); thulite (an Mn^{2+} epidote); hollandite; rhodochrosite ($MnCO_3$); etc.

Although the ore is strongly banded and displays numerous and various layers that alternate at different scales, a type sequence has been defined (Martin-Vernizzi, 1982; Kienast & Martin, 1983; Martin & Kienast, 1987), namely (from bottom to top): micaschists; alurgite+braunite+piemontite-bearing aegyrine-jadeitite; the braunite+piemontite-rich quartzite that was exploited; an irregular dm-

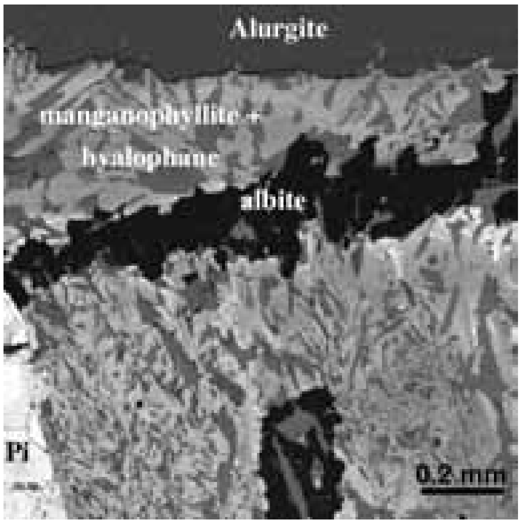

Figure 41 - Praborna: during retrogression, alurgite (i.e., Mn-rich phengite) was partly transformed to a symplectite of manganophyllite and hyalophane. Albite occurs in a late small vein. Pi = Piemontite. Back-scattered electron image.

thick level of $Cr+Fe^{3+}$-clinopyroxene+garnet-rich quartzite, where gold was found; garnet+hematite-bearing quartzite; garnet-bearing clinopyroxenite; chloriteschists; prasinite. The sequence reflects a decrease in Mn valency (*i.e.,* a decrease of O activity) from the braunite-rich layer of the core towards the silicate-rich levels of the boundary (Martin & Kienast, 1987). It can be interpreted in terms of diffusion fronts from core to rim (Mn, Fe, and O) and from rim to core (Na, Ca, Al…).

The ore is thought to be a metamorphosed accumulation of oceanic Mn-bearing nodules and umbers (Martin-Vernizzi, 1982; Mozgawa, 1988; Tumiati, personal communication). This is supported by the abundance of certain elements (Ba, Sb, and Sr) that are typical of such an environment. The Mn-rich body was highly deformed and boudinaged during the eclogite-facies metamorphism, and transposed parallel to the foliation of the surrounding glaucophanite. The most competent levels (pyroxene-rich and braunite-rich layers) were boudinaged and fractured. These fractures were filled with high-pressure minerals such as violan, Mn jadeite, alurgite, piemontite, braunite, greenovite, K-Cl-richterite and quartz (Martin-Vernizzi, 1982). Other fractures and veins developed during retrogression, as they were filled by low-pressure minerals (Mn-tremolite, rhodochrosite, Mn-phlogopite, Mn-chlorite), accompanied by recrystallised braunite and piemontite. Whereas the host rocks were strongly retrogressed, the high-P parageneses were preserved in the Mn ore, which behaved as a gigantic clast in a highly deformed matrix. Nevertheless, some static retrogression is observed, such as low-pressure symplectites around alurgite and clinopyroxenes.

On the way back from Praborna, two alternative paths are proposed. A short path, with a stop at Fontillon (Stop 3.6; glaucophanite, eclogite and view on the Emilius klippe), allows us to come back to the departure point at Druges Hautes (Group A), whereas a longer and more difficult way ("Strada Cavour") passes through the abandoned mining village of Chuc and descends along the Saint-Marcel river down to Plout (Stops 3.7 and 3.8) (Group B).

Group A

Stop 3.6:

Fontillon (N 45° 42.111'; E 7° 27.327', alt. 1819 m)

On the way back to Druges, in front of stop 3.3's slag deposit, turn to the left (*i.e.,* to the north) into the woods. After a 5-minute walk, we'll climb onto the Fontillon ridge. The rocks consist of banded garnet glaucophanite, with lawsonite pseudomorphs, cm-thick green veins of clinopyroxene, N-S-trending decimetre-thick bands of glaucophane-bearing eclogite and chloriteschists. This latter rock has been exploited, likely during the middle ages, for millstone manufacturing. Traces of this activity are visible at the northern extremity of the eastern wall of the ridge (very difficult access).

A view towards the Saint-Marcel river and Monte Emilius (N 45° 42.480'; E 7° 27.239', alt. 1642 m) allows us to observe the N-dipping contact between the meta-ophiolites (greenish) and the Austroalpine gneisses (brownish) of the Monte Emilius klippe (intermediate continental slice). Mylonitic serpentinites occur along this contact.

Group B

Stop 3.7:

The abandoned mining village of Chuc
(N 45° 42.044'; E 7° 26.863'; 1422 m)

On the way back from Praborna, after a 30-mn walk, turn to the left onto the old "strada Cavour" that leads to Plout (fork at N 45° 41.811', E 7° 27.252', alt. 1738 m). The pathway zigzags down to the valley. In a few points, slags similar to those of Stop 3.4.4 are visible.

The abandoned village of Chuc was active from 1854 to 1950 (Cesti, 1978; Lorenzini, 1998). It consists mainly of 3 ruined houses (an office, a guard house, and a workers' dormitory). The site was linked to the Servette and Chuc mines through cableways whose terminal is still visible.

The copper mine of Chuc, whose geological setting is quite similar to that of Servette, was located on the other side of the river at altitudes between 1283 and 1443 m (very difficult access). It consists of five major mineralised levels, WNW-trending and SSW-dipping, that are located at the glaucophanite/chlorite-schist boundary, as observed in the galleries of the mine.

The ore was sent via another cableway to a laver located at an altitude of 1211 m, on the western bank of the river, but visible from "Strada Cavour". There, the ore was crushed and enriched in sulphide, and then transported to Saint-Marcel by a 4-km-long pipe or, in the last years, by a cableway.

Stop 3.8:

"Green fountain" of Acqua verde
(N 45° 42.094'; E 7° 26.940'; 1371 m)

A few hundred metres below Chuc, the pathway crosses a small river that descends from Servette. The water, being saturated in Cu, has deposited a blue gel that covers the rocks and pebbles of the river bed. This spectacular "fontaine colorée" was described by Saint-Martin de La Motte (1784-85), Horace-Bénedict de Saussure (1796, t. 4, p. 459), Prosio (1903), Noussan (1972) and Zinetti (2002). The gel is made of an amorphous Cu hydroxide, which likely precipitates during a change of pH. A few metres uphill it can be seen that the deposit actually results from the mixing of two streams, at the confluence of two small rivers,

Figure 42 - Abandoned village and mine of Chuc. Workshop (top); terminal of the cableway (left); wagon at level 1331 m (right). Antique photographs in Lorenzini (1995).

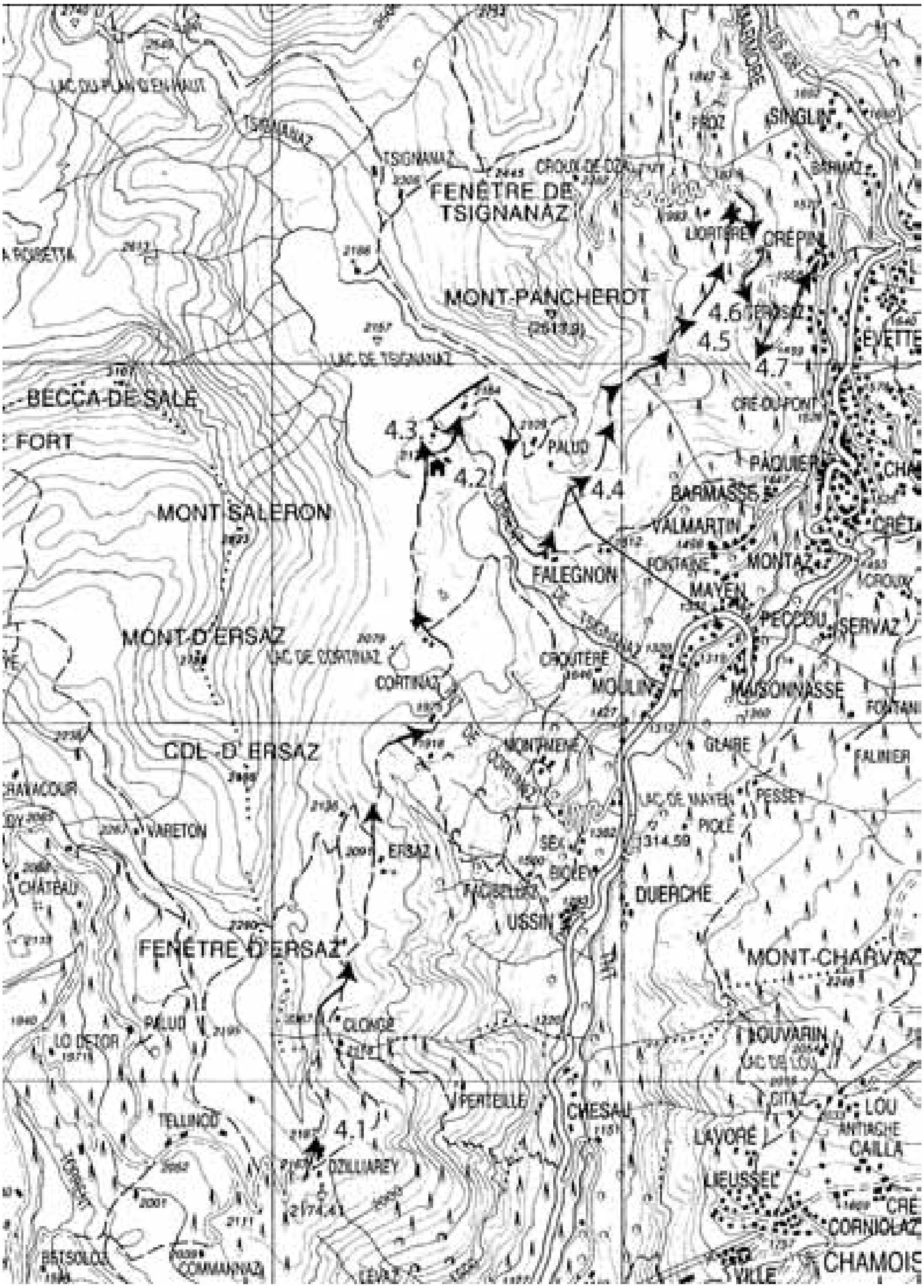

Figure 43 - Itinerary of day 4.

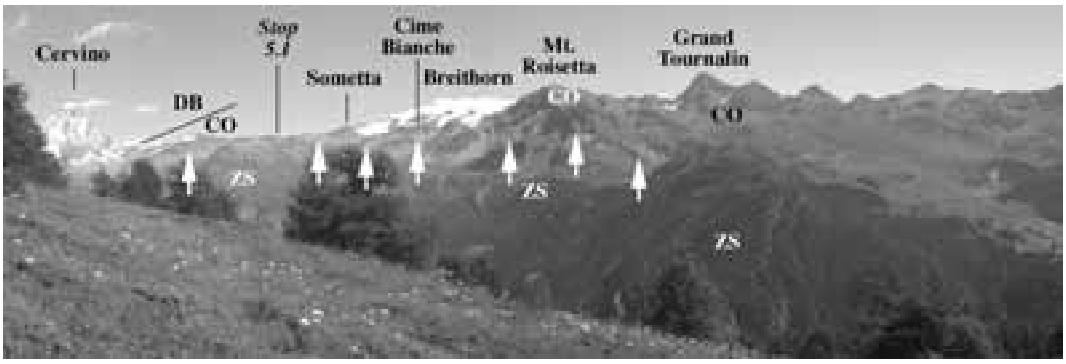

Figure 44 - View northwards from Gillaray (stop 4.1). DB= Dent Blanche nappe; CO=Combin meta-ophiolites; ZS=Zermatt-Saas meta-ophiolites. The white arrows point to the thin slice of Permo-Mesozoic sediments (Pancherot-Cime Bianche unit) that separates the Combin and Zermatt-Saas units, and which generally appears as white cliffs.

one coming from the *Galleria Ribasso* of Servette (1789 m) and the other from the Chuc village (Zinetti, 2002). At the same place loose blocs of glaucophanite and chloriteschists, with chloritoid up to a few cm in size, can be observed.

Continue the path northwards, along the Saint-Marcel River. In the river bed, one can see, together with the meta-ophiolite of the Zermatt-Saas unit, large blocks of marble, eclogite and eclogite-facies gneiss that comes from the Monte Emilius klippe (intermediate continental unit) that overlies the meta-ophiolites. This highly retrogressed eclogite-facies gneiss (the so-called *Gneiss pipernoidi* of Amstutz, 1951) is a banded rock with leucocratic bands (quartz + albite + phengite + microcline + epidote) alternating with layers and lenses rich in chlorite and actinolite, with rare omphacite, glaucophane or crossite. Continue down to Plout, where a splendid 17th century church can be visited.

DAY 4

"Ultrahigh- and high-pressure metamorphism in ophiolites: Cignana and coronitic metagabbros"

The fourth day is mainly devoted to the (ultra-) high-P metamorphism that developed in the Zermatt-Saas ophiolite during the Alpine orogeny. We shall visit the famous coesite-bearing occurrence of Lago di Cignana and the eclogite-facies metagabbro of Crepin, which still preserves its magmatic structure. The excursion also offers the opportunity to observe the tectonic relationships between the Piedmont meta-ophiolites and the overlying Dent Blanche nappe.

The Valtournanche valley was visited in 1792 by H.-B. de Saussurre, who undertook the first trigonometric calculations of the height of Monte Cervino (the Matterhorn), obtaining an estimate of 4505 m (instead of 4478 m). At the end of the 19th century, in 1869, Felice Giordano made the first geological survey and barometric measurements of Cervino (Dal Piaz, 1996). Afterwards, Émile Argand studied the Dent Blanche nappe and interpreted the tectonic structure of the Penninic zone in the Western Alps in terms of multiple recumbent folding (see Dal Piaz, 2001b). More recently, Giorgio Vittorio Dal Piaz and Jean-Robert Kienast have applied the concepts of subduction metamorphism and plate tectonics to the Valtournanche area and surroundings.

Stop 4.1:

Gillaray (alt. 2186 m.) - Panoramic viewpoints

We leave Collegio Gervasone by minibus at 8:00 am and head towards Cignana, entering into the Valtournanche valley. North of Champlong, we follow the Marmore River which cuts across the meta-ophiolites of the Zermatt-Saas unit (serpentinite, ophicalcite, metagabbro, metabasalt and minor metasediments, locally with well preserved eclogitic assemblages), whereas the Combin ophiolites make up the hills on both sides of the valley.

We head up Torgnon and Mangnod, and, from there, a private road (permission required), along which calcschists of the Combin unit are dominant, leads us to Gillaray. As we climb up, grand views of the Valtournanche valley and Cervino appear to us. We leave the minibus near the Gillaray oratory, and climb the small hill behind it to observe the panorama.

To the West, we can see the tectonic contact between the Combin meta-ophiolites (Monte Meabè) and the overlying Dent Blanche-Mont Mary nappe system,

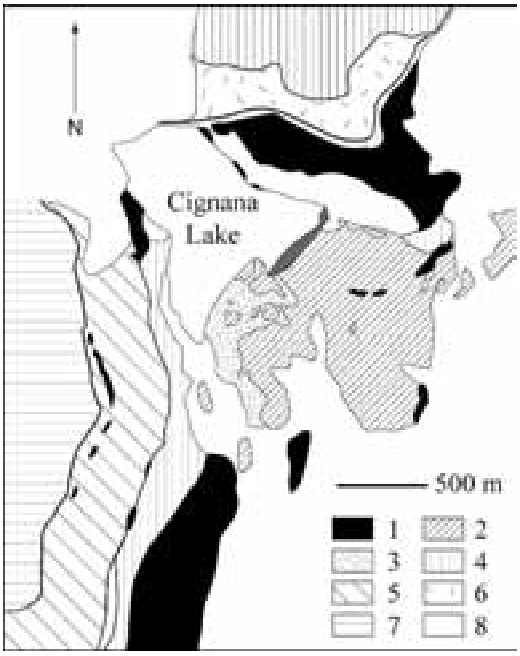

Figure 45 - Simplified geologic map of Cignana Lake surroundings, redrawn from Reinecke (1998).
1 = serpentinized ultramafics; 2 = coesite-eclogites and derived greenschists; 3 = UHPM metasediments; 4 = greenschists interlayered with minor calcschists (Combin Zone); 5 = calcschists with minor greenschists and marbles (Combin Zone); 6 = dolomite – calcite marbles; 7 = Austroalpine undifferentiated; 8 = scree and morain deposits. Solid thick lines = tectonic contacts.

with the *Arolla* Gneiss basement unit (Monte Miracolo) and its Mesozoic cover (Cima Bianca).
To the North, the Pancherot hill is made up of a huge ophiolitic serpentinite capped by Triassic quartzite and platform carbonates of the Pancherot-Cime Bianche decollement unit. Behind that we can observe Testa del Leone and Cervino (southern face), made, from bottom to top, of Permian metagabbro, Arolla gneissic granitoids and overlying Valpelline kinzigite. The Combin ophiolite makes up the tectonic substratum of the Cervino basement rocks (Dent Blanche nappe) as well as the ridge between the Cervino and the Theodul Pass and the Plateau Rosa (Testa Grigia) klippe, whereas the Breithorn, on the right, already belongs to the Zermatt-Saas unit. The contact between these meta-ophiolites and the underlying Monte Rosa basement nappe occurs further east, between the snowy Polluce and Castore peaks.
East of the Valtournanche valley, the contact between the ophiolitic Zermatt-Saas (Plan Maison) and Combin (Grand Tournalin) units is outlined by a light-coloured horizon of Permian-Mesozoic rocks, mainly Triassic (Pancherot-Cime Bianche decollement unit). Further south, the Combin meta-ophiolites are overthrust by the Pillonet klippe (Dent Blanche *s.l.*) which is characterized by a blueschist-facies imprint of Late Cretaceous age (Cortiana *et al.*, 1998).
To the south, on the opposite side of the Aosta valley, one can see the Zermatt-Saas Mt. Avic ultramafic massif, the Austroalpine Monte Emilius continental slice, and the Penninic Gran Paradiso nappe.

Stop 4.2:
<u>Panorama of the Cignana valley</u>, from Rifugio Barmasse
(N 45° 52,590'; N 7° 35,385'; alt. 2182 m)

We continue our way on the minibuses, until we reach the parking lot of Rifugio Barmasse (2169 m), near the Cignana lake (2162 m), which is a famous coesite occurrence. Before looking at the rocks in detail, take a look at the panorama to the north-west, in front of you.
Your feet are resting on the high-P metabasites and metasediments of the Zermatt-Saas unit (micaschists and quartzite with large garnet crystals). To the north-east (*i.e.*, on your right looking at the lake), Mt. Pancherot (2614 m) is composed of a slice of

Figure 46 - View of Cignana Lake and surrounding peaks from Rifugio Barmasse.

folded serpentinite (Zermatt-Saas or lower Combin unit). It is overlain, to the north, by a slice of Permian-Mesozoic continental metasediments (mainly Triassic quartzite, marble and dolomite), which crop out along the lake shore near a small church (2178 m). Behind the lake, the Combin unit, here mainly consisting of calcschists with minor prasinite, metagabbro and serpentinite bands, is tectonically flattened and poorly exposed. Above the Combin unit, the Austroalpine Dent Blanche-Mont Mary composite nappe system occurs from the waterfall to the horizon line, with basement rocks (mainly Arolla Gneiss) and Mesozoic cover (Roisan zone: Château des Dames and Becca di Salè). Further south-west, the two contacts, Zermatt-Saas-Combin and Combin-Dent Blanche, can be seen again on the slopes of the Becca di Salè and Cortina area (*i.e.*, on the left side of the lake), where they dip to the northwest.

Stop 4.3:

Ultrahigh-pressure meta-ophiolites of Lake Cignana

Introduction: The Cignana Mesozoic metasediments crop out as a thin level that extends on the southwestern and southeastern shores of Lake Cignana. They belong to the upper part of the ophiolitic Zermatt-Saas unit, immediately below the contact with the overlying Combin unit. South of the dam, metabasic rocks prevail over metasediments, which gradually predominate to the west and northwest of the lake. The lake shore offers a continuous outcrop that allows observing the superposition of different fabrics and the relationships among various lithologies. Most of the following description is summarised from the detailed studies by Reinecke and coworkers (Reinecke, 1991; Reinecke *et al.*, 1994; van der Klauw *et al.*, 1997; Reinecke, 1998; Reinecke *et al.*, 2000). The various rocks, which are believed to represent a former section of oceanic crust, seem to have undergone a similar metamorphic ultrahigh-P evolution.

Metabasites are represented by variously deformed and retrogressed eclogites. Pillow structures have been identified, and the geochemical signature is similar to that of modern oceanic rocks (N-MORB).

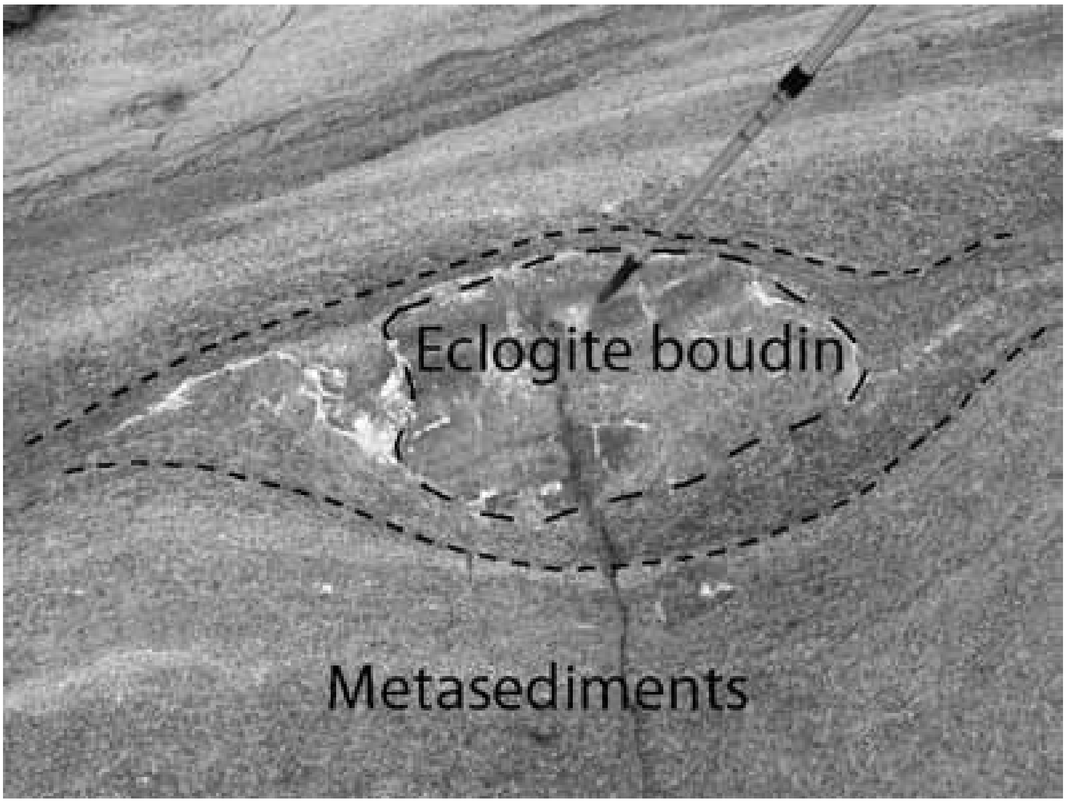

Figure 47 - Eclogitized gabbro boudinaged in metasediments.

Samples that are devoid of retrogression and post-eclogite deformation have an ultrahigh-P assemblage consisting of garnet, clinopyroxene, glaucophane, clinozoisite, zoisite, rutile, apatite and paragonite. Occasionally, phengite and dolomite are found. However, the presence of paragonite texturally in equilibrium with the high-P assemblage is not clearly understandable, as it should not be stable at the P-T conditions determined for these rocks (2.6-3.0 GPa, 600°C). Various degrees of retrogression affect these rocks, from greenschist-facies assemblages rimming high-P minerals to completely retrogressed rocks, especially at the high-strain rims of boudins, consisting of actinolite, albite, chlorite and epidote. Numerous shear bands, variously oriented veins and folds help to constrain the exhumation path (see van der Klauw *et al.*, 1997, for details).

Metasediments are described in detail by Reinecke (1998). The ultrahigh-P assemblage consists of garnet, dolomite, aragonite, lawsonite, coesite, phengite in calcschists and micaschists made of garnet, phengite, coesite ± epidote, talc, dolomite, Na-pyroxene and Na-amphibole. Boudinaged levels of Mn-rich quartzite are also observed.

Contrasting ages of the high-P metamorphism have been recently obtained by two works (Rubatto *et al.*, 1998, U-Pb=44.5±2.3 Ma and 43.9±0.9 Ma; Amato *et al.*, 1999, Sm-Nd=40.6±2.6 Ma). Moreover, Amato *et al.* (1999) infer a rapid exhumation based on the Rb-Sr cooling ages. Note that coesite-free eclogites from the same unit in the nearby upper Ayas valley display Sm-Nd (garnet-pyroxene) and Rb-Sr (phengite) ages of 49 and 46 Ma, respectively (Mayer *et al.*, 1999).

Stop 4.3.1:

N 45° 52.668'; E 7° 35.574'; alt. 2164 m.

Go to the small mound, situated in the parking lot, near the southwestern extremity of the dam. There, you can see a 2-m-high outcrop consisting of banded garnet quartzite, with late quartz veins. You can distinguish two 2-cm-thick pink layers containing alurgite (Mn-mica), spessartine, piemontite and rare lenses of braunite (Dal Piaz *et al.*, 1979a). A green level consists of phengite, epidote, hematite ± garnet.

Stop 4.3.2:

N 45° 52.703'; E 7° 35.551'; alt. 2159 m.

Descend to the lake shore, near the southern extremity of the dam.

Eclogite bands and lenses, deformed together with metasediments, occur on the shore. They are often layered, with bands rich in garnet+omphacite and others rich in glaucophane. Phengite and epidote are also visible. The foliation and lineation are outlined by prismatic minerals of the high-P assemblage, especially glaucophane. The foliation wraps garnet crystals, and pressure shadows consist of coarse-grained omphacite. The eclogites are variously retrogressed to greenschist facies, and retrogression is complete towards the rims.

Stop 4.3.3:

N 45° 52.673'; E 7° 35.495'; alt. 2159 m.

Continue on towards the southwest, along the lake shore, where a few dm-to-m-sized lenses of coarse-grained metagabbro occur in the metasediments (micaschists; quartzite containing garnet crystals up to 5 cm in diameter). The undeformed metagabbro,

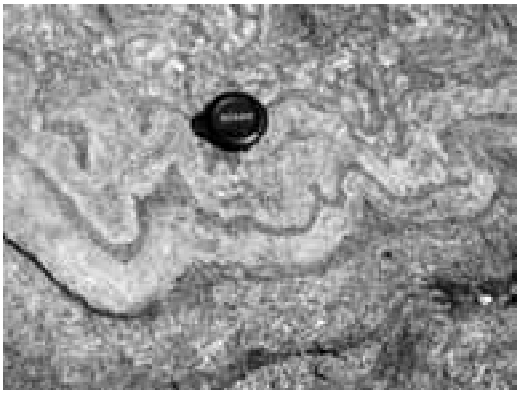

Figure 48 - Deformed reaction rim between a basic boudin (to the top) and metasediments (to the bottom). Note dark chlorite layers and light epidote layer towards the metasediment. Lens cap is 3 cm.

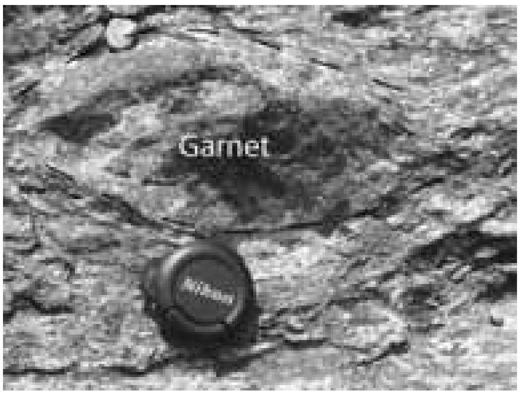

Figure 49 - Decimetric garnet in quartz-rich metasediments. Lens cap diameter 3 cm.

wrapped by mylonitic metagabbro, has preserved its igneous texture demonstrated by up to 5 cm emerald-green clinopyroxene crystals, now mainly omphacite, often retrogressed to green amphibole at margins and along cracks. A few metres above, a polished surface allows us to see the relationships of less deformed lenses with mylonites (interference Figureures) and the folded contact with metasediments.

Stop 4.3.4:

N 45° 52.60'; E 7° 35.422'; alt. 2160 m.

Going further south along the lake, we can observe metabasite boudinaged within metasediments. Between metabasites and quartz- or carbonate-rich metasediments, reaction rims consist of a cm-thick discontinuous band of chlorite (close to the metabasite) and a dm-thick band rich in epidote (close to the metasediment). Note also the superposition of different deformation phases (interference Figureures). Further south, metasediments prevail, with marble levels.

Stop 4.4:

<u>Zermatt-Saas meta-ophiolites</u>, below Cignana dam (*e.g.*, N 45° 52.509'; E 7° 36.530'; alt. 1891 m)

We leave Cignana following pathway N1 (yellow triangle), descending south of the dam. Below the dam, we cross prevalent metasediments (quartzite, micaschists, calcschists with lawsonite pseudomorphs) and metabasites (banded eclogite and glaucophanite). On the way down, various metabasites (eclogite, metagabbro, serpentinite) are found in debris along the path (give a look at the stair steps).

After the ruins of the village of Falegnon, turn to the left (fork at N 45° 52.302', E 7° 36.218', 1908 m). The path passes under the pipe of the hydroelectric power station (small tunnel at N 45° 52.402', E 7° 36.295', 1923 m).

At about 350 m after the pipe, large outcrops are visible on the left side of the pathway (N 45° 52.509'; 7° 36.530'; alt. 1891 m.). Banded eclogite, glaucophanite, serpentinite, calcschists and layered marble alternate and are folded together. The foliation and transposed layering dip of about 45-50° towards the northwest.

Carbonate-rich rocks contain calcite, white mica, epidote and rare tourmaline, all aligned along the main foliation. Rounded flattened aggregates consist of plagioclase, epidote and white mica (plus minor opaques), and could represent former lawsonite.

Eclogites are fined grained. They consist of garnet, omphacite, rutile and glaucophane. Rims of green barroisitic amphibole are present.

From the pathway, we can see the Breithorn and Gobba di Rollin (Zermatt-Saas serpentinite) and the Grand Tournalin, on the other side of the Valtournanche valley. Note the contact between the Zermatt-Saas and Combin units outlined by a light-coloured horizon of Triassic rocks (Grand Tournalin; see Stop 4.1).

At N 45° 52.687', E 7° 36,903' (alt. 1892 m.), the path divides into two branches, which, actually, lead to the same major path that must be followed northwards.

Stop 4.5:

<u>Rodingitized gabbro dykes in serpentinite</u>

(N 45° 52.878'; E 7° 36,954'; alt. 1804 m.)

Along the main path, 20 m south of the junction with the upper branch of the pathway, near sign "17", two boudinaged dm-thick dykes of rodingitized metagabbro are visible in the serpentinite. They are mainly made of Ca-Fe garnet and epidote, with minor diopside and chlorite.

Figure 50 - Macroscopic reaction rim between gabbro (on the right) and serpentinite (on the left). See text for details.

Stop 4.6:

<u>Serpentinite lens within metagabbro</u>, along the path to Liortere

(N 45° 53.144'; E 7° 36,893'; 1826 m.)

Continue along the path towards north. We first observe dominant strongly-foliated serpentinite, with a few transposed and boudinaged dykes of metagabbro. Further north, the metagabbro, which displays a flaser structure by places, prevails over the serpentinite, which occurs as lenses a few metres in size.

One of these serpentinite lenses shows a 30-cm-thick

reaction rim, with concentric bands:
serpentinite | tremolitite | tremolite + talc | chlorite + tremolite | transformed gabbro, with epidote + chlorite | metagabbro.

Stop 4.7:

<u>Crepin eclogitic gabbro and troctolite</u> (*e.g.*, N 45° 52.619'; E 7° 37.095'; alt. 1630 m)

From Liortere, the pathway zigzags downhill towards Crepin. A huge mass of blocks, which resulted from an ancient rock fall, occurs at a few tens of metres

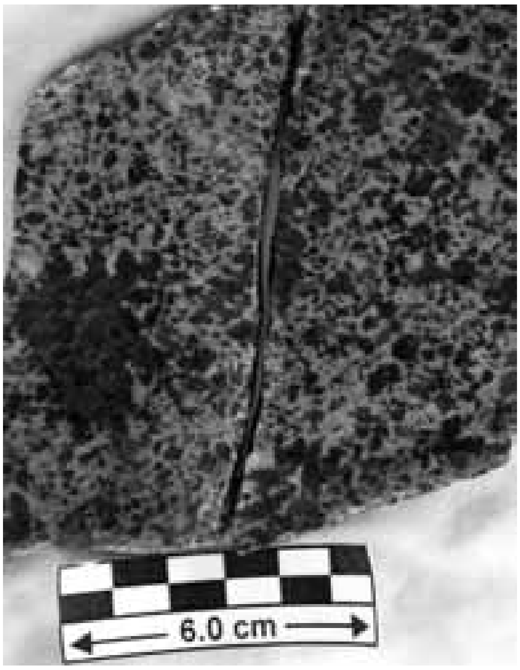

Figure 51 - Fine-grained metatroctolite with poecilitic clinopyroxene. Olivine: dark and rounded, plagioclase: white, pyroxene: grey.

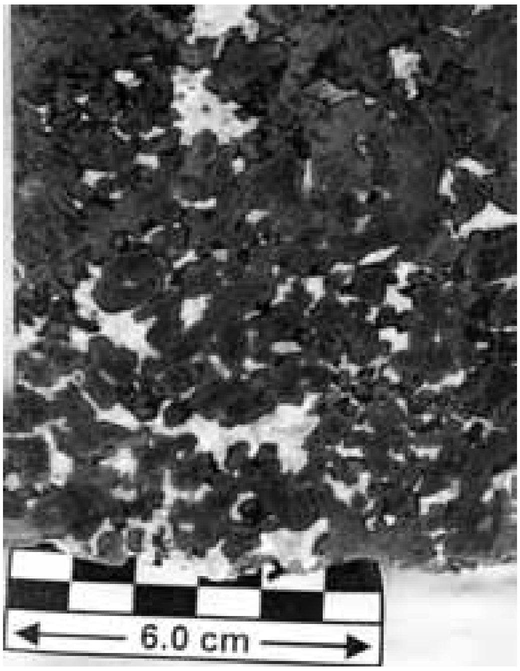

Figure 52 - Coronitic troctolite from Crepin. Plagioclase is white, olivine dark grey and rounded, with lighter talc and darker garnet concentric coronas.

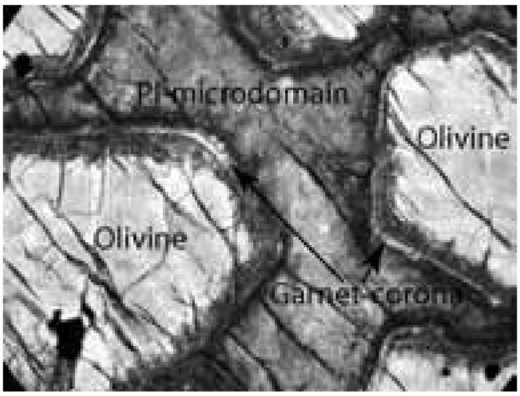

Figure 53 - Partially eclogitized troctolite (Crepin). Plagioclase is completely transformed to a fine-grained aggregate. Olivine is preserved. A thin, complex corona develops between the two. See text and following figure for detailed assemblages. Olivine grains are 3-5mm, plane-polarized light.

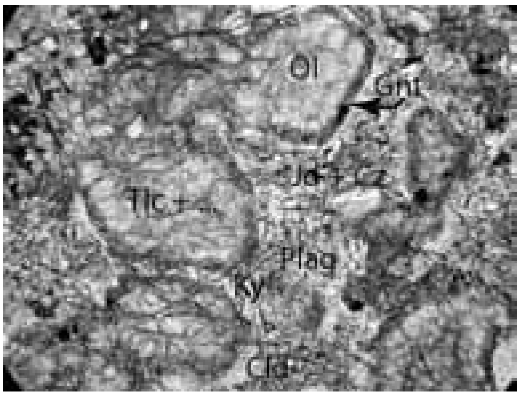

Figure 54 - Completely eclogitized troctolite. Texture is distinguishable (rounded olivine and anhedral plagioclase). See text for assemblages. Olivine grains are 2-4 mm.

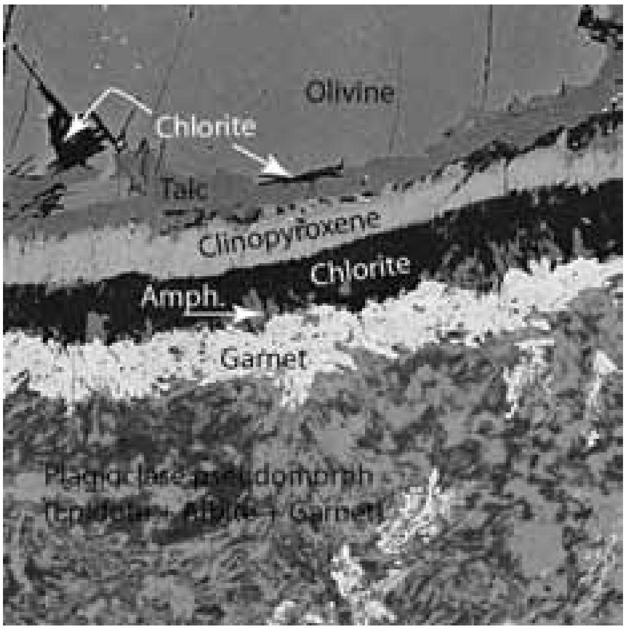

Figure 55 - Crepin: multilayered corona developing between olivine and plagioclase in incompletely eclogitized metatroctolite. Back-scattered electron image.

southwards of the pathway. It is easily accessible from the last bend in the pathway before the village of Crepin (N 45° 52.619'; E 7° 37.095'; alt. 1630 m). The blocks are mainly made of metamorphic troctolite and gabbro, with a dominant eclogite-facies imprint. They come from an inaccessible ridge below Mt. Pancherot.

These rocks show peculiar textures and metamorphic transformations. Troctolite and gabbro, originally composed of olivine, plagioclase and clinopyroxene, have undergone static metamorphic reactions. Rocks display a whole range of transformations, from very thin coronitic reactions, giving rise to eclogite-facies minerals, to complete replacement of igneous minerals by new high-P assemblages.

In completely transformed troctolite, fine-grained jadeitic clinopyroxene and clinozoisite replaced igneous plagioclase. Towards olivine microdomain, small kyanite crystals are found around large clinozoisite, together with micas (phengite and paragonite), chloritoid and garnet that forms irregular coronas at the former plagioclase-olivine interface. Olivine is mainly transformed to talc. Nonetheless, large tremolite crystals are common, together with very fine-grained omphacite, phengite, chloritoid, chlorite, kyanite and even rare quartz. Cr-rich clinopyroxene is partially to completely overgrown by omphacite. This latter may be overgrown by Cr-rich chloritoid and talc.

In incompletely eclogitized rocks, igneous minerals (olivine and clinopyroxene) are rimmed by eclogite-facies complex coronas:

Olivine | talc | clinopyroxene | chlorite | garnet | plagioclase pseudomorph.

Augitic clinopyroxene | omphacite | plagioclase pseudomorph.

Plagioclase pseudomorph is made up of clinozoisite + albitic plagioclase + garnet ± jadeite ± kyanite.

The various degrees of development of eclogite-facies reactions are related to the intensity of the oceanic hydrous alteration that took place before eclogitization (Ayas-Valtournanche area: Ernst & Dal Piaz, 1978; Mt. Viso: Messiga *et al.*, 1999). The effect of oceanic metamorphism in the Zermatt-Saas ophiolites has also been proven through isotope studies (Cartwright & Barnicoat, 1999). The main effect of oceanic metamorphism was the development of low-grade hydrous assemblages, which favoured the chemical homogenisation of the igneous microdomains and the kinetics of subsequent eclogite-facies metamorphic reactions (Messiga & Tribuzio, 1991). It is thus possible to find, side by side, classic and hydrous eclogitized metagabbros.

Geothermobarometric computations and calculation of P-T pseudosections for the various microdomains of these rocks (Rebay & Powell, 2002) have provided P-T estimates of $P \geq 2$ GPa and $T \approx 600°C$ for the eclogite-facies reequilibration.

Among the blocks, there are also several examples of metatroctolite and metagabbro that underwent greenschist-facies retrogression following the high-pressure metamorphism, with the development of green amphibole, chlorite and albite.

We now return to the pathway, which we follow down to the village of Crepin. The rendezvous point is set at the parking lot located at around 100 m after the charming oratory of the village.

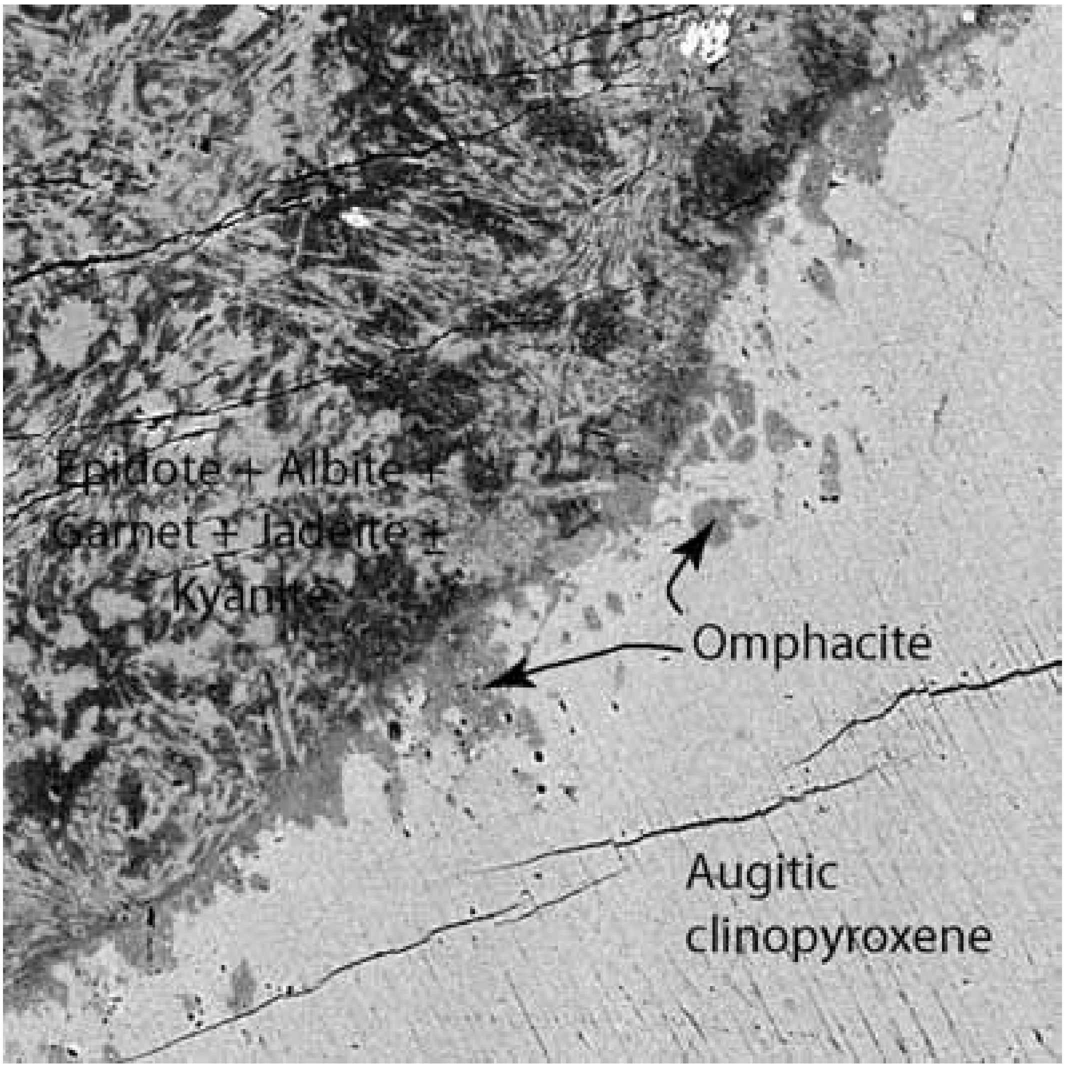

Figure 56 - Crepin: corona between augitic cinopyroxene and plagioclase in partially-transformed eclogitic gabbro. Back-scattered electron image.

DAY 5

"Spectacular views of the Western Alps' structure/nappes"

We leave Collegio Gervasone early in the morning, for an optional excursion (only if the weather is good) to Rifugio Guide del Cervino (3480 m, Testa Grigia-Plateau Rosà), southeast of Cervino (Matterhorn). We arrive at Breuil (Cervinia) and take cableways, first to Plan Maison and Plan Tendre Lake, and then to Testa Grigia, from where we have a spectacular view of the collisional zone of the Western Alps, particularly those tectonic units we have been crossing on this field trip.

Stop 5.1:

View from Plateau Rosà.

The Testa Grigia summit is made up of a small klippe of the Pancherot-Cime Bianche unit, which separates the Zermatt-Saas meta-ophiolites (below Testa Grigia) from the Combin unit (above, present to the NW). It is a decollement cover sheet made up of tabular sediments deposited near a continent, like white quartzites, marbles, sedimentary breccias and

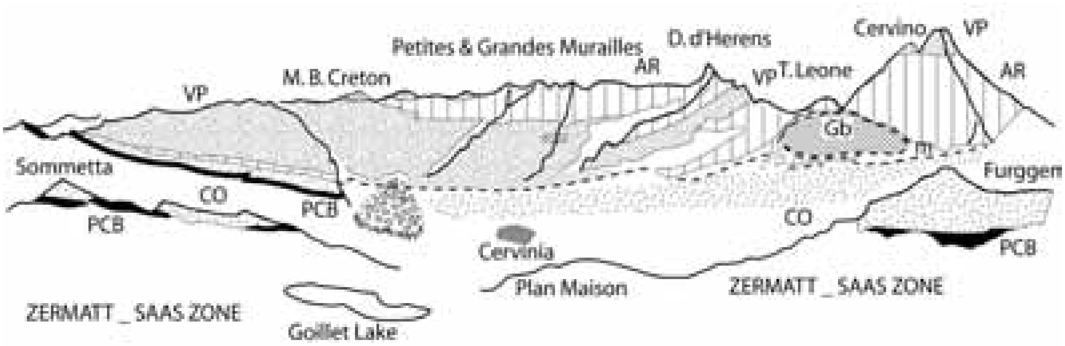

Figure 57 - Panoramic view from Testa Grigia towards the SW (from Dal Piaz, 1992, vol. 1, Fig. 7.14). VP – Valpelline kinzigitic units, AR – Gneiss Minuti and metagranitoids of Arolla; Gb – Permian gabbros; m – milonites around gabbros; CO – Combin ophiolites; PCB – Pancherot-Cime Bianche-Bettaforca Unit.

calcschists, of Eo-Trias to Jurassic age (Dal Piaz, 1992).

From the top to the base of the Cervino, we can observe several elements: the Dent Blanche (i) kinzigitic gneiss and (ii) gneissic metagranitoids of the Arolla series; (iii) a thick mylonitic horizon from metagranitoids and metagabbros; (iv) the huge Lower Permian metagabbro body, underlain by (v) thin basement mylonites; and (vi) the underlying ophiolitic Combin unit. The Dent Blanche-Combin (Africa-Tethyan ocean) tectonic contact is visible along the whole ridge, between Cervino and Mt. Rous, through the Grandes et Petites Murailles. The whole nappe stack, from the Zermatt-Saas ophiolite to the Dent Blanche-Mont Mary nappe system, through the Combin unit and the Etirol-Levaz slice, can be seen along the western flank of the upper and middle Valtournanche.

At our feet we have the Plan Tendre-Plan Maison area, with the eclogite-facies ophiolitic rocks of the Zermatt-Saas unit, all around the Goillet Lake. To the left of the lake, from Sommetta to Roisetta (Figure 57), a NNW-SSE-oriented light-coloured ridge is again made up of the Pancherot-Cime Bianche exotic metasediments, presently trapped between the Zermatt-Saas and Combin ophiolitic units.

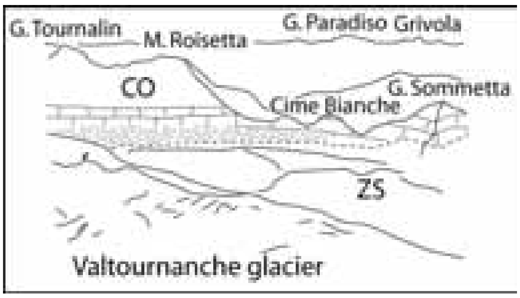

Figure 58 - Panorama from Testa Grigia towards the Sommette-Grand Tournalin ridge (SW) (from Dal Piaz, 1992, vol. 1, Fig. 7.15). CO – Combin greenschist ophiolites; ZS – Zermatt-Saas eclogitized ophiolites.

The Breithorn serpentinitic massif (Zermatt-Saas unit; 4139 m) is visible to the east. The two following peaks, Polluce (Zermatt-Saas; 4090 m) and Castore (Monte Rosa unit; 4225 m) point out the limit between the ophiolite (*i.e.*, Tethys ocean) and the Penninic (*i.e.*, European) domains.

From the Chalet we have a view towards Switzerland, on the African (Austroalpine) continental fragment of the Cervino-Weisshorn ridge. We also see the underlying Combin and Zermatt-Saas units, which are thrust over the Upper/Inner Penninic Monte Rosa nappe (European margin) and capped in turn by the Mid-Penninic Gran St. Bernard (Briançonnais) nappe along the Mischabel backfold; far to the north is the Helvetic basement in the Bern Oberland.

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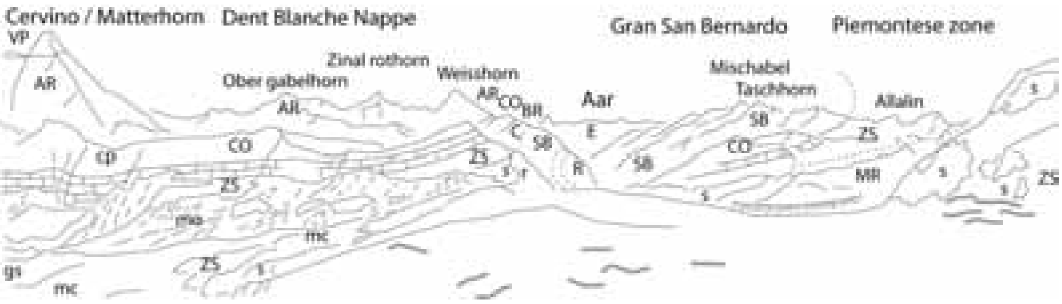

Figure 59 - View from Testa Grigia (the Chalet) towards Switzerland (looking towards N). From Dal Piaz, 1992, vol. 1, Fig. 7.16. AR – Gneiss Minuti and metagranitoids of the Arolla Unit; CO – Combin greenschist ophiolites; ZS – Zermatt-Saas eclogitic ophiolites; MR – Monte Rosa; SB, C, BR and R – Gran San Bernardo Units. s – serpentinite; r – rodingite; gs – gabbro and serpentinite; mc – garnet-chloritoid micaschists with basic inclusions; cp – calcschists and prasinites; mo – morains.

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Figure 60 - Authors ready to climb Piramide Vincent (in the back).

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