Volume n° 2 - from B16 to B33

32nd INTERNATIONAL
GEOLOGICAL CONGRESS

THERMO - MECHANICAL EVOLUTION OF THE ALPINE BELT, FROM THE ENGADINE WINDOW TO THE MATTERHORN

Leader: G. Gosso

Associate Leaders: M. Engi, F. Koller,
J.M. Lardeaux, R. Oberhaensli, M.I. Spalla

Field Trip Guide Book - B29

Florence - Italy
August 20-28, 2004

Pre-Congress

B29

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

Published by:
APAT – Italian Agency for the Environmental Protection and Technical Services - Via Vitaliano Brancati, 48 - 00144 Roma - Italy

APAT
Italian Agency for Environment
Protection and Technical Services

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Acknowledgments:
The 32nd IGC Organizing Committee is grateful to Roberto Pompili and Elisa Brustia (APAT, Roma) for their collaboration in editing.

Graphic project:
Full snc - Firenze

Layout and press:
Lito Terrazzi srl - Firenze

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Front Cover:
Alpe Albion, Southern Steep Belt, Central Alps
(Ticino, Switzerland)

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Introduction

This field trip illustrates the advances in investigation strategies and the definition of tectonic processes which took place at various stages of the Alpine orogeny; recent results are summarised in a data base supporting the new tectonic and metamorphic map of the Alps (see T12.03 topical symposium). About a century ago, a progressive shortening episode was envisaged to have generated the thickened crust of the Penninic nappe belt, a multiply deformed stack of continental and oceanic materials, constructed during the Africa-Europe convergence and elimination of interposed sedimentary and ophiolitic basins (Figure 1, a and b).

In the last thirty years, crustal thickening processes have been envisaged to be more complex than previously thought: in this period, nappe formation was demonstrated to be polyphased, and was revealed, in the continental crust (and/or ophiolites), by the tectono-thermal signatures of P-T regimes, related to lithosphere-scale tectonic events of pre-orogenic rifting, subduction, or collision. Contrasting P-T imprints and tectonic coupling/decoupling of the units were recognised within continental or oceanic crustal slices (and related Permian-Mesozoic to Lower Tertiary sedimentary covers) of the Alpine nappe stack. This interpretation of the nappe formation process is nowadays, however, under thorough revision, in accordance with the tectonic mechanisms of plate dynamics; the comparison of tectono-metamorphic imprints of continental and oceanic basements and covers, have added constraints to reconstructions of nappe formation, and to the role of crustal blocks in forming the lithospheric frame of the belt (Adriatic, Apulian, or African outer margin=Southern Alps block; Austroalpine block; Penninic block; and the European inner margin=Helvetic-Dauphinois-Provençal block).

In this excursion, the nature, origin and timing of sedimentary, igneous or metamorphic protoliths, and their contribution to the unravelling of the tectonic

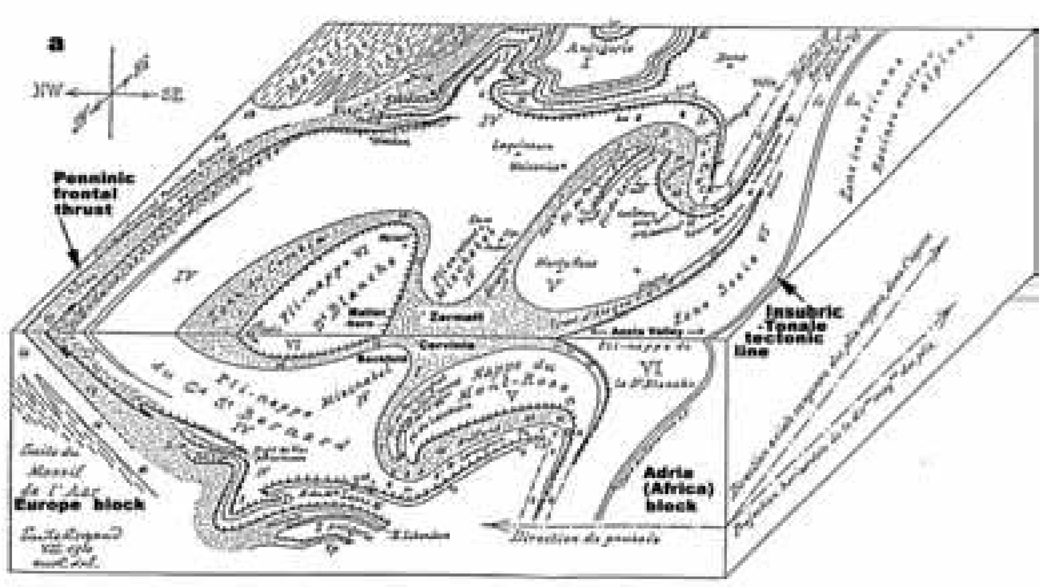


Figure 1 - a: block diagram of the central western Alps, illustrating the oceanic suture zone (Penninic nappes) between the European and African continental margins, located in the axial part of the belt; the tectonic structure is traced by the pre-Alpine crustal rocks (unornamented), and Mesozoic sediments+ophiolites (shadowed); it shows the regional scale complexity of the nappe implications, as reconstructed by Argand (1911), applying the principle of down dip projection of orientation of structures at the surface. The plunge of the fold axes of the nappe structure towards the front face (along the Aosta Valley), is shown to expose the topmost structural element of the pile (Dent Blanche, with the Matterhorn-Cervino); axes culminate to the northeast. The historical names of the pre-Alpine continental crust nappes, from I to VI, are respectively: Antigorio, Lebendun, Monte Leone (Simplon-Ticino, lower Pennine nappes), Grand St.Bernard, Monte Rosa, Dent Blanche (upper Pennine nappes); the intervening nappes consist of Mesozoic materials.

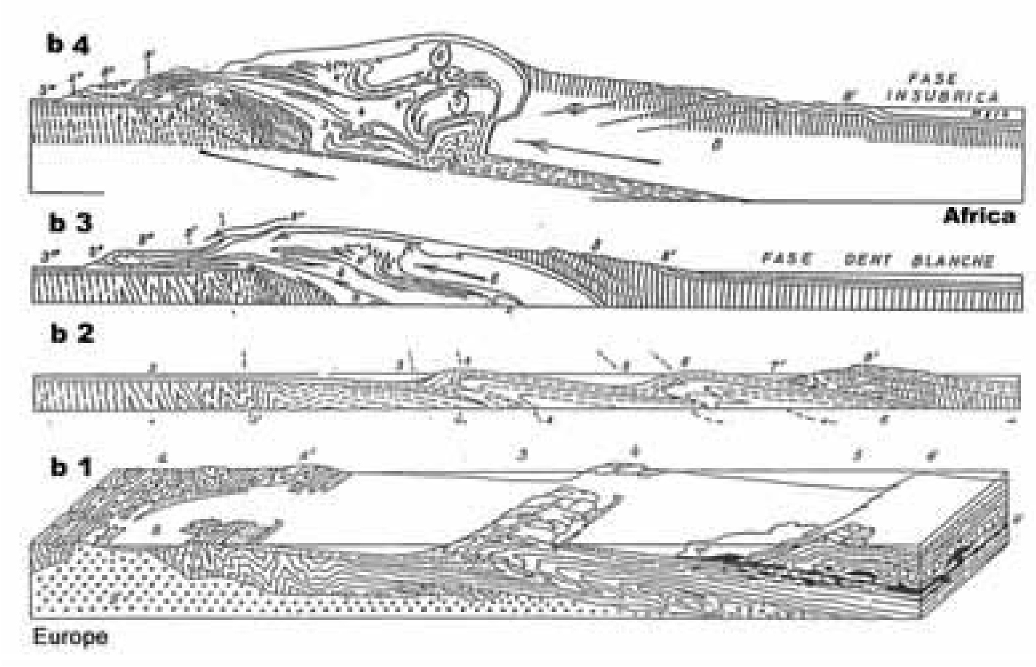


Figure 1 - b: four (b1 to b4) progressive stages of the tectonic development of the fold nappes, as depicted by Argand's (1911) "embryotectonic" kinematic interpretation of the Alpine orogeny; crustal thickening derives from implication within recumbent fold stacks of a pre-orogenic lithostratigraphy, consisting of: a thin pre-Alpine continental crust flooring the Penninic ocean (crosses in b1), its Mesozoic sedimentary sequences (folded lines), hosting interlayered ophiolites (black). In the final stage, corresponding to the front face of Figure 1a, the continental margins of Europe and Africa are closer facing, on each side of the ocean basin's suture.

history, will be discussed as we visit key localities to study the rocks, and to admire structural views, through an eight-day trip from Milano to the Swiss-Austrian border in the Engadine, and back to the Tessin and Aosta regions, ending at Mt. Cervino, (on the Italian side of the Matterhorn), and finally back to Florence.

During the field trip, the significance of differences in the structural, metamorphic, and time evolution of nappes, from three of the four main tectonic blocks forming the wide scale tectonic frame of the belt, will be discussed, along three cross sections (see localities visited in days 1-2-5-6, 3-4 and 7-8 in Figure 6).

The Southern Alps, Austroalpine and Penninic blocks will be visited (see also the tectonic map of Figure 2); only the Helvetic domain (European margin) will not be crossed. An outlook to the pre-orogenic rock associations of the continental and of the oceanic crusts will be delineated when we visit the well preserved rocks of the Lake Como (day 1) and of Bürkelkopf – Flimspitze and Piz Mundin (days 3-4: otherwise only day 3; still better: south vs. north Penninic domain). Only Alpine rocks will be studied on days 2, 5-6 and 7-8.

Regional geologic setting

The present-day structure of the Alpine belt has been investigated over the last 25 years by the Ecors-Crop, NRP20, and the TransAlp deep seismic exploration traverses, fanning respectively from the West to the East of the belt; new geological interpretations were constructed to interpret geophysical models (seismic, gravimetric, and magnetic) of the collisional suture (axial belt), and the multiply indented continental crustal margins of Europe and Adria (Apulia or Africa) (e.g. Roure et al., ed., 1990; Pfiffner et al, ed., 1997; TransAlp Conference Abstr., 2003).

Although velocity models might appear complex (Figure3), objectively the Moho depth reflects well the distinction of the belt into sectors of coherent geological history (Figure4). The Alps are subdivided geologically, from top to bottom and from the internal to the external side, in the following elements (see Figure 2 and 6, and cross sections of Figure 5): (1) the Po river plain hinterland, which represented also the Cretaceous – to Recent fore-land of the

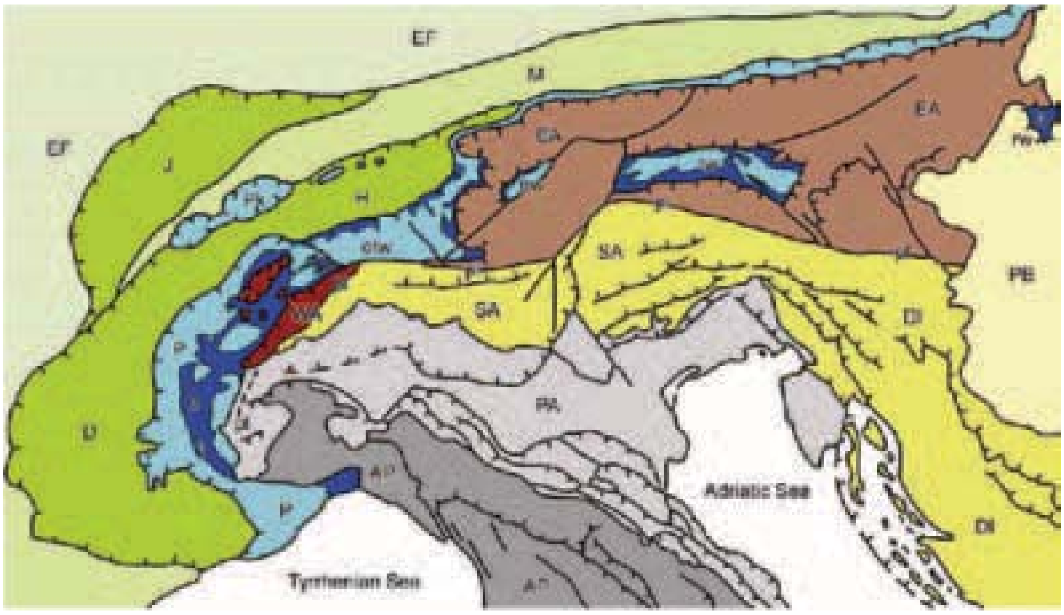


Figure 2 - Tectonic map of the Alps - (1) Europe-vergent collisional belt: i) Western (WA) and Eastern (EA) Austroalpine; ii) Penninic domain: continental and ophiolitic (o) nappes in the western Alpine arc, (P) and tectonic windows (otw: Ossola-Ticino window; ew: Engadine w.; tw: Tauern w.; rw: Rechnitz w.; Prealpine klippen: (Pk); iii) Helvetic-Dauphinois-Provençal (H-D) domain; iv) Molasse foredeep (M); v) Jura belt (J). (2) Southern Alps (SA), bounded to the north by the Periadriatic lineament (pl), Pannonian Basin (PB), European (EF) and Po Valley-Adriatic (PA) forelands, and the Dinaric (DI) and Apenninic (AP) thrust-and-fold belts. From Dal Piaz et al., 2003.

Southern Alps; (2) the South-vergent nappe system of the southern Alps, conventionally bounded to the north by the neogene Peri-adriatic (Insubric-Tonale) fault system; (3) the Europe-vergent Alpine nappe system, including: (a) Austroalpine cover and basement nappes, (b) Piedmont/Ligurian ophiolitic units, and their central and eastern Alpine equivalents (Platta-Arosa, Malenco-Avers, Glockner, Rechnitz), (c) the upper Penninic Monte Rosa/ Gran Pradiso/ Dora-Maira, Suretta, and Tauern basement nappes, (d) the middle Penninic Grand St. Bernard and Tambò cover and basement nappes, (e) the lower Penninic basement nappes of the Simplon-Tessin core, (f) the ophiolite-poor Valais calcschists, and the external north-Penninic flysch units of the Sion-Courmayeur to the Rheno-Danubic border zones; (4) the Helvetic basement and cover units, and related décollement nappes, overlain by (5) the Prealpine pile of décollement sheets; (6) the Swiss-Austrian molasse foredeep; (7) the Jura thrust belt, and (8) the European fore-land. The vertical crustal structure, interpreted from surface geological data, across the over 1000 km-long Alpine arc is shown in the cross-section fan of Figure 5; the crustal wedge delimited by the Periadriatic Lineament (or Tonale-Insubric-Canavese line, PL), and the Penninic Front (PF) records the syn-metamorphic subduction- and collision-related tectonic evolution at deep structural levels, and contains the ophiolitic suture.

The deep geological interpretation of the present-day structure of the Alps does not substantially diverge from that envisaged by Argand, (1911) (Figure1a). The interpretation of continental basement-mesozoic sediments and ophiolites nappe architecture, made nearly a century ago, is impressive indeed; however, the earliest authors were not able to envisage a realistic kinematic picture of nappe formation during lithospheric convergence, because a previously held tenet of ocean basins evolution was the imposition of a thin continental crust as the ocean basement: the continental crust flooring the Penninic ocean would on this premise, therefore, have nourished the crustal fragments of the recumbent fold-nappes of the axial Alpine zone (e.g. the classic Pennine nappes, see the "embryotectonic" history of nappe formation in Fig 2b). The nomenclature of continental nappe sheets, introduced at the beginning of 1900s (large-scale

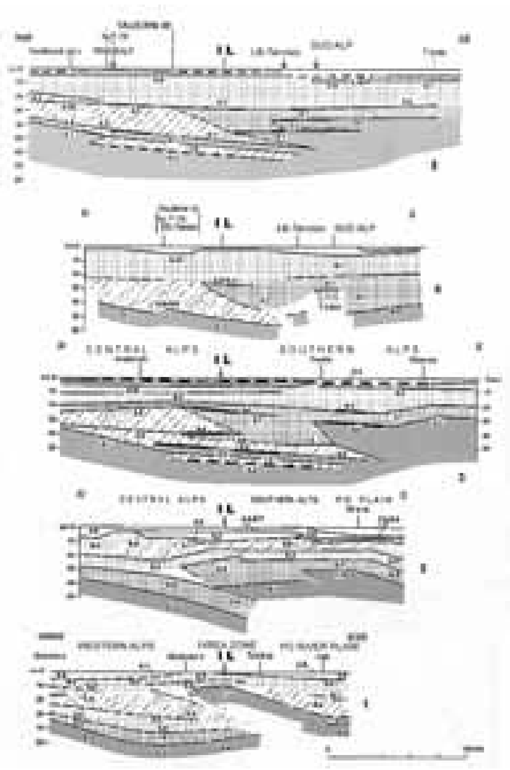


Figure 3 - Comparison of velocities and Moho depths after recent DSS, WARR, and NVR seismic sounding experiments in five stripes across the Alps, compiled by Cassinis and Scarascia (2003); a fan profile is localised in Figure 4.

recumbent folds, known as “Penninic-style nappes”), is still in use; their kinematic history may now be interpreted in accordance with tectono-thermal imprints of tectonic mechanisms active during pre-Alpine roifting, subduction, continental collision, and orogenic denudation.

The present day discriminatory ability of the effects of various superposed lithosphere-scale tectonic processes, however, generates new, and somewhat transversal, definitions of units, (tectono-metamorphic u., thermally-characterized and structurally distinct), with a marked physical (thermo-tectonic) connotation; corresponding tectonic histories are now credited to lithologic associations, carrying equivalent mineralogical, structural, and chronological signatures.

The new regional inventory of peak mineral assemblages– the first numerical inventory of Alpine metamorphic and tectonic stages (see the map presented at T12.03 topical symposium of this World Conference)– may support and consolidate this trend. The new regional inventory is implemented locally, with information on the relationships between the metamorphic history and the evolution of successive structural imprints. This is an approach which exploits the full structural and mineralogical memory of metamorphic tectonites, (assemblage evolution vs. syn-metamorphic foliations, regional cleavage and fold belts, shear, and mylonitic zones), and will eventually be illustrated during the trip. The tectono-thermal study, supported in several Alpine cases, defines orogenic terrains into tectonic units, which are noticeably different in shape and size in relation to the ones defined by litho-stratigraphic affinities (i.e. litho-tectonic units) (Spalla, 1996; Spalla, 2000, and references therein). A first result of such criteria is the separation of subducted from non-subducted tectonic units.

Field itinerary and schedule of the excursion

First day: Wed, 11 Aug 2004. Leave from Malpensa International Airport – Milano, at 15.00, taking our bus to Valtellina (Central Alps, Italy). A short roadside stop on the northeastern bank of Lake Como: tectono-metamorphic history of pre-Alpine rocks of the Southern Alps basement (protoliths of the alpinised continental crust). Maps of the tectono-metamorphic history. Hotel overnight in Tirano, lower Valtellina, Italy.

Second day: Thurs, 12 Aug 2004. Transfer to

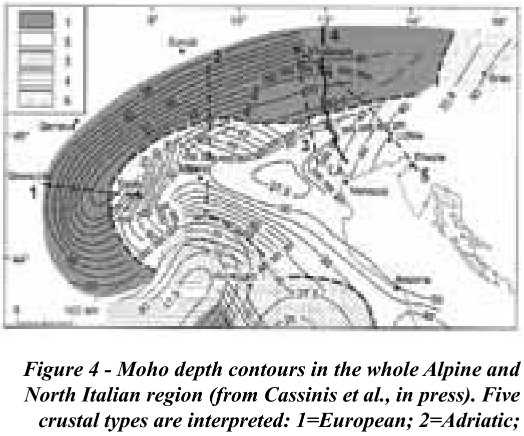


Figure 4 - Moho depth contours in the whole Alpine and North Italian region (from Cassinis et al., in press). Five crustal types are interpreted: 1=European; 2=Adriatic; 3=Transitional peri-Tyrrhenian; 4=Suboceanic; 5=Western corner of the Pannonian basin. Traces 1 to 5 of the five profiles of Figure 5 are located.

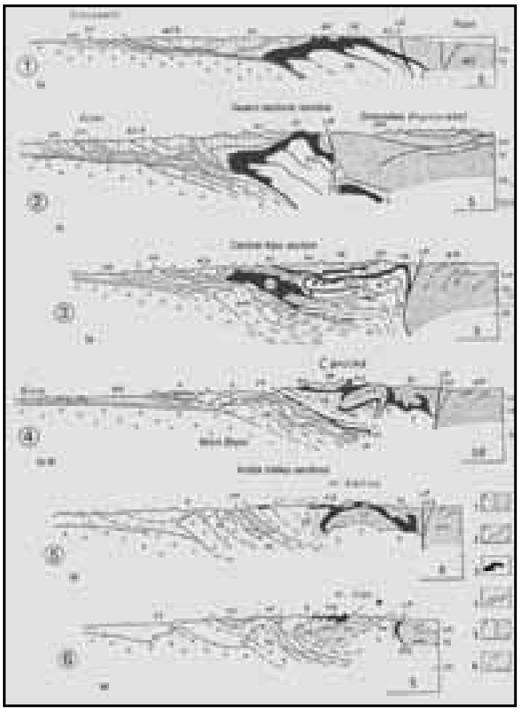
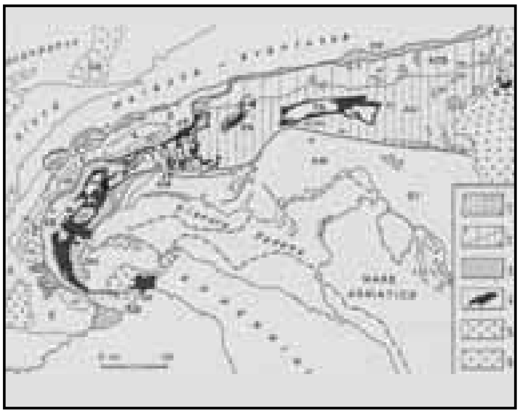


Figure 5 - (a) Popular, multi-authored, and generally credited, simplified cross sections across the Eastern (1), the Central (2), and the Western Alps (3). Legend: 1= Penninic nappe system, mainly deriving from continental crust; 2= Austroalpine system: (a) cover units and (b) mainly basement units; 3= ophiolites and related flysch and mélanges; 4= flysch décollement units, mostly Cretaceous in age; 5= Tertiary European (a) and Po River plain (b) molasses; 6= Late Alpine plutons of Eocene-Oligocene age (45-25 Ma); 7= Southern Alps thrust system, unaffected by high-P Alpine metamorphism. Black stars indicate the position of Alpine UHP rocks. Labels: AD= Adula-Cima Lunga nappe, AU= Austroalpine basement and cover system, TW= Tauern window, CA= Canavese zone, DB= Dent Blanche nappe, Austroalpine, GO/TV/AAR/MB= Gotthard, Tavetsch, Aar, Mont Blanc Helvetic-Dauphinois cover units, HE= Ultra-helvetic, Helvetic and Dauphinois cover units, LPN= Simplon Tessin lower Penninic nappes, NCA= northern Calcareous Alps, Austroalpine, P= Prealpine décollement nappes; PA/GL/MA/PI/AN= Platta-Arosa, Glockner, Malenco-Avers, Piedmont and Antrona ophiolitic units, TN/SU/TA/MR/SB/GP/DM = Tauern, Suretta, Tambò, Monte Rosa, Grand St. Bernard, Gran Paradiso, Dora Maira Penninic basement nappes, SA= Southern Alps, SL= Sesia Lanzo zone, Austroalpine, VA= Valais ophiolitic and flysch units, PF= Penninic thrust front, PL= Periadriatic Lineament.



Mortirolo Pass (1900 m, Italy) - road-side geology with very short walks (light shoes). Continental rocks of the Austroalpine units of the Southern Steep Belt, located right north of the Insubric-Tonale regional tectonic Line, separating the Southern Alps block from the Austroalpine. Permian intrusives with Alpine metamorphic imprint in the Austroalpine. Maps of the tectono-metamorphic history. Transfer to Samnaun, Switzerland, by bus and hotel overnight.

Third day: Fri, 13 Aug 2004. Transfer from Samnaun (Switzerland) to the Idalm area (Austria) by cable car. High altitude hiking, between 2800-2400 m (mountain shoes), on the Engadine window South-

Figure 6 - Location of itineraries progressively visited during the excursion (day numbers with short line segments), in a tectonic scheme of the Alpine chain, with some essential metamorphic and sedimentary features. 1: distribution of blueschist and eclogitic metamorphism in the continental units of the western and central Alps (undistinguished in ophiolitic units); 2: very low grade (a) and HP-LT, greenschist and amphibolite facies assemblages (b) in the eastern Austroalpine cover and basement units; 3: Cretaceous to Eocene flysch deposits and Gosau beds; 4: undifferentiated ophiolitic units (with eclogitic-blueschist imprint in the western Alps and Tauern-Rechnitz windows); 5: main Oligocene (-Eocene in Southern Adamello) plutons along the Insubric-Tonale-Pusteria-Gailtal fault system; 6: perialpine and intramontane Oligocene and Miocene basins (Po valley molasse not indicated). A: Adula nappe; Ad: Adamello pluton; AU: eastern Austroalpine cover and basement nappes; B: Bergell pluton; D: Dinarides; EW/TR/RW: Engadine, Tauern, and Rechnitz tectonic windows; HE: Ultrahelvetic, Helvetic, and Dauphinois Provençal units; LPN: lower Penninic nappes; MR/GP/DM/S: upper Penninic Monte Rosa, Gran Paradiso, Dora-Maira and Suretta nappes; NCA: northern calcareous Alps; PF: Penninic front; SA: southern Alps; SB: Grand St. Bernard nappe; SC: Subalpine chains; SL/DB: western Austroalpine and Dent Blanche nappes.

Penninic units, up to the overlying Austroalpine Silvretta nappe, in Austria. The Swiss-Austrian border will be crossed by hiking: please do not forget your passport. Hotel overnight in Samnaun.

Fourth day: Sat, 14 Aug 2004. Transfer from Samnaun (Switzerland) to Martina by private bus, and from Martina to Alp Tea with shuttle; 1,5 hrs. high altitude (2300-2700 m; mountain shoes) hiking to Piz Fot. in the Engadine tectonic window North-Penninic units. Descent to Martina by shuttle. Transfer from Martina to Roveredo by bus; ascent from Roveredo with shuttle to Capanna Gesero and overnight in simple mountain cabin.

Fifth day: Sun 15 Aug 2004. Full day mountain hike (mountain shoes): Alpe Gesero-Passo San Jorio-Alpe Albion-Alpe Gesero. Transect through SSB: fragmentation of (sub)oceanic and supracrustal bodies in TAC (Tectonic Accretion Channel); deformation and magmatism along the Insubric Line.

Sixth day: Mon, 16 Aug 2004. Transfer with shuttle to Val d'Arbedo (deformation, migmatites) (light shoes); Castione calschists and metabasics. Alpe Arami-Gorduno: Garnet Peridotite, eclogites; decompression history. Descent to Arbedo with shuttle. Transfer to Breuil-Cervinia (Italy) by private bus and hotel overnight.

Seventh day: Tue, 17 Aug 2004. Transfer from Breuil-Cervinia (2000 m, Italy) to Plateau Rosa (3500m, Swiss border) by cable car: tectonic landscape on the Alpine nappe pile. 2 hrs. easy down-walk (mountain shoes), from 2900 to 2500 m, on the eclogitised oceanic rocks of Zermatt Saas unit. Hotel overnight in Breuil-Cervinia.

Eighth day: Wed, 18 Aug 2004. Transfer from Breuil-Cervinia to the Lower Aosta Valley by bus: road side geology with very short walks (light shoes) on the eclogitised continental crust of Sesia Lanzo Zone. Departure by bus to Florence at 14.00 h.

DAY 1

The pre-alpine metamorphic basement of the southern alps (piona peninsula - como lake - valtellina, italy)

***Guido Gosso*[1]*, Maria Iole Spalla*[1]*, Gian Bartolomeo Siletto*[2]**

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The Southalpine thrust belt represents the African (Adria) deformed plate margin, involving thick-skin pre-Alpine basement and Permian-Mesozoic cover slices, and is the hinterland of the Alpine arc. The Southalpine domain is limited from the Penninic-Austroalpine north-verging nappe system by the Periadriatic tectonic lineament (Insubric-Tonale line), and was only locally affected by very low- to low-grade metamorphism (Colombo, 2001). The Southalpine basement of Lake Como consists of two Alpine slices (the Musso unit, Val Colla-S.Marco unit) separated by cataclasites (Musso Alpine fault zone Schumacher, 1996). The Musso Fault Zone (MFZ) represents a pre-Alpine greenschist facies mylonitic belt (Bertotti, 1991; Bertotti, 1993; Gosso, 1997; Heitzmann, 1983; Siletto, 1990), reworked during Alpine times. The shallow Musso Alpine unit of Schumacher and Laubscher (1996), displays a homogeneous metamorphic pre-Alpine evolution (di Paola, 2000; di Paola, 2001), and coincides with the Domaso-Cortafò Zone (DCZ) described by Fumasoli (1974) and Bocchio, (1980). Conversely, the lithologically homogeneous Val Colla-S.Marco unit of Schumacherand Laubscher (1996) consists of portions recording heterogeneous pre-Alpine metamorphic evolutions, namely the Dervio-Olgiasca and Monte Muggio Zones (DOZ, MMZ) (e.g. Gosso*,* 1997; Spalla*,* 2000). The boundary between the northern (DOZ) and southern (MMZ) units is the Liassic syn-sedimentary Lugano-Val Grande normal Fault Zone (LVGFZ), a greenschist mylonitic belt, overprinted by a pre-Alpine cataclasis (Bertotti*,* 1993; Siletto, 1991).

The pre-Alpine metamorphic basement consists of similar lithologic associations in all three zones: gneisses and micaschists (local names: Morbegno and Stabiello Gneisses), with interlayered amphibolites, quartzites, marbles, calcschists, and metagranitoids; pegmatites occur exclusively in the Bt- and Sil-bearing schists of the DOZ, representing the only difference in the litho-stratigraphy of the three zones. Protoliths of metapelite have been interpreted as Early Palaeozoic in age (Mottana, 1985). Relationships with the non-metamorphic Permo-Mesozoic sedimentary cover differ in the three zones: i) deposits of the Verrucano Lombardo Fm. non-conformably overlie the leucocratic metagranitoids of MMZ; ii) slices of Permo-Mesozoic dolostones, conglomerates, and siltstones are separated by tectonic boundaries (MFZ, IL) from the DCZ basement; iii) no Permo-Mesozoic sediments are in contact with the DOZ basement.

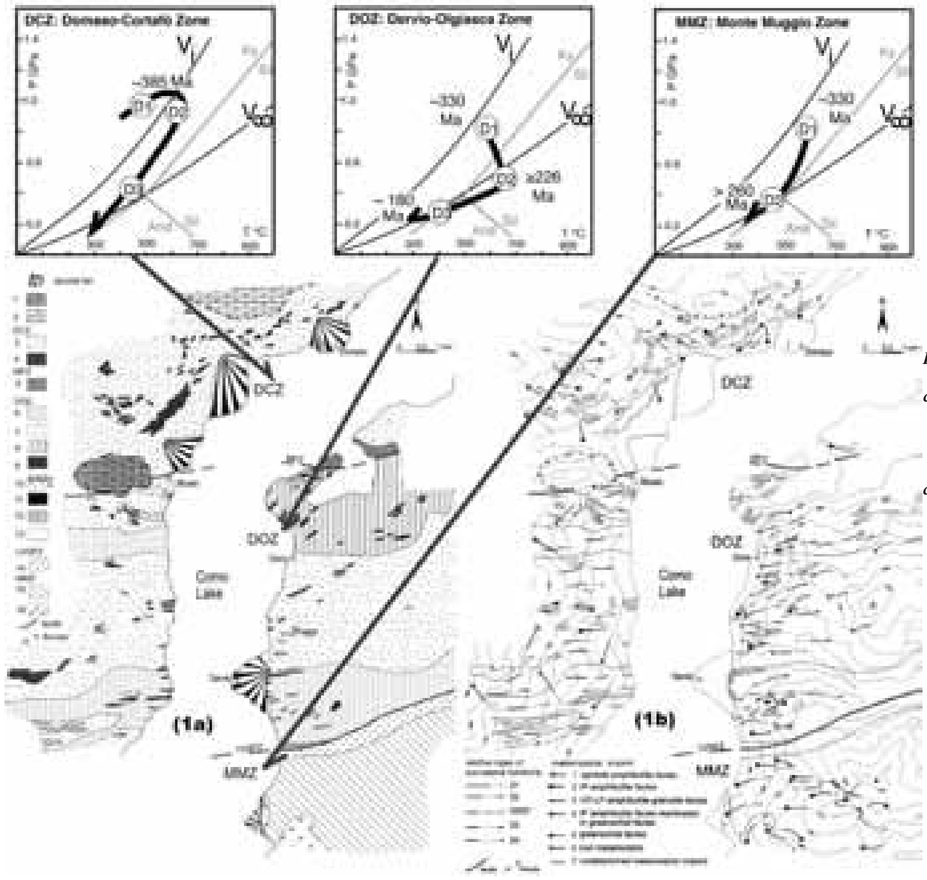

Figure 1.1 - a : Geologic map of Domaso-Cortafò, Dervio-Olgiasc,a and Monte Muggio tectono-metamorphic units (DCZ, DOZ, and MMZ respectively on the map,) separated by the greenschist mylonites defining the Musso Fault Zone (MFZ) and the Lugano-Val Grande Fault Zone (LVGFZ). Legend: 1= Dolomia Principale (Norian): re-crystallised massive dolostones, locally cataclastic; 2= massive medium to fine-grained and calcareous breccias at the contact with the micaschists (sedimentary slices along the Insubric Line). DCZ: 3= metapelites with BtII, MsII, Pl, Grt, ±St, and ±Ky defining the S2 foliation reactivated during D3; Chl, opaque minerals, MsIII, BtIII, and Ab define S3. Relics of S1 are underlined by BtI, MsI, and Cld; 4= amphibolites with HblII, Pl, ±Ilm, ±Qtz, defining the S3 is underlined by Ep, Chl, and Ttn. HblI and Grt occurs as porphyroclasts in S2. MFZ: 5= mylonites with Chl, Ms, Ab, and ribbon Qtz, locally with ultramylonitic texture. s-c structures and extensional crenulation cleavages are widespread. DOZ: 6= micaschists and gneisses with Chl and Ms underlining S3, in places with mylonitic textures, or s-c cleavages; Grt and Bt relics are preserved; the modal amount of Chl increases towards the LVGFZ; 7= Grt-St-bearing micaschists and minor gneisses containing MsI, BtI, GrtI, and St contemporaneous with S1; S2 crenulation cleavage is defined by BtII, MsII, GrtII, ±Si; Chl and MsIII grow during D3; 8= Sil-Bt-bearing micaschists and minor gneisses with Ms, BtII, GrtII, Sil, Pl, ±Kfs mark S2; BtII and Sil define s-c structures and extensional crenulation cleavages; relics of GrtI, Ky, and St are locally preserved. Centimeter-sized and poikiloblasts grow during late D2; 9= amphibolites with Pl, HblII, ±Qtz, ±Grt, ±Bt, ±Ep, and relics of HblI; amphibolites with Hbl, Di, Pl, ± Ttn; S2 is defined by the HblII and Pl compositional layering, or by the SPO of Hbl and Di; rare hornblendites with Chl, Ttn, Ilm, show coronitic textures; 10 a= metagranitoids with Ms and Chl, containing relics of Bt and Grt. Compositional layering defines S2; 10b= fine-grained mylonitic metagranitoids, with Ms and Chl, containing millimeter-sized Kfs porphyroclasts; 11= Qtz, Kfs, Ms, tourmaline, ±Grt-bearing pegmatites. Generally with undeformed cores and foliated (S2) margins; 12= quartzite layers of centimeter to meter thickness, containing Chl, Bt and Ms; 13= fine-to medium -grained, white to light grey marbles, locally containing amphibole and pyroxene; silicate-rich layers are constituted by Zo, Tr, Tlc, and Chl. LVGFZ: 14= mylonitic micaschists and gneisses with Qtz, Ms, Chl, and Ab underlining S3; shear-zones with s-c structures and extensional crenulation cleavages, and dark coloured ultramylonites are widespread; cataclastic feldspar, sericite- bearing gneisses, with granular texture; S3 is well-developed at the boundaries with the mylonites. MMZ: 15= metapelites with Chl, Ab, MsII, ±Mrg underlining S2 foliation. Relics of Grt, Bt, St, Pl, and Ky, developed during D1. Grt-amphibolites rarely occur as meter-sized lenses elongated in S2; rare quartzite layers of centimeter to meter thickness, containing Chl, Bt, and Ms have compositional layering parallel to S2; 16= metagranitoids with Ms, Chl, ±Bt; mineralogical layering defined by alternating quartz-feldspar and sheet silicates layers is parallel to S2.

P-T-d-t trajectories of DCZ, DOZ, and MMZ rocks located in the tectono-metamorphic map of the Lake Como pre-Alpine basement. The metamorphic evolutions and relative radiometric ages are discussed in the text. The unperturbed (V_i) and maximally relaxed geotherm (V÷) are after England and Thompson (1984); Aluminum silicate triple point after Holdaway (1971). Legend: 1= Penninic nappes; 2= Austroalpine nappes; 3= Bergell pluton; 4= Domaso-Cortafò tectono-metamorphic unit; 5= Dervio-Olgiasca tectono-metamorphic unit; 6= Monte Muggio tectono-metamorphic unit; 7= greenschist belts, mainly with mylonitic fabric; 8= slices of Carboniferous conglomerates; 9= Permo-Mesozoic sedimentary cover units; 10= faults: IL= Insubric Line; LVGFZ= Lugano Val Grande Fault zone; MFZ= Musso Fault zone; OL= Orobic tectonic line.

b : Foliation map of DCZ, DOZ and MMZ tectono-metamorphic units. MFZ and LVGFZ correspond respectively to Musso Fault Zone and Lugano Val Grande Fault Zone. The lithological boundaries are shown for reference; the mineralogical assemblages related to successive fabrics in each rock type are listed in the legend of Figure 1 a. The information on the relative chronology of superposed foliations, and on the metamorphic environments in which they developed, are specified respectively by relative ages and metamorphic imprints symbols. In the DCZ, the D2/D3 foliation symbol is used to discriminate S_2 foliation reactivated during D_3. Keys of the metamorphic imprint symbols: 1= epidote amphibolite-facies; 2= intermediate pressure amphibolite-facies; 3= low pressure amphibolite-granulite -facies (corresponding to the HT-LP metamorphic imprint of the text); 4= intermediate pressure amphibolite-facies reactivated in greenschist-facies; 5= greenschist-facies; 6= non metamorphic; 7= undetermined metamorphic imprint. (Stop 1.1)

Different P-T-d-t evolutions (Figure 1.1) are recorded in three zones that therefore represent three different tectono-metamorphic units (Spalla, 2002):

DCZ: the earliest metamorphic imprint in epidote-amphibolite facies conditions (TA550°C), developed during the formation of D1 planar fabric; during D2, rocks re-equilibrated under amphibolite facies conditions (T= 560-650°C and P= 0.7-1.1 GPa); during D3, greenschist facies minerals assemblages developed (T<550° C and P< 0.6 GPa). The D1-D2 portion of the inferred P-T loop (Figure 1) has been interpreted as the thermal record of eo-Variscan subduction and mid-Variscan continental collision; the available K-Ar age of ˜385 Ma fits this tectonic outline (di Paola, 2000; di Paola, 2001);

DOZ: the earlier metamorphic assemblage grew in amphibolite-facies conditions (T= 530-630°C and P = 0.7-1.2 GPa), during the development of D1 structures, re-equilibrated at T = 650-750°C and P = 0.4-0.55 GPa during D2 deformation, and finally underwent greenschist facies conditions (T< 500°C and P = 0.2-0.3 GPa), during the formation of D3 structures (di Paola, 2000; Diella, 1992). An age of ˜330 Ma may be proposed during D1, by comparison with the analogous syn-D1 thermal state of MMZ. Timing of D2 is constrained at ˜226 Ma (Rb-Sr and K-Ar mineral ages; (Sanders, 1996) by syn-D2 pegmatite emplacement, and the D3 greenschist retrogression may be related to Liassic normal faulting along the LVGFZ (e.g, Gosso, 1997). The inferred P-T loop for DOZ (Figure 1.1), has been interpreted as the result of deep-seated Variscan crust exhumation during Permo-Triassic rifting (e.g. Diella, 1992; Spalla, 1999);

MMZ: the earlier metamorphic imprint, contemporaneous with D1 deformation, developed under amphibolite facies conditions (T = 560-600°C and P = 0.8-1.1 GPa); during D2 fabric development, rocks re-equilibrated under greenschist facies conditions (T< 500°C and P< 0.4 GPa) (Bertotti, 1993; Spalla, 2002). A K-Ar age of ˜330 Ma may be attributed to the syn-D1 amphibolite facies metamorphic imprint (Mottana, 1985). Syn-D2 greenschist retrogression predates the deposition of the Verrucano Lombardo sedimentary sequences in Late Permian times (B260 Ma). This tectono-metamorphic evolution (Figure 1.1), has been considered to be the result of the thickened continental crust exhumation, during the thermal relaxation induced by Variscan continental collision (Spalla, 2000).

The foliation trajectory map (Figure 1.1) shows the finite strain field by means of the planar fabrics configuration, and the systematic information on the mineral re-equilibration steps in relation to microfabric changes: location, thickness (less than 5 km), and areal extent of each unit are here confidently constrained. On this map, the association of relative fabric age and metamorphic environment is not univocal across the whole area; actually an independent use, either of the relative chronology of superimposed fabric, or of the different metamorphic imprints, would have induced us to correlate syn-metamorphic structures actually developed in different times and in different geodynamic environments. For example, fabric D2 in DOZ, that developed in LP-HT metamorphic conditions at about 226 Ma, cannot be correlated with fabric D2 in MMZ, which was developed in greenschist metamorphic conditions and predates the deposition of Permian sedimentary covers (and is therefore older than 260 Ma). Conversely, as discussed above, greenschist re-equilibration in DCZ, DOZ, and MMZ took place in different times and under different geodynamic environments.

Stop 1.1:

Locality: Piona Peninsula, north-eastern shoreline of the Como Lake. Map: 1:200.000 scale Road Atlas of the Italian Touring Club.

Topics: Permo-Triassic tectono-metamorphic imprint in Southalpine metapelites and pegmatite emplacement; pre-Alpine protoliths outside the deep-seated Alpine collisional belt (i.e. south of the Insubric Tectonic line). Illustration of the use of foliation maps to unravel the tectono-metamorphic history of polydeformed metamorphic basements.

Equipment and program: road geology, with a 5+5 min. walk on a forest path (light shoes).

The only stop of the first day is reached by following the highway Lecco-Colico (S.S. n°36) to the Piona exit, eastern shoreline of the Como Lake; drive backwards on the road (S.P. n°72) to the Piona peninsula, and cross the village of Olgiasca. Stop some hundred meters before the Piona Abbey, in a parking area. Excursion stop is located in Figs. 1.1 and 1.2. Short walk (10 min.) through a holly wood, up to a small abandoned quarry, where a pegmatite was emplaced along a Sil-Bt-bearing shear zone. Pegmatite contains Qtz, Tur, Ms, Ab, Kfs, minor Bt, and Grt; accessory minerals are monazite, uraninite, zircon, beryl, chrysoberyl, pyrite, arsenopyrite, etc. The grain-size decreases from the undeformed core to the foliated margins. The Sil-Bt shear bands, widespread in the northern part of DOZ (Figure 1.3),

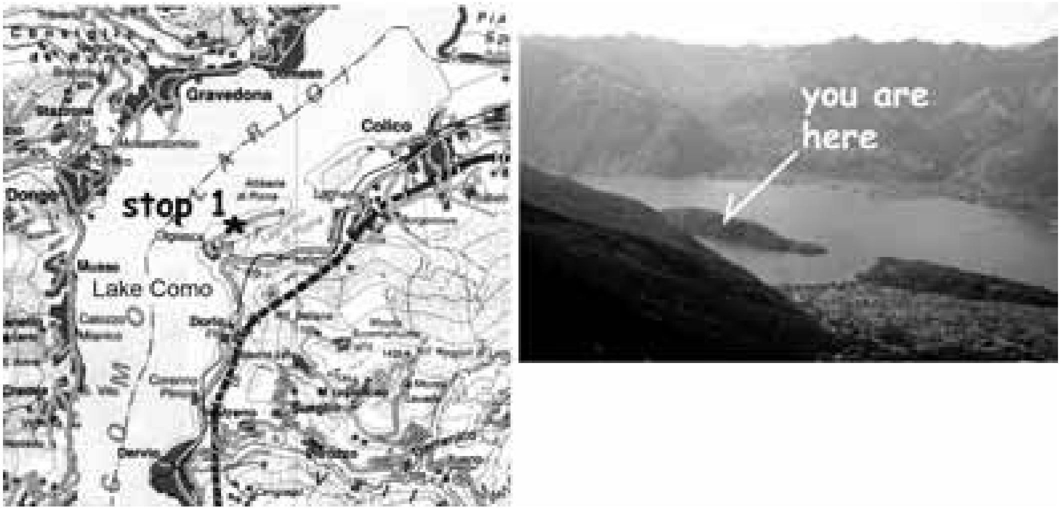

Figure 1.2 - Geographic location of Day 1 Stop on Lake Como, and panoramic view of the Piona peninsula and Musso fault zone. (Stop 1.1).

dipping to S-SSW, show a dextral sense of movement along the sub-horizontal stretching lineation. The composite s-c foliation (s = 176-195/60-75; c = 198-210/80-87), lies at a low angle to the pegmatite (185/70; Figure 1.3 c, e, f). Microstructural analysis evidentiates that cleavage asymmetries are compatible with extension (Figure 1.3 d). These observations indicate a syn-D2 pegmatite emplacement. High-T shear bands dominate the fabric of small outcrops along the road and downhill. Fibrolite and BtII intergrowths define a marked stretching lineation and both shear and foliation planes of D2 (Figure 1.3 d). Fibrolite and prismatic Sil grew contemporaneously in different microstructural sites: fibrolite underlines shear and foliation planes and prismatic Sil occupies microlithons. Grt is incompletely pseudomorphosed by aggregates of fibrolite and BtII (Figure 1.3 a), which occupy also asymmetric pressure shadows. Relict white mica is rarely preserved, is overgrown by small needles of fibrous Sil, and commonly has lobate margins (Figure 1.3 b). Locally S2 grades into sigmoidal domains (up to centimetric), of polygonal Qtz aggregates, Pl, minor K-fs, and red-brown Bt with lobate margins, bounded by s and c planes.

DAY 2

Eo-Alpine HP metamorphism on the Permian intrusives and their country rocks in the Austroalpine units within the Southern Steep Belt, right north of the Insubric tectonic line (Mortirolo Pass, on the Valtellina - Upper Val Camonica watershed, Italy). Illustration of the use of foliation maps to individuate tectono-metamorphic units in polycyclic (poly-orogenic) metamorphic terrains

In spite of the widespread and well documented HP-LT eo-Alpine metamorphic imprint in Austroalpine units, from the western and eastern Alps (e.g. Dal Piaz, 1972; Compagnoni, 1977; Hoinkes, 1991; Thoeni, 1993), in the Austroalpine domain of the central Central , Western and Eastern Alps are toponyms, not just adjectives Alps, records of this tectono-metamorphic stage are scanty (Vogler, 1981), and localised in the Southern Steep Belt, due north of the Insubric Line. Abundant eo-Alpine eclogites, even if heterogeneously distributed, in the uppermost structural level of the Alpine nappe pile (Spalla, 1996, and refs. therein), invalidates the idea that the Austroalpine domain represents a unitary and homogeneous tectonic system, and indicates two types of Austroalpine units: i) units unaffected by the eo-Alpine subduction metamorphism (the Alpine orogenic lid); ii) units deeply involved in the subduction zone, such as the ophiolitic and Penninic continental basement nappes. At a regional scale, a sharp continuous boundary between them has not yet been defined. In the Austroalpine units, exposed along the upper Val Camonica – Valtellina ridge, Permian diorites and granitoids constitute discriminating tools to detect Alpine tectono-metamorphic histories.

The Upper Austroalpine units of the central Alps include the Languard - Campo Nappe (LCN), and

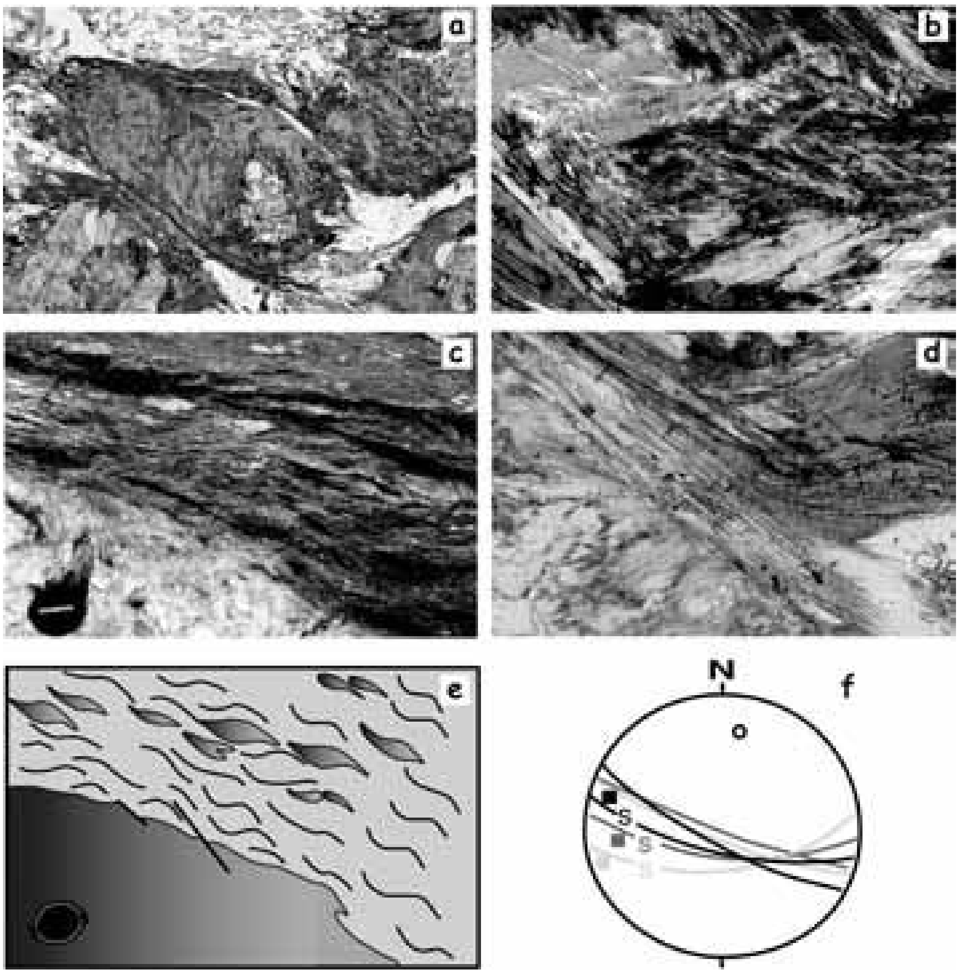

Figure 1.3 - Photomicrographs of microstructural relationships between critical minerals and mesoscopic structures of rocks from the Dervio-Olgiasca tectonometamorphic unit (DOZ). (Stop 1.1 on Lake Como). a) garnet porphyroblasts replaced by sillimanite-biotite intergrowths. Fibrous sillimanite and biotite mark both shear and foliation planes and occur in asymmetric garnet pressure shadows. Granoblastic domains contain mainly quartz and plagioclase, with minor K-feldspar and red-brown biotite – plane-polarized light, long side of photomicrograph = 15 mm; b) white mica, biotite I and plagioclase, partly replaced by a fine aggregate of fibrolite and biotite II – cross-polarized light, long side of photomicrograph = 0.8 mm;

c) Pegmatite near the Piona Abbey, showing “s-c” structures at the rims: shear and foliation planes developed during deformation D2, at pegmatite margins and in biotite-sillimanite gneiss.

d) shear and foliation planes, marked by sillimanite and biotite II intergrowths. Biotite II displays a Ti content higher than that of relict biotite I (Diella et al., 1992), indicating T-increment during D_2. *Plane-polarized light, long side of photomicrograph = 2.5 mm.*

e) Interpretation of structural patterns of figure c): pegmatite emplacement is assisted by an extensional effect, contemporaneous with a s-c cleavage. Diameter of black disc is 5 cm long.

f) In a Schmidt plot (lower hemisphere), s-c planes are shown together with Sill-bearing mineral lineation. O = pole to pegmatite bedding; S = foliation planes; squares = sillimanite-bearing lineation. (Stop 1.1, near the Piona Abbey on Lake Como).

the Tonale Series (TS), both consisted of a poly-metamorphic rock association. LCN and TS display a generally steeply dipping attitude immediately north of the Insubric line (Southern Steep Belt,Schmid, 1996). LCN represents the highest unit capping the Lower Austroalpine (Margna, Sella, and Bernina nappes) in which thin tectonic elements with ophiolitic affinity (Corvatsch and Platta) are interlayered (Figure 2.1 b).

In the literature, LCN has been distinguished from TS on lithological grounds, and, consequently, on the depth of crustal derivation. According to Venzo, (1971, and refs. therein), LCN comprises low to medium grade muscovite-, Bt- and minor St- gneisses and micaschists, with interlayered amphibolites, marbles, quartzites, and pegmatites, whereas TS is formed by

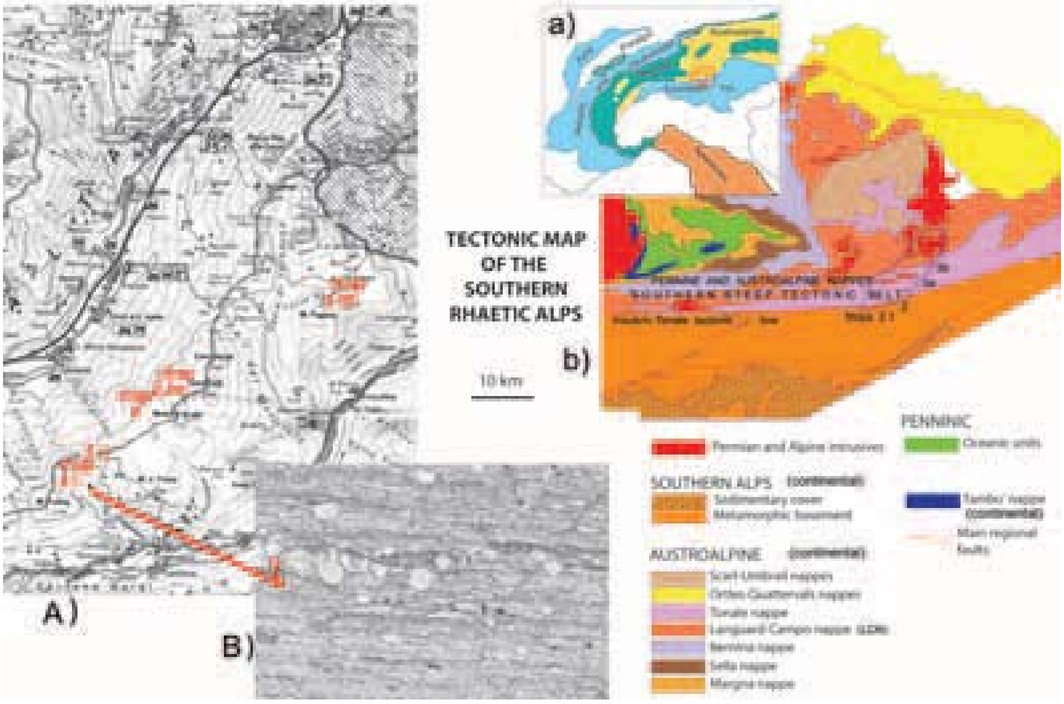

Figure 2.1 Location of Day 2 stops, near Passo del Mortirolo, on the Valcamonica-Valtellina ridge (inset A); tectonic map of a portion of the Central Alps (=Southern Rhaetic Alps, with legend, insets a and b), and a microstructure of a mylonite from the Insubric-Tonale tectonic line (inset B). Day 2 stops are also located in the oblique polygon inside inset B) reporting the detailed map location of Figure 2.2. In inset b), the Insubric-Tonale tectonic line (related mylonites shortly visited at Stop 2.1), separates the continental and oceanic Alpine nappe belt generated at depth during subduction and collision tectonic episodes (Austroalpine and Pennine nappes of the southern steep tectonic belt, North of this tectonic line) from the continental upper crustal thick-skin (basement+covers) overthrusts of the Southern Alps (South of this tectonic line); the Southern Alps thrust belt is south-verging and tectonic units are bounded by EW and SW-NE trending overthrust faults of Alpine age (see Southern Alps block in legend of inset b); it developed under very low – to low metamorphic conditions. B) shows a typical microstructure of greenschist facies–dominated mylonites, with feldspar porphyroclasts and fine-grained chlorite+white mica in the foliation planes.

Figure 2.2. - a): Simplified geological map reporting lithostratigraphy and km-scale strain (fabric) gradients within Permian-age metaintrusives. Legend: grey=undifferentiated country rocks of the Permian intrusives; Red=Grt-bearing pegmatites. Gradients of colour shading identify the fabric gradients, from coronitic to normally foliated (tectonitic) and mylonitic, within metagranodiorites (yellow to orange), and metadiorites (pale blue to dark blue). The LCN (Languard-Campo nappe) extends from top north to the red dashed line, also corresponding to the Mortirolo tectonic line; TS (Tonale series) extends from south to the dashed red line. STS=Scisti del Tonale series; CRS=Cima Rovaia series; PRS=Pietra Rossa series (Bonsignore & Ragni, 1966; 1968). b): P-T-d-t paths of the Languard Campo Nappe - Tonale Series (after Gazzola et al. 2000; Zucali, 2001); inset c): pre-Alpine and Alpine P-T paths compared with the stable geotherm (Vi).

higher grade Sil-bearing gneisses and micaschists, Grt- and Bt-bearing amphibolites, marbles, and pegmatites. In both these units (Figure 2.1b), post-Variscan intrusives (granitoids, diorites, and minor gabbroids) commonly occur (Tribuzio, 1999,and refs.) with mineral ages clustering in two groups: the first, ranging from 298 to 224 Ma, is interpreted as magmatic cooling ages (Tribuzio, 1999), whereas the second, ranging from 125 to 78 Ma, is considered as the effect of Cretaceous reactivation during Alpine tectonics (Del Moro, 1981). LCN and TS have been considered as inhomogeneously affected by an Alpine metamorphic imprint, never exceeding greenschist facies conditions (e.g. Bockemuehl,1985), until new petrological and structural data attributed higher pressure conditions to this metamorphism (Spalla, 1995; Gazzola, 2000; Zucali, 2001). Permian intrusives represent a time reference which has been utilized to separate Alpine from pre-Alpine structural and metamorphic characters. Pre-Alpine structures consist of sets of pre-D2 fabrics, marked by contrasting mineral assemblages in the metapelites (pre-D2a: St + Grt + BtI + MsI + Qtz + Pl ± Ky; pre-D2b; Grt + Bt + Sil + Pl + Qtz). D2 structures include the most prominent pre-Alpine folds and related foliation; they are synchronous with the emplacement of Permian diorites and granodiorites (260-280 Ma), and are underlined by BtII + Sil ± Grt ± Crd ± Kfs + Pl + Qtz in metapelites. And + MsII overgrew S2. During Alpine times, three groups of superposed structures overprint the pre-Alpine syn-metamorphic fabrics and deform Permian intrusives. HP assemblages developed during D3 in metapelites (GrtII + MsIII + Qtz + Ab ± Cld ± Ky ± Ts), and in metaintrusives (Grt + Ab + Qtz + Zo/Czo + Phe ± AmpII). S3 maxima occur at 162/55 and 355/87. Two groups of large-scale fold systems (D4 and D5), are associated with greenschist facies re-equilibration, during which Alpine Bt grew (120-80 Ma; (Del Moro, 1981); joint sets and Chl/Kfs-bearing fracture systems overprint D5 structures. The quantitative P-T-d-t path of Permian intrusives, and their country rocks, corresponding to the described pre-Alpine and Alpine evolution, is summarised in Figure 2.2 b.

The goal of the second day field trip is to show that the different lithostratigraphic units, in which this Austroalpine basement has been subdivided, reflect an Alpine strain gradient, coinciding with a metamorphic transformation gradient; in addition, these lithostratigraphic units belong to a single tectono-metamorphic unit during Alpine evolution. This is easily perceived in Figure 2.2a), where planar fabric gradients (in metaintrusives), foliation ages, and related evolving metamorphic conditions are represented together on a single map.

Stop 2.1:

Locality: Monte Padrio, Valle di Guspessa (Valtellina – Val Camonica ridge, near Mortirolo Pass). Map: 1: 200.000 scale Road Atlas of the Italian Touring Club.
Topics: Mylonitic belt, marking the Insubric Line.
Equipment and program: mountain road geology, with a 10+10 min. walk offroad (light shoes recommended).

The first stop of the second day is reached by following the road from Aprica to Mortirolo Pass; drive backwards on the road up to Monte Padrio, and park along the road where some outcrops of mylonites of the Insubric tectonic line are located (Figure 2.1 b and B). South of the mylonitic belts, the pre-Alpine metamorphic rocks of the southern Southern is a geological term in this case (a paleogeographic domain!) Alps thrust belt are exposed; they consist mainly of metapelites, with interlayered quartzites which underwent a polyphase Variscan metamorphic evolution from intermediate pressure amphibolite facies, to greenschist facies (Spalla, 1999). Alpine tectonic evolution occurred under very-low to low grade metamorphic conditions. North of the Insubric-Tonale mylonitic belt poly-cyclic (poly-orogenic) Austroalpine metamorphic rocks, that will be studied in detail at the next stops, are exposed.

Stop 2.2:

Locality: Mt. Motto della Scala western slope (Valtellina – Val Camonica ridge). Map: 1:200.000 scale Road Atlas of the Italian Touring Club.
Topics: Tonale Series metamorphic rocks (Tonale Series=part of Tonale nappe of Figure 2.1 b) with a dominant high grade pre-Alpine metamorphic imprint; low strain Alpine deformation zone.
Equipment and program: mountain road geology, with a 10+10 min. walk offroad (light shoes).

The second stop (2.2), is reached following the road towards Mortirolo Pass up to Alpe Troena, at the foot of Mt. Motto della Scala; parking along the road, where some outcrops of high grade metapelites with interlayered marbles and amphibolites occur (Figure 2.1). In these high-grade Bt-Sil gneisses and schists, with interlayered Grt- and Bt-bearing amphibolites, marbles and pegmatites, the dominant fabric is foliation S2, a high temperature pre-Alpine mineral layering. D2 structures consist of tight to isoclinal folds from centimeter to kilometer scale; relics of foliation S1 are locally preserved (Figure 2.2 a and 2.3). In metapelites, S2 foliation films are defined by Sil and red-brown Bt, whereas Grt, Pl and prismatic Sil occupy the microlithons; locally Kfs and Crd occur. In granoblastic metabasics, foliation S2 is a mineral layering in which Hbl-bearing layers alternate with An-rich Pl and Scp-bearing layers. Bt from Ca-rich metapelites have Ti and Al^{VI} contents, indicating a T-range of 650°-750°C. Hbl is generally zoned: Ti content in Amp cores indicates 730°<T<820°C, whereas Ti content in the faded rims is 550°<T<600°C, according to Otten (1984). For these two T-intervals, the coexistence of amphibole with An-rich plagioclase and Grs-Adr-rich garnet suggests P≤ 0.5 GPa. During Alpine deformation, foliations are poorly pervasive, and concentrated in narrow zones, actually pre-Alpine fabrics and mineral assemblages are widely preserved. In this case Alpine minerals develop as reaction rims (Fig 2.3).

Stops 2.3:

Locality: *Stop 2.3a* - Il Boschetto, western slope of Cima Cadì (Valtellina – Val Camonica ridge);

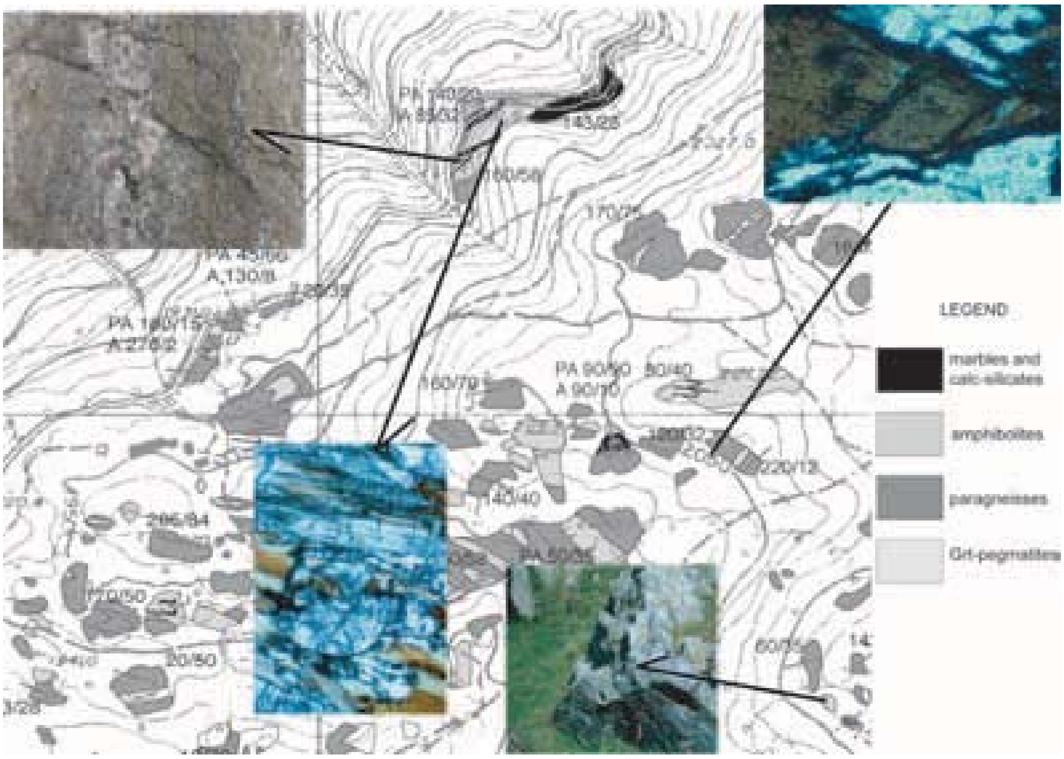

Figure 2.3. - Map of high grade metapelites with interlayered marbles and amphibolites at the foot of Monte Troena; the dominant granular scale fabric (S2) of all rocks is pre-Alpine; it is overprinted in the metapelites, by Alpine corona-texture transformations (with no strain associated). D2 folds deform the lithologic layering.
Lower left photomicrograph: S2 foliation in metapelites, marked by biotite and sillimanite preferred dimensional orientation (PDO), with pre-Alpine garnet porphyroblasts and ilmenite included; crossed polars (CP), lower side of photograph(LSP) = 4 mm.
Lower-right photograph: garnet pegmatites deformed by D2 folds. LSP = 2 m.
right photomicrograph: strain-absent corona metamorphic transformations of Alpine age, generate tschermakitic amphibole at the rims of pre-Alpine biotite grains, within high grade metapelites (kinzigites), that macroscopically do not appear to have been reactivated; crossed polars (CP), LSP = 3 mm.
Upper-left photomicrograph: Amphibolites with pre-Alpine mineral scale foliation S2 parallel to lithologic layering (Sl), within the pre-Alpine high grade metapelite-marble-amphibolite sequence; LSP = 45 cm. Stop 2.2

Stop 2.3b Pianaccio (Valle di Grom) at the base of Monte Pagano northern slope (Valtellina – Val Camonica ridge).

Topics: Permian intrusives and their country rocks, affected by Alpine HP metamorphism; high strain Alpine deformation zone.

Equipment and program: mountain road geology, with a 10+10 min. walk offroad.

In both stops, Permian intrusives (diorites) and their country rocks show various type of Alpine deformations and metamorphic transformation patterns (Figure 2.4). Metadiorites still preserve igneous textures and mineral associations across meter-size volumes: igneous textures are defined by mm to cm-size dark Amp, displaying euhedral to subhedral shape; Pl is interstitial. Alpine metamorphic minerals occupy extremely small volumes within the texture of undeformed

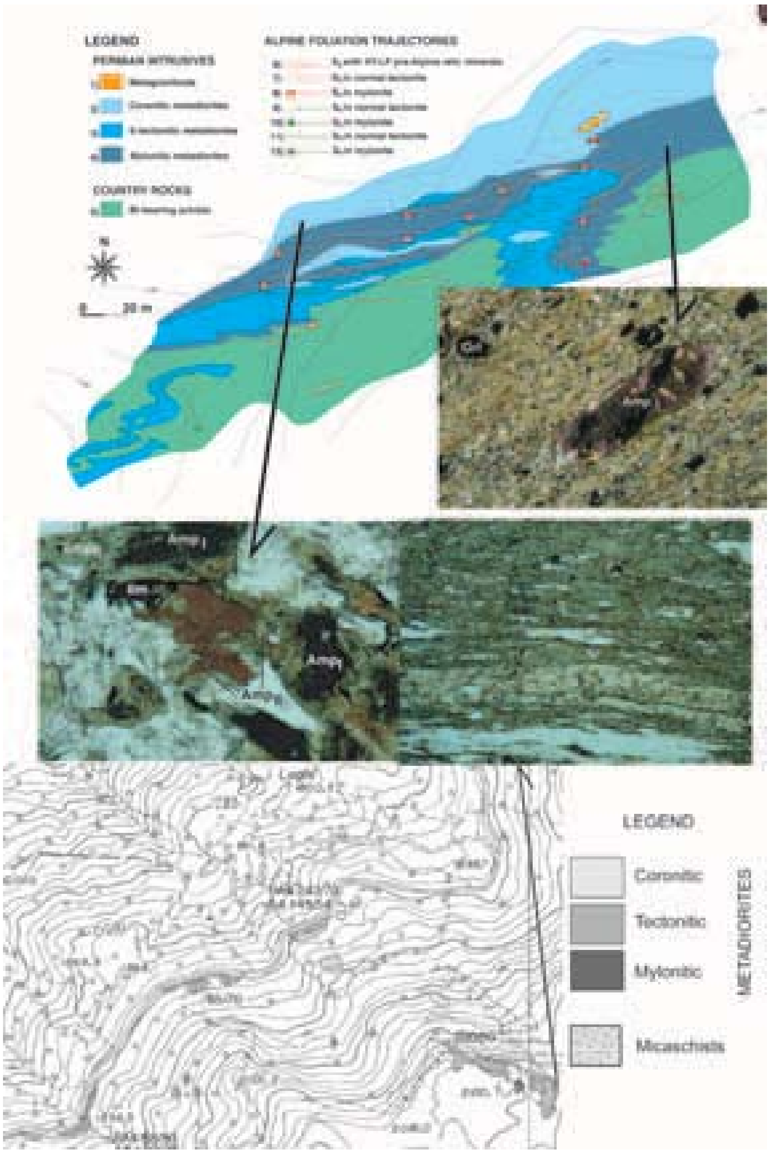

Figure 2.4. - Top image: form surface map of the Monte Pagano Permian diorite, deformed during Alpine polyphase metamorphism. States of increasing strain in Permian intrusives are mapped with trajectories of the Alpine superposed foliations; their relative chronology is shown by the number of dots. The metamorphic conditions, under which successive fabrics developed, are specified by different colors: red= HP eo-Alpine (epidote-amphibolite facies) imprint; green= green-schist facies imprint. Where metadiorites are undeformed, metamorphic minerals mimic the igneous fabrics (coronitic texture).

Top photomicrograph: mylonitic foliation in metadiorite, which wraps garnet porphyroblasts (Grt) and igneous amphibole porphyroclasts (AmpI), is defined by a fine-grained aggregate of amphiboleII, white mica and clinozoisite. AmpI shows subgrains and new grains of amphibole II at the margins; crossed polars (CP), LSP = 3 mm.

Lower-left photomicrograph: coronitic tschermakitic amphibole (AmpII) develops at the boundary of dark igneous hornblende (AmpI) and biotite (BtI), in an undeformed metadiorite; plane polarised light, low side of image = 2 mm.

Lower-right photomicrograph: S3 foliation is marked by the shape preferred oriention of light green alpine amphiboles, quartz ribbons and white mica + garnet-rich layers; ppl, lsi = 8 mm.

Lower map: 1:10.000 original map of Alpe Boschetto region, with partitioning of strain in Permian intrusives, which were deformed during eo-Alpine metamorphic re-equilibration.

metadiorites (i.e. *coronitic* domains): Alpine reactions produce corona-like growth of white mica, Grt and pale-blue Amp in the lack of new planar or linear fabric. In *tectonitic* (i.e. normally foliated) and *mylonitic* domains, the newly grown Alpine minerals (pale-blue Amp, Grt, white mica, Pl, and Zo/Czo) mark foliations and lineations developed during D3 Alpine deformation; in tectonitic domains, relics of igneous minerals are still preserved as mm-size porphyroclasts within the S3 foliation; in mylonitic domains, relics of igneous assemblage are no longer visible, and the mylonitic foliation S3 is exclusively marked by Alpine pale-blue Amp, white mica, Zo/Czo, and Pl (albite), Grt (Figure 2.4). In country rocks, new Alpine minerals define D3 fabrics (white mica, Cld, Mg-rich Chl and Grt) where tectonitic and mylonitic texture developed and randomly replace the pre-Alpine assemblage in coronitic domains. D4 and D5 deformations developed under greenschist facies conditions; they mainly consist of m- to dm-scale shear zones or fold systems. The newly-formed foliations are marked by the SPO of white mica, Chl, Ab and Ep ± BtII in metadiorites; and by white mica, Chl and Qtz in micaschists.

DAYS 3 - 4

The Engadine Window at the border of the eastern and western Alps

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Introduction:

When, in 1904, for the first time, Pierre Termier described the geology of the lower Engadine as a window, he qualified it as *"de plus bel exemple que l'on puisse citer"* ("the most beautiful example we may cite"), due on the one hand to the straight contacts between the different units, and on the other hand to the mapping evidence (Figure 3. 1).

The Engadine window is an antiform trending NE-SW (Klay, 1957), situated between the Eastern and Central Alps. It exposes a stack of Penninic nappes, overlain and framed by Austroalpine nappes (Figure 3.2). The rocks of the Engadine window can be subdivided into several distinct units (Hammer, 1921; Cadisch *et al.*, 1968; Trümpy, 1975; Oberhäuser, 1980); from top to base, they are as follows:

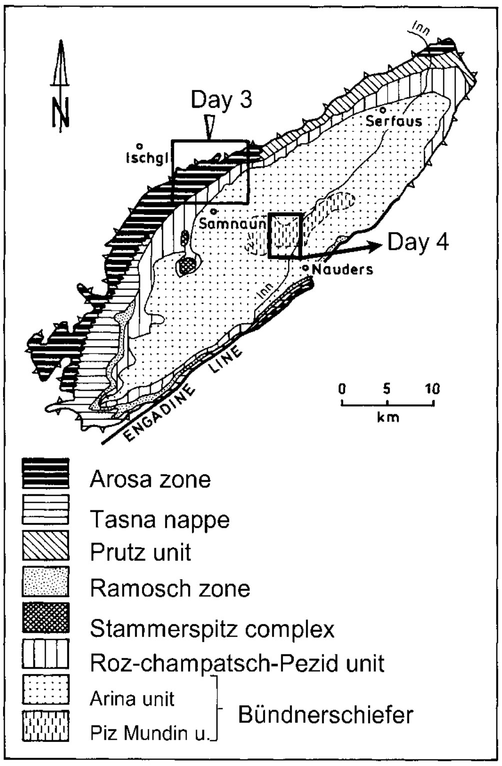

Figure 3.1 - Tectonic sketch map of the Engadine tectonic wondow, with location of areas visited in days 3 and 4.

The Arosa zone ***(that will be visited on the third day)*** is a highly tectonized ophiolite-bearing unit, a few tens to more than a thousand m thick (Ring *et al.*, 1990). It includes an ophiolite series, mostly composed of serpentinites and gabbros (Höck & Koller, 1987), and a sedimentary series of radiolarian cherts, pelagic limestones and black shales of Hauterivian-Aptian age (Weissert & Bernoulli, 1985), and flysch deposits. The Arosa zone in the eastern part of the Grisons continues southward in the Platta nappe, with similar compositional and paleogeographic features (Dietrich, 1976; Frisch *et al.*, 1994). It is likely also correlative with the Matrei zone in the Tauern window (Frisch *et al.*, 1987), that was interpreted as part of an imbricated thrust stack formed by the overriding

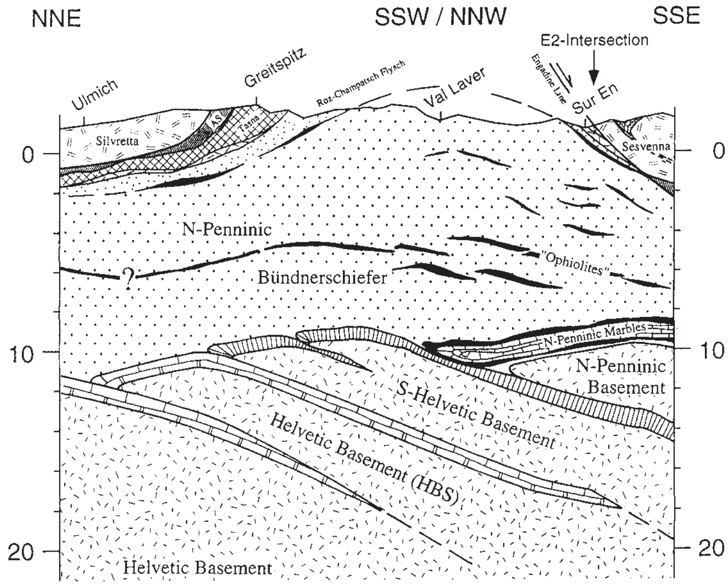

Figure 3.2 - Geological cross-section across the Engadine tectonic window.

of the Austroalpine units, that can be compared to an accretionary prism (Ring, 1992) (Figure 3.2).

The Tasna nappe is a continuous sedimentary sequence from the Permo-Triassic to the Upper Cretaceous, locally associated with slices of continental basement (Waibel & Frisch, 1989). The Lias-Cretaceous sequence is composed mainly of turbidites with associated debris flows and pelagic limestones. However, recent studies in the Tasna nappe basement (Florineth & Froitzheim, 1994), revealed a preserved transition from the continental crust of the Briançonnais terrain to the oceanic crust of the Valais basin.

The Ramosch Zone represents the transition between a continental unit (Tasna nappe) and an oceanic domain (Valaisan ocean) (Florineth & Froitzheim, 1994). The main unit is of a serpentinized peridotite-body associated with ophicarbonates and serpentinite breccias (Vuichard, 1984). Metagabbros are lenticular within. and adjacent to the serpentinite body. Directly underlying the serpentinite along an Alpine, top-north directed thrust fault, pillow basalts represent a part of the Valais ocean (Froitzheim *et al.*, 1996).

The Bündnerschiefer ***(that will be visited on the fourth day)*** underlies the Engadine window (Hitz, 1994), with up to 10 km of calcschists interbedded with shales and quartzites. It grades upward into flysch deposits that are lithologically very similar to the Bündnerschiefer, and are dated as Upper Cretaceous to Eocene (Ziegler, 1956). Some mafic bodies are intercalated within the schists, particularly in the core of the window. These bodies are mainly composed of pillow basalts and hyaloclastites associated with metaradiolarites, where geochemical criteria suggest an oceanic basement (Dürr *et al.*, 1993). This unit is the remnant of the northern Penninic ocean, the Valais basin (Trümpy, 1980; Stampfli, 1993). The metapelites are metamorphosed at blueschist facies (Goffé & Oberhänsli, 1992; Oberhänsli *et al.*, 1995) while metabasites have a greenschist (crossite, lawsonite) metamorphic overprint (Leimser & Purtscheller, 1980).

The LEW is overthrust by the Silvretta crystalline unit, consisiting of medium to high grade metamorphic augen-gneisses, biotite bearing paragneisses, and micaschists, as well as amphibolites and even eclogites. Occasionally, small wedges at the base of the Silvretta unit are found, consisting of slightly metamorphosed sandstones, dolomites, and limestones.

The exposure of Penninic units in the window is not only due to erosion of the Austroalpine nappes, but also to the movement along the Engadine line, which runs along the southeastern border of the window. The Engadine line is a tectonic lineament along which oblique slip and block rotation took place in Late

Tertiary times (Schmid & Froitzheim, 1993). It acted in this area as a southeast-dipping oblique normal fault, so that the Penninic units were uplifted relative to the Austroalpine nappes in the southeastern block (Hitz, 1994). The vertical throw is estimated to be approximately 4 km (Schmid & Haas, 1989).

DAY 3

Fimber unit and the Idalp ophiolite (South Pennic unit, Lower Engadine Window; Austria-Switzerland)

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Introduction

The northwestern and western part of the Lower Engadine Window (LEW) is formed by two units, the lower Tasna nappe, believed to be of Middle Penninic (Brianconnais) origin, and the higher Arosa zone, which is assigned to the South Penninic (Ring et al 1990, Bousquet et al. 1998). Occasionally, a Fimber unit is delineated containing elements of the South Penninic Arosa zone and parts of the Middle Penninic Tasna nappe (Fuchs and Oberhauser, 1990, Bertle 2000). In the following descriptions, we will distinguish between the Idalp Ophiolite and the Fimber unit, the former being in a higher tectonic position.

The LEW is overthrust by the Silvretta crystalline unit, consisting of medium to high grade metamorphich augen-gneisses, biotite-bearing paragneisses and micaschists, as well as amphibolites, and even eclogites. Occasionally, small wedges at the base of the Silvretta unit are found, consisting of slightly metamorphosed sandstones, dolomites and limestones. They are termed "Subsilvrettide zone" (Dauerer 1980, Oberhauser 1980).

Fimber zone

The stratigraphic sequence in the Fimber zone starts, apart from blocks of granitic and metamorphic rock, as well as dolomites and limestones, with the Upper Triassic Keuper beds, which contain sandstones, quartzites, limestones, rauhwackeys, variegated shales, and gypsum. They are overlain by the Liassic Steinsberg limestone. Its biostratigraphic classification is based on ammonites, brachiopods, bivalves, and microfossils. The limestone is overlain by Posidonia shales, and the Doggerian Idalp sandstone. The Jurassic formations end with Malmian limestone breccias and limestones similar to the Aptychus Limestones. The Lower Cretaceous is represented by bluish to greyish calcschists with microbreccias (Neocomian Flysch), and the Tristel beds middle Lower Cretaceous fine-grained limestone breccias. They are followed in turn by sandstones interbedded with micro- and macro- breccias of the late Lower Cretaceous (Alb). The overlying Couches Rouges with Globotruncanae are most likely of Late Cretaceous age (Campan to Santon). The uppermost section is formed by the "variegated Bündnerschiefer", consisting of sandstones, breccias and shales. Based on the occasional findings of foraminifera, their stratigraphic age ranges from Late Cretaceous to Eocene.

Metamorphism of all formations mentioned above is badly constrained. First of all, fluid inclusion investigations, from late metamorphic discordant veins (Bertle & Goetzinger 2003), clearly demonstrate an alpine HP-event in Triassic carbonates just south of Greitspitz. P_{max} was estimated with 4.25 kbar for pure aqueous fluid inclusions at a trapping temperature of ca. 200 °C. Secondly, age dating of detrital micas from the Idalpsandstone shows the influence of alpine heating, at low temperature steps in the Ar-release diagram (Bertle 1999). Deformation lamellae of calcite from Tristelschists indicate deformation at temperatures above 200 °C.

The Idalp Ophiolite

The Idalp ophiolite displays the uppermost unit of the LEW and is overlain to the north and northwest by the Austroalpine Silvretta unit, and the "Subsilvrettide zone" (see above) At its southern border,, the ophiolite body rests tectonically on Mesozoic sediments of the Fimber zone. The ophiolite body itself is subdivided into two independent units called Flimsspitze nappe (southern part) and Bürkelkopf nappe (northern part) by Daurer (1980). They are separated by a tectonic slice, consisting of diaphtoritic micaschists, gneisses, and amphibolites, known as the "Flimjoch wedge", which originated from the Silvretta unit.

The reconstructed columnar section of the Idalp ophiolite can be seen in Figure 3.3. The ophiolite sequence starts with 60-80m thick serpentinites They contain some small inclusions of rodingites (metagabbros). The serpentinites are separated by a tectonic contact from the overlying isotropic gabbros, which are intruded by rare diabase dikes. The volcanic section has a tectonic contact at its base, and starts with pillow lavas intercalated with several layers of massive diabase, and with some hyaloclastites that increase in abundance towards the upper levels. At the stratigraphic top, tuffs with radiolarian schists are deposited. The whole volcanic pile (including the sediments) has a thickness of 250 to 300 meters.

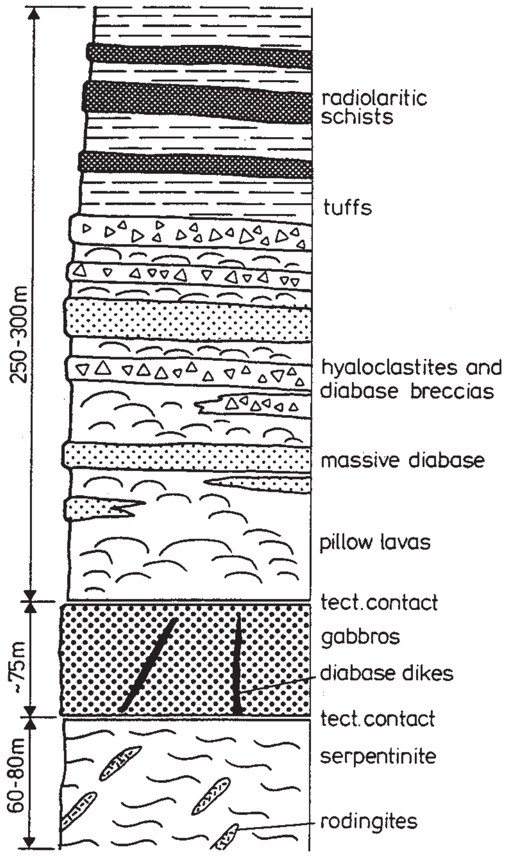

Figure 3.3 - Interpretative lithostratigraphy of the Idalp ophiolite.

The two tectonic subunits of the ophiolite complex have the same tectonic style, which consists of, firstly, a serpentinite-gabbro association with a maximum thickness of 150 m at its base; and resting on this, but tectonically separated, a large recumbent fold overturned towards the north, consisting of a small serpentinite-gabbro body in the core, surrounded by massive lava-flows and pillows. The hyaloclastites, tuffs and radiolarites form the outermost part of the fold (Figure 3.4).

The metamorphism of the ophiolites is twofold; an older HT oceanic metamorphic event can be separated from a younger HP imprint. Evidence for the former comes from the replacement of gabbroic clinopyroxenes by amphiboles (pargasite, magnesian-hornblende to actinolite) formed at relatively high temperatures. This, together with some metasomatic changes of the bulk geochemistry (mainly Na enrichment), and some local strong oxidation, argues for this hydrothermal event. Remnants of the E-W striking oceanic high temperature deformation planes in the gabbros, show black amphibole formation in their vicinity, as a common indication of H_2O infiltration (Figure 3.5). The cores of these amphiboles in the altered gabbros, still contain high Cl contents, of up to 4000 ppm. In the hyaloclastites and pillow breccias, the hydrothermal influence locally causes ~E-W striking epidote-rich veins, and high oxidation with an intense red color.

The Alpine metamorphic grade of the Idalp ophiolite sequence belongs to the low-temperature conditions at the transition between greenschist and blueschist facies, with 7-9 kbar at ~300°C. The mineral assemblages are defined by pumpellyite + chlorite + albite. The

Figure 3.4 - Geologic cross-section of the Silvretta Austroalpine and Idalp ophiolite units, between Flimspitze and Bürkelkopf, showing the two tectonic units of Flimspitze and Bürkelkopf nappes.

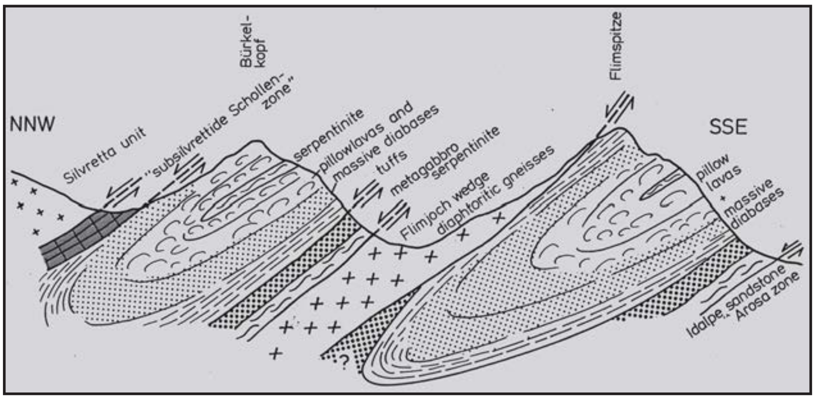

Figure 3.5 - Hydration reactions in the Idalp gabbros.

pumpellyite of the metagabbro is Mg-rich, the green pumpellyite of the diabases with a Fe^{tot} / (Fe^{tot}+Al) range between 0.11-0.15. Prograde replacements by epidote are rare. In the metabasite, a high phengitic mica, with an Si of 3.6, was locally found.

The Idalp ophiolite is typical among many ophiolitic occurrences in the Alps: it is highly dismembered and displays a very small ultramafic-mafic cumulate section; its lateral extension is a few kilometers only, with a thickness of several hundred meters. Metabasalts and metatuffs are closely comparable to N-type MORB, derived from a depleted mantle by partial equilibrium melting, with a subsequent crystal fractionation resulting in highly evolved Ti-, Zr-, and V-rich magmas. From a geochemical point of view, the Idalp ophiolite is very similar to ophiolites from the Hohe Tauern (Höck 1983, Höck and Koller 1989, Koller and Höck 1990), and to same ophiolitic rocks of the Rechnitz window at the easternmost end of the eastern Alps (Koller, 1985).

Excursion log 3rd day (Idalp Area)
Riding up to Viderjoch from Samnaun by cable-car
Part 1: walking from Viderjoch – Flimspitz northern and western ridge – Pardatschgrat back to Viderjoch
Part 2: walking from Viderjoch to Greitspitz and back to Viderjoch
Back to Samnaun by cable-car

Part 1: Trip from Viderjoch to Pardatschgrat: guided by F. Koller and V. Höck, R. Bousquet

Stop 3.1:

Pillow lavas

The basaltic unit of the ophiolite consists of low grade metamorphic equivalents, of pillow lavas, pillow breccias, hyaloclastites, and fine-grained tuffs as well as of massive basalt flows, locally with large pyroxene phenocrysts. In general, all these rocks show a very fine-grained matrix. Primary structures, such as ophitic, intersertal plagioclase and flow textures are well-preserved. All glassy areas and fragments are replaced by a dark-green chlorite mass.

The fine-grained basaltic groundmass is partly replaced by a metamorphic assemblage, containing albite, epidote, calcite, rare pumpellyite, actinolite, and lesser amounts of quartz, haematite, and sphene.

The metabasalts and metatuffs are tholeiitic in chemistry, resembling abyssal tholeiites. The K_2O contents are very low, the concentration of TiO_2 as well as the content of trace elements, such as Zr, Y, V, Cr, and Nb, are in the range of typical MOR basalts, but some may reach values more typical of a within-plate environment (ocean island basalts).

Stop 3.2:

Basaltic Dikes in Gabbros

Isotropic gabbros cross-cut by E-W-striking basalt dikes with MORB composition. Their chemical composition is relatively less evolved with respect to the pillow lavas of stop 3.1 (Figure 3-3).

Stop 3.3:

Isotropic gabbros and gabbro pegmatites

The plutonic sections consist mainly of a clinopyroxene-plagioclase gabbro, which is poor in iron oxide minerals. The grain size shows a strong variation (from 5 mm up to 10cm), in pegmatitic areas. Among the primary magmatic minerals only clinopyroxene has survived, and may be sheared and deformed or has partly reacted to form amphiboles. The former plagioclase is only a form relict, and has been replaced by a fine-grained brown mass of epidote-clinozoisite, or pumpellyite and albite. In the few ferrogabbroic dykes, form relicts after ilmenite and titanium-magnetite were also found, replaced mainly by sphene and haematite. Amphiboles deriving from the clinopyroxenes show a complex mineralogical history. They consist of an older brown magnesium-hornblende, or a green hornblende. These older phases were replaced by a greyish-green or blueish-green actinolitic amphibole and, later on, by newly-formed, weakly-colored actinolite needles. The metamorphic mineral assemblages of the gabbros are the same as those of the extrusive rocks. In gabbroic dykes inside the serpentinites, rodingitization has taken place, with a new formation of hydrogrossular or idocrase.

Stop 3.4:

Hyaloclastites and radiolarites

Hyaloclastites are heterogeneous breccias of lava fragments and devitrified glass components, sometimes with sediment participation, often red-coloured due to finely-dispersed haematite. Tuffs and tuffites are heterogeneous mixtures of minerals, lava and glass relics without volcanic textures, and with variable participation of sedimentary material. Sedimentary intercalations are rich in carbonate, muscovite, and quartz, with decreasing volcanogenic participation. Radiolarites occur mainly in the Bürkelkopf nappe, forming layers of some meters thick. They are red, extremely fine-grained, sometimes banded rocks, with questionable relics of Radiolarians.

Stop 3.5:

”Subsilvrettide zone”

Dolomites, banded and partly-folded calcareous slates of uncertain Triassic or Jurassic age. An isolated block of dolomite within the Flimspitze Nappe belongs to this zone, too.

Stop 3.6:

Silvretta crystalline rocks, including “pseudotachylites”

Ortho- and paragneisses, micaschists, amphibolites. In the area of the “Subsilvrettide Schollen”, the rocks are well-preserved, and almost not retro-metamorphosed. Immediately above the thrust plane, pseudotachylites (ultramylonites resembling fine-grained dike rocks), cut the crystalline rocks. Going westwards, retro-metamorphic transformations increase.

Retro-metamorphic two-micaschists and amphibolites tectonically separate the ophiolite nappes. Pseudotachylites in the micaschists are strong arguments for the tectonic imbrication of Silvretta Crystalline unit.

Part 2:Trip from Viderjoch to Greitspitze (2871 m), guided by R. Bertle

Stop 3.7:

Bunte Bündnerschiefer: Lens between two slices of ultramafic rocks:

Outcrop of typical breccias of “Bunte Bündnerschiefer” of Upper Cretaceous age, as indicated by age-constraining planktonic foraminifera. Components of breccia are mainly carbonates, but also minor volcanics and metamorphic rocks (micaschists).

Stop 3.8:

Bunte Bündnerschiefer – Palombini type:

The outcrop exposes typical Palombini-type Schistes lustrés of South Penninic origin: sandstones with intercalated dark phyllites, both intensely folded together. Heavy mineral investigations show chromite as an accessory mineral, which is assumed to be an index mineral for Cretaceous South Penninic sediments. The age is given by *Globigerina archaeocretacea* (Early Cretaceous; Bertle, 2002).

Stop 3.9:

Grenzstein 5 - Tristelformation:

Typical rocks of the Middle Cretaceous Tristelformation are exposed – carbonatic microbreccias, containing well-preserved index microfossils of Barremian to Aptian age: *Dictyoconus* sp., *Palorbitolina lenticularis* Blumenbach, *Salpingoporella* sp., etc. The Tristelformation will also be visited on the next day, at Piz Mundin. The source of the breccias can be located in the Tasna microcontinent (Schwizer, 1983; Oberhauser, 1983, Bertle, 2002)

Stop 3.10:

Greitspitze – Peak:

The peak of the Greitspitze consists of limestones of the “Steinsberger Lias”. It can be classified as grainstone after Dunham, however intense recrystallisation took place during alpine metamorphism. Nevertheless, index ammonites of Liassic age can be found: *Paltechioceras* sp. of *raricostatum*-Zone (Sinemurian). Small outcrops of “Posidonienschiefer” and “Idalpsandstein” can also be found. The age of the Idalpsandstein is given by *Hammotoceras insigne* of Toarcian age; the age of the underlying Posidonienschiefer outcrops is given by their position between Idalpsandstein and “Steinsberger Lias”.

DAY 4

HP/LT metamorphism within the North Penninic ocean (Lower Engadine Window; Austria-Switzerland)

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Ferro- and magnesio-carpholite: an index mineral of HP-LT metamorphism in the metasediments

The name carpholite derives from the Greek word carphos, meaning “hair of fire”, due to the yellow-colored needles of the mangano-carpholite (Werner, 1871) found in the Ardennes massif. Ferroan and magnesian carpholite form a continous solid solution from the pure-iron end-member, Fe-carpholite {$0.5 < XFe = Fe/(Fe+Mg) < 1$} to pure-magnesium end-member, Mg-carpholite {$0.5 < XMg = Mg/(Fe+Mg) < 1$}. These two minerals were discovered relatively recently: De Roever found first the Fe-carpholite in Sulawesi Island in 1951, and Goffé et al. (1973) described the Mg-carpholite in the western Alps (Vanoise massif). Since the beginning of the 1980s, these minerals have been intensively studied, and so they have become the index-mineral for the HP-LT metamorphism of the metasediments. The stability field (Figure 4.1) was experimentally determined by Vidal et al. (1992). Since then, many occurrences have been discovered in the Tethyan mountain belts all over the world: in the Western Alps (Goffé & Chopin, 1986, Goffé et Bousquet, 1997), Central Alps (Goffé & Oberhänsli, 1992), in Corsica (Daniel *et al.*, 1996), the Apennines (Theye et al. 1997,), Calabria (De Roever et al., 1967), the Betics (Goffé et al., 1989,), Rif (Bouybaouène et al., 1995), Crete and the Peloponnese (Theye et al., 1992), Turkey (Oberhänsli et al., Rimmele et al., 2003); Oman (Goffé et al., 1988), and in New Caledonia (Black et al., 1993).

These minerals occur practically in all kinds of HP-LT metasediments, which previously contained mineral association with kaolinite and chlorite or chlorite and illite, but these metasediments are always deprived of feldspar and plagioclase. We can find (Fe, Mg)-carpholite in metabauxites, pelitic schists, calcschists, or conglomerates. So it appears in three different ways:

Well-preserved, as macroscopic curved fibers up to 30 cm in length, in quartz or calcite veins. These metric-sized veins are often stretched and parallel to the main schistosity. Then (Fe, Mg)-carpholites can also occur in the rock itself as centimetric rosettes.

Partially-retrograded, but always visible to the naked eye, as small fibers in disaggregated quartz veins. (Fe, Mg)-carpholite are replaced by associations composed of sheet silicates (micas, chlorite, pyrophyllite). In this case, no relic can be found in the country rocks.

In relic, as small needles (between 0.5 µm to around 50 µm length), only recognizable with a microscope in old sheared quartz veins.In some case, all relics can disappear, and vestiges of (Fe, Mg)-carpholite can be recognized due to the fibrous and woody aspect of the quartz.

All these various kind of (Fe, Mg)-carpholite correspond to different tectono-metamorphic evolutions during subduction and exhumation processes.

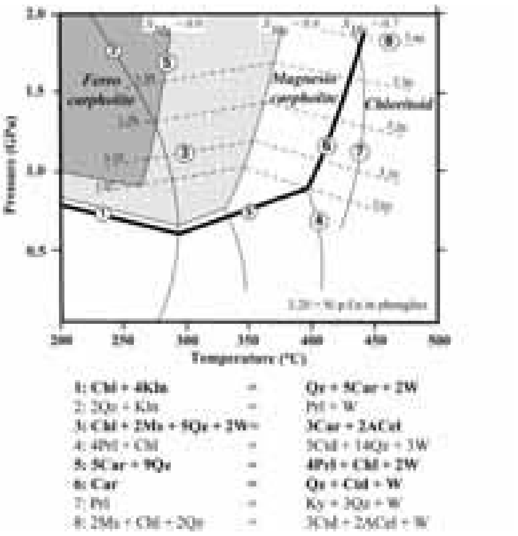


Figure 4.1 - P-T stability field of carpholites, according to Vidal et al., 1992.

(Fe, Mg)-carpholite in the Engadine window

In the north Pennine metasediments of the Engadine window, two units display distinct metamorphic histories (Bousquet et al., 1998; Bousquet et al., 2002).

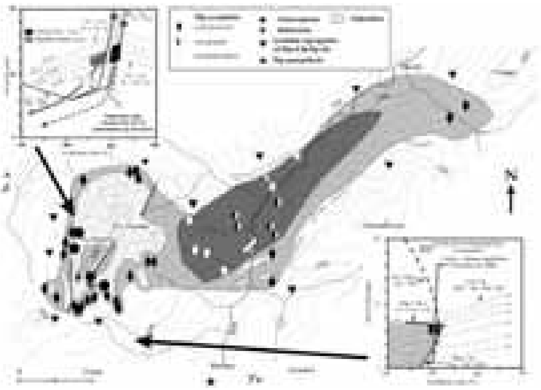


Figure 4.2 - Field occurrences of critical metamorphic minerals.

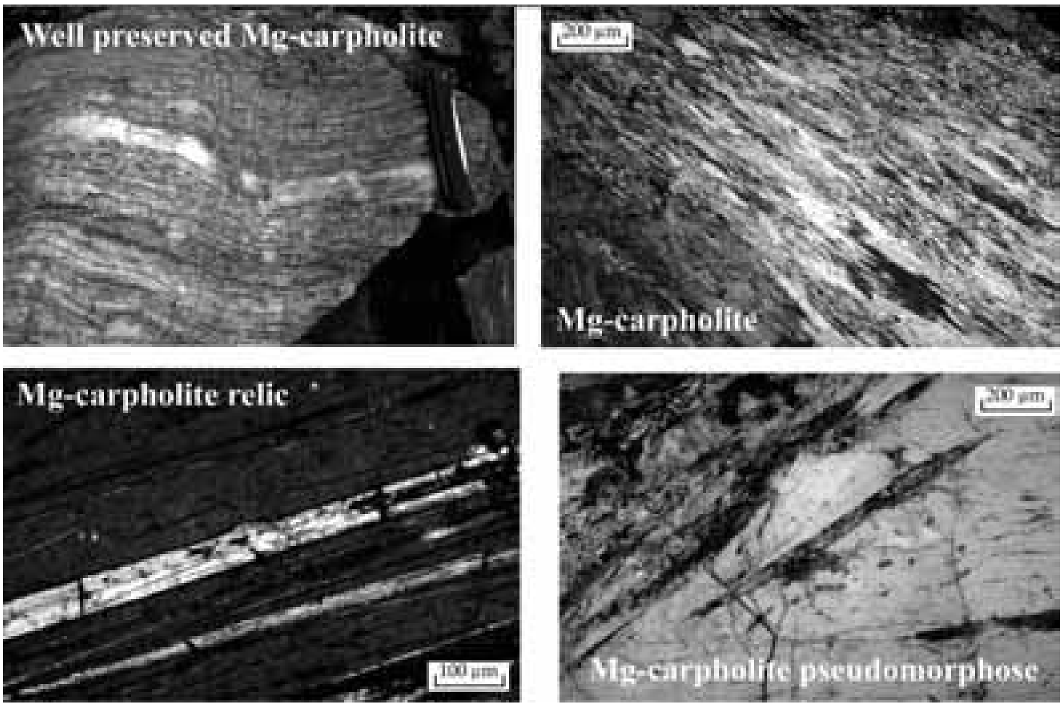


Figure 4.3 - Field and microscopic appearances of carpholite occurrences at Piz Fot (Piz Mundin).

The structurally lower unit (Mundin unit) has a clear HP-LT history, whereas the upper unit (Arina unit), does not show obvious HP-LT mineral assemblages. (Fe,Mg)-carpholite in metapelites (Figure 4.2) and glaucophane in metapillows are exclusively found in the central part of the window (i.e., the Mundin unit), forming the core of a late anticline.

In the overlying Arina unit, evidence for HP metamorphism is scarce. However, crossite and lawsonite occur in metabasites (Leimser & Purtscheller, 1981), and Mg-pumpellyite and associations with Chl - Alb – Phg, occur in metapelites of the Arina unit. In the core of the Mundin unit antiform, carpholite appears as relics (Figure 4.3). In contrast, in the upper part of the same unit, immediately below the contact with the Arina unit, carpholite is well preserved. For the Mundin unit, *P-T* estimates range between 11 and 13 kbar for a temperature around 350-375°C (Bousquet et al., 2002). The PT conditions for the Arina unit range around 6 kbar, 300°C (Figure 4.3). However, the composition of mica in this unit is quite variable. In particular, the pyrophyllite to alumino-celadonite proportions increase with increasing distance from the Mundin unit. Such a variation is consistent with pressures decreasing upwards in the Arina unit, i.e. with increasing distance from the HP (Mundin) unit. The pressure gap between both units is at least 5 kbar.

Carpholite fibers within quartz lenses and between boudins, mark a consistent northwest-southeast mineral lineation. Later stretching increments, in the same direction, reworked the carpholite fibers, which are boudinaged, and finally opened cracks filled only with quartz. This late deformation was also less ductile and less penetrative than the first event, which occurred during the HP metamorphism. Observations in the *X-Z* plane reveal chiefly top-to-the-northwest sense of shear, localized preferentially in a major shear zone, called the Mundin shear zone (Figure 4.4; Bousquet et al., 1998).

Above the Mundin shear zone, deformation in the carpholite-free zone is characterized by the same stretching direction, although strain is much less penetrative and intense. The most common structures are northwest-verging folds, whose axial planes tend to be less oblique in relation to the regional foliation of the Mundin shear zone. The folds change from open folds, far from the contact between both units, to sheath folds, with axes parallel to the stretching

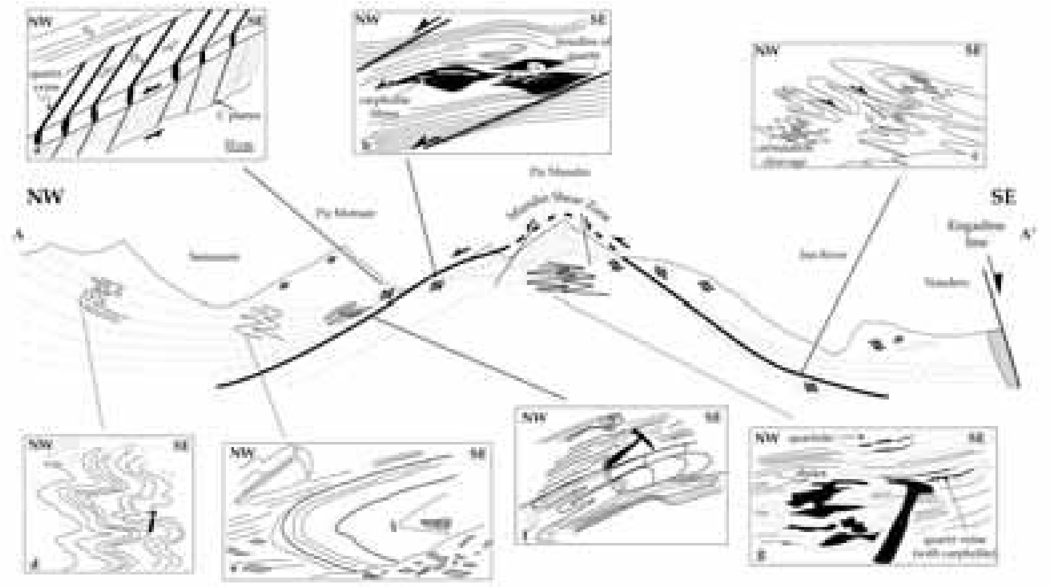


Figure 4.4 - Geological profile across the Piz Mundin area in the Engadine window Bündnerschiefer.

lineation near the contact (Figure 4.4). This change suggests that the shearing was distributed in the whole upper part of the Bündnerschiefer, though shear strain was greatest in the Mundin unit (Bousquet et al., 1998; Jolivet et al., 1998).

Field itinerary

Stop 4.1:

Costa Bella – Contact basalts-sediments.

First view of the metamorphism. Contacts between MOR-basalts and sediments (stratigraphic or in the accretionary wedge?) can be seen. Metasediments and metabasalts show the same metamorphic evolution:

Mineralogy of the metasediments in the Mundin unit

Carpholite occurs in synfolial segregations of quartz and calcite as green-white colored fibers up to 20 cm in length. This aspect is typical for carpholite in metapelites throughout the Alps (Goffé & Chopin, 1986; Goffé & Bousquet, 1997). Carpholite fibres are always elongated in the same direction, and show kinking. Two types of carpholite can be clearly distinguished: relics of carpholite and pseudomorphs, after carpholite in the core of the Mundin unit (lower part), and a fresh carpholite at the edge (upper part). Fresh carpholite forms rock-forming fibers 200-300 mm thick, or microfibers, 10 to 100 mm long, and 0.5 to 10 mm thick, trapped in quartz and calcite crystals. XMg ranges from 0.52 - 0.72. Pseudomorphs after carpholite are composed of Mg-rich chlorite and white mica, whereas relics appear as microfibres in quartz. Any sudoite, pyrophyllite, or kaolinite occur in the pseudomorphs after carpholite. The fluorine content shows a very large variation from 0.3 to 4.6 wt. % (Goffé & Oberhänsli, 1992), with a mean around 2-3 wt. %. F-rich carpholite is always well-preserved, but F-poor carpholite appears also as fresh fibres in the upper part of the Mundin unit.

White micas are fine-grained phengite and paragonite, in which there is relatively high Na-content in phengite and K-content in paragonite; both phases are finely intergrown. The mean Si^{4+} content of phengite in the lower part is higher (3.32 with 3.40 as maximum) than the mean in the upper part (3.22 with 3.34 as maximum, Si p.f.u).

Mineralogy of the metabasalts in the Mundin unit

Na-amphiboles of two types occur rarely in the mafic body of Piz Mundin (Bousquet et al., 1998): glaucophane with albite, tremolite, chlorite, and epidote, as a rock-forming assemblage in metapillows, and riebeckite in association with epidote, chlorite, stilpnomelane, and albite, (Oberhänsli, 1978) in crosscutting veins. Glaucophane is extensively retrogressed and appears as fine needles in less deformed zones or in the core of large crystals of

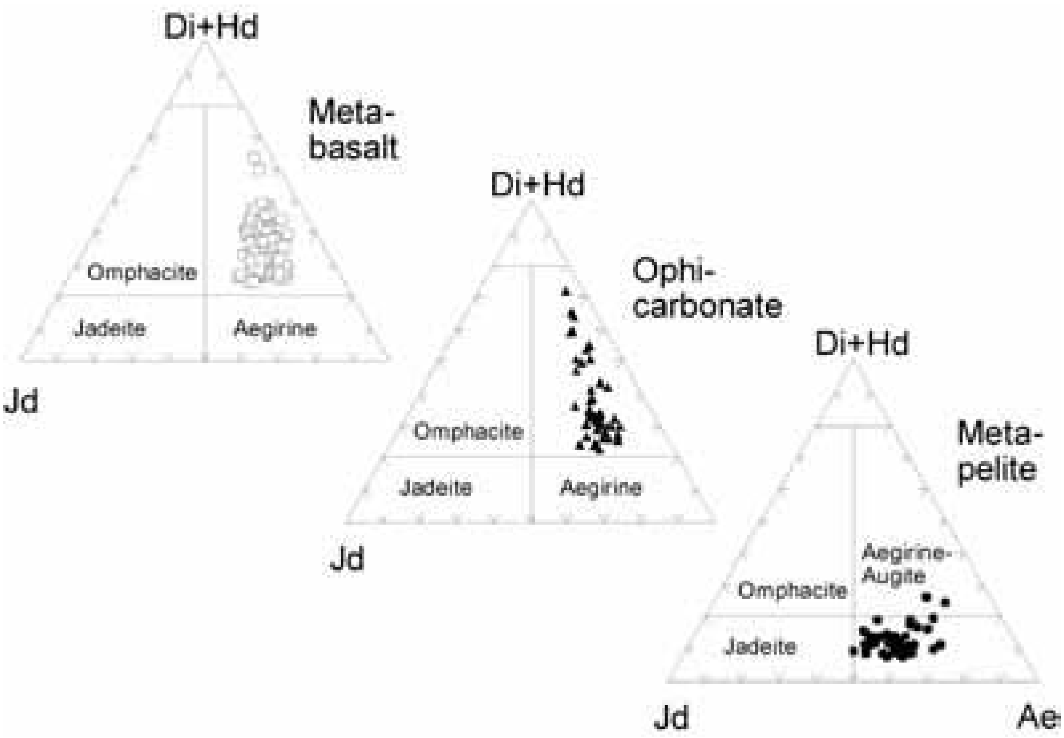


Figure 4.5 - Compositions of high-pressure-related clinopyroxenes in the Costa Bella metaophiolites of Piz Mundin.

green actinolite.

Na-pyroxene can be found in the following three types of samples, 1) in metabasites, 2) in ophicarbonates, and 3) in graphite-bearing metapelites close to the metabasites. It must be noted, that all Na-pyroxene-bearing samples underwent, prior to the pyroxene formation, alterations through oceanic metamorphism, or through interaction with oceanic fluids. From this influence a higher oxidation stage, and sometimes Na excess in the rock is common. In metabasite and ophicarbonates, all Na-pyroxenes are green aegirine-augite, with a 12-20 % Jd component in the metabasitesl and 10-20 in the ophicarbonates (Figure 4.5). In the rare pyroxene bearing metasediments, the Na-pyroxene composition is close to the join aegirine-jadeite, with a 25-45 % jadeite component (Figure 4.5). The following mineral assemblages can be described:

Metabasite: *Aegirine-augite ± Mg-riebeckite + chlorite + epidote + haematite + quartz*

Ophicarbonates: *Aegirine-augite ± Mg-riebeckite + calcite/aragonite + chlorite + clinozoisite/epidote ± stilpnomelane*

Metapelites: *Aegirine-jadeite ± Mg-riebeckite + quartz + phengite + chlorite + graphite ± haematite*

Most of the blue amphiboles of the Na-pyroxene assemblages are riebeckite to Mg-riebeckites, and seem to replace the pyroxenes.

Aragonite was found as a relict in the Na-pyroxene bearing assemblages, partly or strongly replaced by calcite.

In this stop S-C-fabrics may be observed; they indicate a to-the- northwest sense of shear, and some isoclinal folds. The stretching lineation, oriented NW-SE, is formed by the carpholite fibers. On the way to stop 2, axinite might be found, as well as large blocks of blueschists.

Stop 4.2:

Costa Bella – Pillow-basalts

Beautiful and well-preserved pillow basalts can be seen. These pillows are greatly deformed and stretched in the same direction as the carpholite fibers. In these pillow-basalts, some relics of magmatic structures can be found. Blue amphibole is present in thin sections. Geochemical data show MOR-characteristics for these basalts (Dürr et al., 1997).

Stop 4.3:

Piz Fot – Mega-needles of carpholite

Pitz Fot is the best outcrop for carpholite in the Engadine window: elongated needles of more than 50 cm are found here.

The sediments occurring here never underwent HP/LT conditions. In these sediments, the following minerals can be found:

White micas, as in the Mundin unit, are phengite and paragonite. Analyses of paragonite give results that are close to the end-member composition. There are two types of phengites: large crystals, with no preferential orientation, showing numerous aspects of alteration, are probably detrital and newly grown. In fine-grained micas in the foliation, in association with Chl and Alb, the Tschermak substitution varies from 3.05 - 3.35 (Si p.f.u), with a deficit in the interlayer site, which can be important (K^++Na^++ Ca^{2+}=0.75 to 0.95). In these phengites, the Tschermak substitution decreases with distance from the Mundin unit.

Pumpellyite was found in one sample of schists in the Arina unit as small brown-colored twinned prisms, associated with chlorite, is Mg-rich (XMg = 0.82).

Kaolinite occurs as unoriented lamellae in the youngest veins, synchronous with D2, in association with albite and phengite in one sample of the Arina zone.

Albite only occurs in the metapelites of the Arina unit, in the mineral association, or as veins. Large grains of albite contain inclusions of phengite (that can contain up to 5% Ba).

DAYS 5 - 6

The southern steep belt of the central alps

Martin Engi and Alfons Berger (University of Bern, Switzerland)

Fifth day – *A section of the Southern Steep Belt, between Alpe Gesero and Passo San Jorio (Swiss - Italian border): High-strain mélange sequence, metamorphosed in upper amphibolite facies, with abundant partial melting, cut by the Jorio-Tonale segment of the Insubric Line, delimiting the Central Alps to the Southern Alps (unaffected by Alpine metamorphism).*

The Southern Steep Belt (SSB), terminates the collisional core complex of the Central Alps against the northern margin of the Adriatic (=Apulian) plate. A segment of the Insubric Line, the Jorio-Tonale Line (Cornelius & Furlani-Cornelius, 1930), forms the steep E-W trending fault contact between the Southern Alps and the SSB (Figure 5.1). The role of the SSB has long been enigmatic. It was classically regarded as the "root zone" from which the Pennine and lower Austroalpine nappes (Argand, 1911) were supposed to have emerged. However, detailed field work (e.g. Knoblauch et al., 1939; Knup, 1958; Fumasoli, 1974; Bächlin et al., 1974; Milnes et al., 1981), failed to support such an interpretation. Knoblauch (1939) had found, on the basis of meticulous mapping in the Bellinzona-Jorio area, that he could not distinguish individual thrust sheets corresponding to the crystalline nappes further north. Instead he proposed various "zones", in order to group the extraordinary variety of rock types found in the SSB, but the tectonic significance was left open. It proved impossible, prior to the concept of plate tectonics, to account for the great variability of rock types and late-orogenic magmatism found within the SSB, and to comprehend the relation of this high-strain complex to the basement nappes which make up most of the Lepontine Alps.

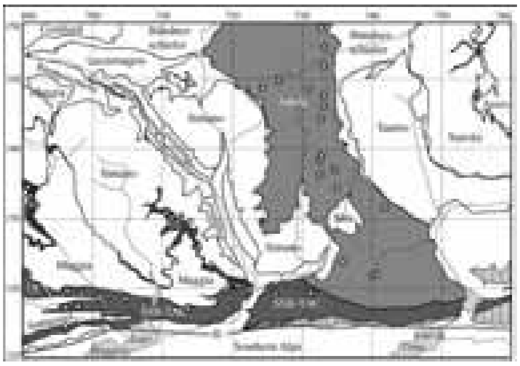


Figure 5.1 - Schematic tectonic map of the Central Alps. Units shaded in gray are mélange units with HP-fragments, considered part of the Alpine TAC (tectonic accretion channel: CL – Cima Lunga unit, Or – Orselina zone, So – Someo zone, SSB-TAC – collection of TAC-fragments making up the bulk of the Southern Steep Belt. IL: Insubric Line. Swiss coordinate network labelled in km.

This part of the field trip aims to present and discuss the evidence that lead Engi et al. (2001a) to interpret the major portion of the SSB as an exhumed Tectonic Accretion Channel. This TAC is thought to have initiated early during convergence, along the plate interface (Figure 5.2), where the tectonic mélange unit is likely to have been fed by tectonic slivers from both

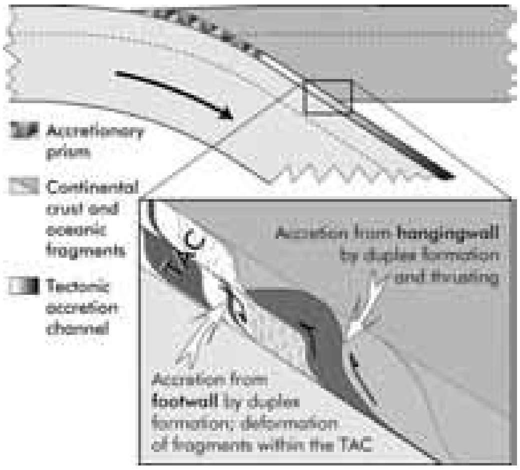


Figure 5.2 - Schematic cross-section through the convergent margin to Asthenospheric depth, showing the position of the TAC (tectonic accretion channel) at the plate interface. Inset: Cartoon of mechanisms feeding the TAC, both during subduction and collision/extrusion

plates. Continued evolution of this unit during and following the collision stage, and the particular significance of the TAC to the tectonometamorphic characteristics of the Central Alps, will be the main theme of this field trip (5th and 6th day). Special emphasis is placed on discussing petrological and geochronological data, in the context of results from numerical simulations, in order to understand the processes responsible for (a) the rapid extrusion of HP-relics from Mantle depths, (b) the high-temperature Barrovian (medium pressure) regional metamorphism in the Lepontine, (c) the origin and character of the migmatite belt linked with the TAC, and (d) possible implications on paleo-geographic reconstructions.

Base maps: Regional topography (1:100,000) on Swiss sheet "Sopraceneri"; detailed maps (1:25,000) are "Passo S. Jorio" (sheet #1314) for the 5th day, and "Bellinzona" (sheet #1313) for the 6th day. These are *essential* for geologists willing to go on the hikes on their own! An equally detailed geological map is available only for the 6th day (Bächlin et al., 1974), whereas the Jorio map sheet (Knoblauch et al., 1939), is unfortunately out of print.

Regional geologic setting

The Lepontine belt of the Central Alps reveals a type example of a collisional orogen, characterized structurally by a stack of crystalline thrust sheets (Figure 5.1) derived from the Penninic area. Some 82% of the (pre-Quaternary) units surfacing in the Lepontine have witnessed one or more pre-Alpine orogenies. Evidence of polymetamorphism is thus widespread, with relics from the Variscan (ΞHercynian), Caledonian, and even Pre-cambrian orogenies, having been recognized. The Alpine overprint is quite variable, especially in the northern Lepontine, a fact that has plagued early efforts in documenting regional metamorphic patterns (Niggli, 1974). Through the study of the metamorphic grade of post-Permian sediments, i.e. post-Hercynian protoliths, the now well-established metamorphic zonal pattern could be deciphered (Figure 5.3, 5.5). Mineral zone boundaries and isograds form a fairly regular concentric pattern, which appears to cross major nappe boundaries. This indicates that the regional metamorphic overprint, at least at its peak conditions, must have been reached *after* thrusting

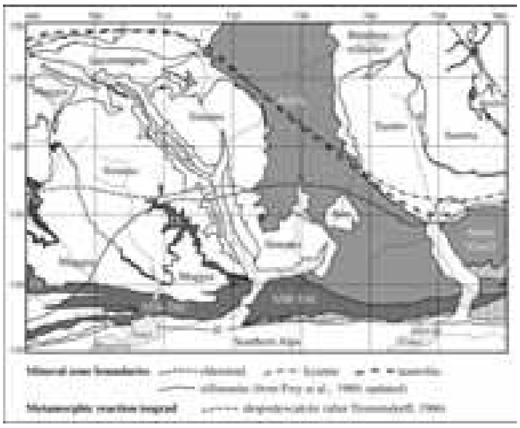


Figure 5.3 - Metamorphic mineral zones and isograds in the Central Alps (after Frey & Ferreiro Mählmann, 1999, and sources therein). Abbreviations as in Figure 5.1

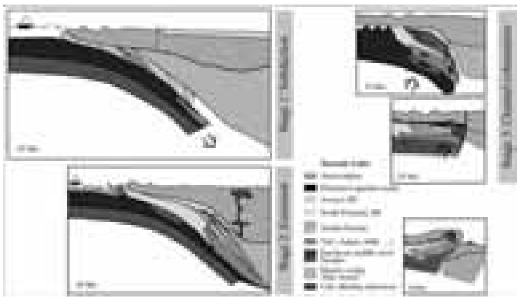
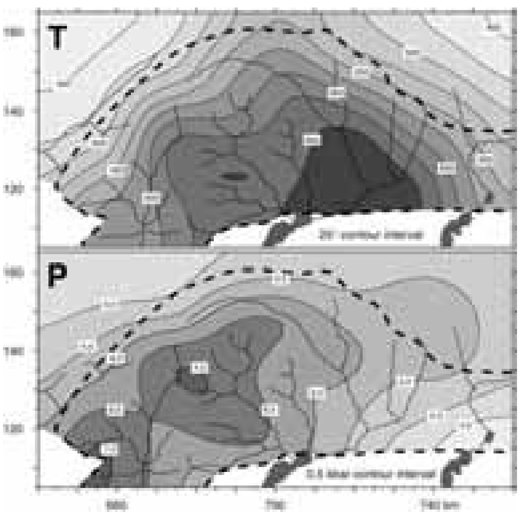


Figure 5.4 - Schematic scenario of the tectonic evolution of the Central Alps (simplified from Pfiffner et al., 2000)

had essentially ceased. The Insubric Line is younger yet, as it transects the zone of highest Barrovian metamorphism in the Central Alps, whereas the adjacent Southern Alps are but minimally affected by Alpine heating (Colombo & Tunesi, 1999).

However, the tectonometamorphic evolution of the Central Alps (Figure 5.4) is not as simple as the above scenario might suggest. Firstly, the quantitative metamorphic field gradient of the classic Barrovian (medium-pressure) belt is odd: whereas the *isotherm map* (Figure 5.5) shows a pattern similar to the metamorphic isograds, with the Insubric Line cutting through the core of the thermal dome, the *isobar map* shows two maxima in the center of the Lepontine. This delineates two structural domes: the Leventina dome (E), and the Verampio dome (W) which are separated by the synformal Maggia nappe, trending NNW. Secondly, the thermal conditions mapped in Figure 5.5 are certainly *diachronous*, as mineral formation ages (Figure 5.6) indicate a protracted metamorphic evolution. This is confirmed, thirdly, by the range of P-T paths documented from several units, as well as the occurrence of high pressure relics in the Lepontine – Alpine eclogite relics appear to be entirely restricted to remnants of the TAC (Figure 5.1); relic blueschist facies conditions are known from (post-Variscan) Valaisan units. Recent age data indicate that the HP stage is Eocene throughout. Fission track data for the Lepontine indicate cooling age patterns with little resemblance to Barrovian T_{max} and formation ages.

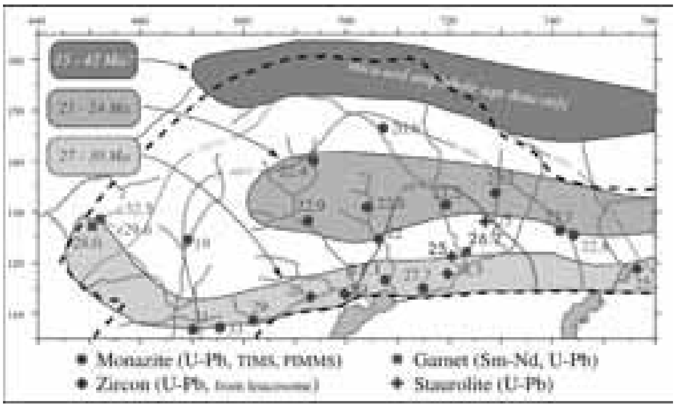
Figure 5.5 - Metamorphic isotherms and isobars (updated from Engi et al., 1995; Todd & Engi, 1997); these data are thought to reflect conditions near T_{max} and P at/near T_{max} for each sample. The pattern is substantially diachronous across the orogen.



These observations constrain models of how the Alpine nappe stack was assembled, i.e. how deeply each unit had been subducted prior to being assembled, and in what sequence the thrust sheet contacts were (re-)activated during stacking. To the best of our present knowledge, TAC fragments were the only units in the Central Alps to have reached depths >30 km in the Eocene, around 40 Ma ago, with P_{max} >28-30 kbar. In the SSB, the calcalkaline magmatism (e.g. Jorio tonalite), migmatite formation, and thermal overprint in upper amphibolite facies overprint, have been dated at 32-29 Ma, with pressures at the time of T_{max} near 5.5-6 kbar.

These constraints, combined with a wealth of

Figure 5.6 - Three age belts in Lepontine: Map of select age data interpreted as mineral formation ages formed during Alpine Barrovian overprint (Köppel & Grünenfelder, 1975; 1978; Köppel et al., 1981; Vance & O'Nions, 1992; Schärer et al., 1996; Gebauer, 1999; Engi et al., 2001b).



Three age belts in Lepontine: Map of select age data, interpreted as mineral formation ages formed during Alpine Barrovian overprint (Köppel & Grünenfelder, 1975, 1978; Köppel et al., 1981; Vance & O'Nions, 1992; Schärer et al., 1996; Gebauer, 1999; Engi et al., 2001b)

Three age belts in Lepontine: Map of select age data interpreted as mineral formation ages formed during Alpine Barrovian overprint (Köppel & Grünenfelder, 1975; 1978; Köppel et al., 1981; Vance & O'Nions, 1992; Schärer et al., 1996; Gebauer, 1999; Engi et al., 2001b).

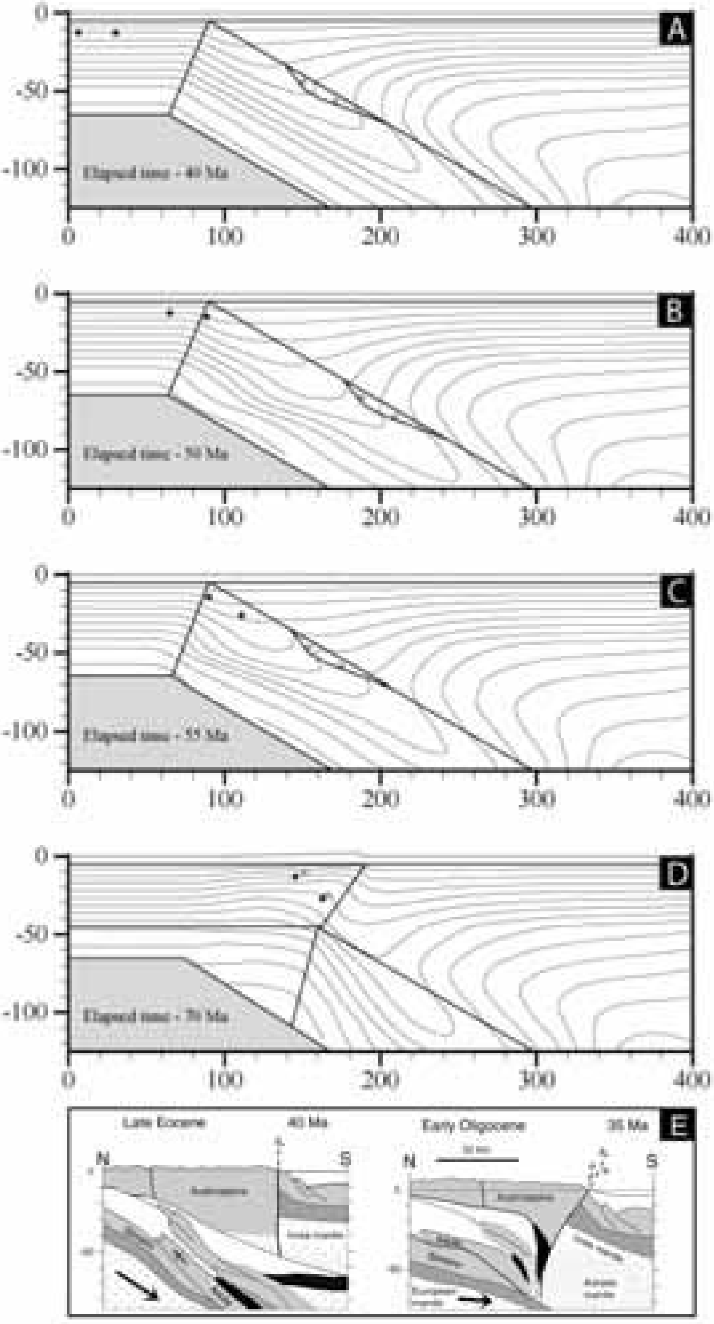


Figure 5 - Results of numerical modelling: Computed time slices through the model orogen. Note location of tracking points that move with the deforming grid. A: Late subduction stage, with the mobile tectonic fragment (scaled to the current dimension of the Adula thrust sheet), descending into the subduction channel at the same velocity ($v(z) = 0.8$ cm yr^{-1}) as the subducting plate; B: Maximum pressure stage for the tectonic fragment ($v(z) = 0$ cm yr^{-1}), but with subduction continuing ($v(z) = 0.5$ cm yr^{-1}); C: Extrusion stage of fragment ($v(z) = -0.8$ cm yr^{-1}), depicted at a level just prior to its juxtaposition with an underlying unit (mimicking the Simano nappe) that is still subducting at $v(z) = 0.5$ cm yr^{-1}; note shape of isotherms at base of TAC-fragmen,t due to the combined effects of advection and shear heating; D: Final exhumation stage of entire nappe stack, kinematically described by several channels, mimicking uplift and retroshear displayed by the Insubric Line (labelled IL in E), with a high erosion rate (approx. 0.25 cm yr^{-1}) specified to keep the evolving topography below 4 km in depth; E: Tectonic model sections (slightly simplified from Pfiffner et al., 2000) for two stages of the orogenic evolution of the Central Alps. The Late Eocene situation corresponds approximately to the model stage shown in C, whereas the Early Oligocene situation depicts the kinematics just prior to the stage shown in D.

other geophysical, tectonic, petrological, and geochronological data, have been integrated to construct thermal models of collisional orogeny (Roselle et al., 2002), on the basis of the geometry, large-field kinematics, and actual material properties for the Central Alps. Results of such simulations (Figure 5.7, 5.8), provide a basis by which to interpret the dynamics of the thermal evolution, and to address the effects of individual factors such as partial melting.

Field itinerary

1. Hike to Alpe d'Albion

Start: Swiss coord. 729.9/115.9/1775 m

We start our hike towards the north, along the road from Gesero to Cadinello; stops are not numbered, since observation may be continuous along the path. A subvertical series of massive gneiss slabs, trending E-W, form the steep 400 m flank to the crest north of Corno di Gesero. This series is

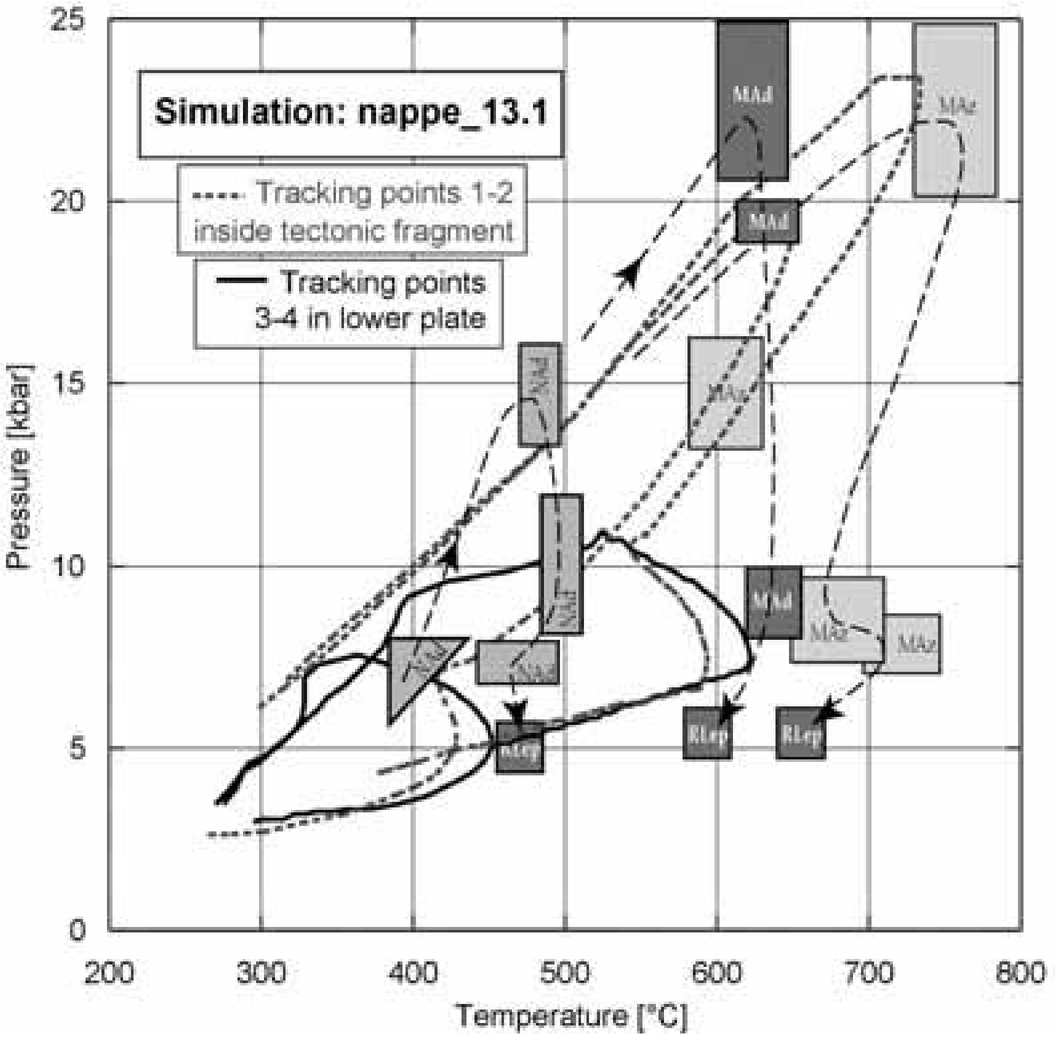


Figure 5.8 - PTt-paths in the Lepontine. Comparison for groups of samples documented along a N-S profile (Figure 5.1b), with numerical simulations for corresponding locations (Engi et al., 2001a; Roselle et al., 2002). The latter are shown as asterisks (subducted plate), and open circles (TAC fragment) in Figure 5.7 (A-D). Thermobarometric data and P-T paths for samples from northern Adula (NAd: Heinrich, 1983; Löw, 1987), Middle Adula (MAd: Partzsch & Meyre, 1995; Meyre et al., 1997; Nagel, 2000), Mergoscia-Arbedo zone (MAz: Tóth et al., 2000; Brouwer & Engi, 2004), regional Lepontine conditions (RLep: Todd & Engi, 1997).

part of the Bellinzona-Dascio zone, a sequence of TAC that is quite uniform in structure: subparallel bands of leucocratic alkalifeldspar-rich to mesocratic biotite-plagioclase gneisses alternate with pyroxene-amphibolite layers (commonly only cm to dm thick), with layers of pelitic schist and lenses of diopside marble, calc-silicate and ultramafic rocks. Considering the high metamorphic grade (sillimanite-Kspar zone), most lithotypes are surprisingly fine-grained. This is attributed to continued recrystallization during strong transpressional deformation. This gneiss package shows many of the regionally typical features, including mylonitic banding, isoclinal folds with both steep and flat E-W axes, rootless hinges, and a few microlithons resisting the strong flattening strain. Crosscutting and conformable pegmatites occur (dm- to m-thick), the latter commonly show boudinage or pinch-and-swell structures.

On clear days, Alpe di Cadinello offers a splendid view towards the west: Between densely forested knobs of the SSB and the Monte Rosa massif in the distance, the Insubric Line first runs E-W to the Magadino delta, then bends to the SW, following the shoreline north of Lago Maggiore. To the south, pre-Alpine basement units – notably the Ceneri gneiss of the Southern Alps – emerge, whereas to the north, massive gneiss slabs outline the Verzasca antiform, which bends the flat-lying Pennine nappe stack of the central Lepontine into a subvertical position. Thus the highest unit of that stack, the Maggia nappe, resting on TAC-remnants and the Simano nappe, reaches the lowlands just north of the Magadino plain.

From Cadinello we begin our hike (trail –> SE) up towards Cima da Cügn. Excellent exposures along the trail display the variability of rock types in the mélange sequence, showing sillimanite-Kspar grade metamorphism, with evidence of partial melting, and fabrics due to strong high T (dextral) transpressive deformation. Along the way to Alpe Albion, vistas to the north and east continue our panorama geology: low down in the broad Mesolcina valley, the Simano nappe is topped by the main mass of the Adula thrust sheet, composed largely of TAC material. It forms most of the middleground as well as the main peaks visible to the north (Pizzo di Groven, Adula) and west (Cima di Paina). Looking north, an axial dip ~20° E is evident within the Adula unit; this post-nappe folding (D_3, D_4), affected the entire nappe stack, and formed the Leventina dome.

At Alpe Albion, the buff colors of several ultramafic lenses enclosed in the gneiss package stand out (note the flora change). The largest mass (~120*50 m), is *harzburgitic,* and its main assemblage is spinel-chlorite-enstatite-olivine. A polyphase evolution can be inferred: (1) early (mantle-origin?) structures (dunite bands, with seams or aggregates of chromite, opx layers, or veins); (2) intrusion of gabbroic and sparse plagiogranitic dykes, cpx veining; (3) hydration to serpentinite and associated metasomatism (rodingite formation); (4) prograde metamorphic dehydration, isoclinal folding, metasomatism (blackwall formation), and late hydrothermal veining (antigorite+talc stable). Spectacularly zoned *metarodingite* veins and pods are abundant, as are hydrothermal veins with olivine, talc ± anthophyllite, and pennine. In the Central Alps, metarodingite veins are not rare in ultramafic rocks (Trommsdorff & Evans, 1980), and their observation is critical, for they indicate a metasomatic origin, linked to serpentinization of peridotite. Metarodingite in high-grade (spinel or garnet) peridotite thus demands a shallow hydration prior to subduction. SHRIMP dating of zircon from plagiogranite veins, indicates a Jurassic magmatic age (146 Ma, Stucky, 2001) and has been interpreted to show an origin from the Piemonte cean for the Alpe Albion ophiolite rocks.

Neither garnet peridotite nor eclogite have been reported from the Bellinzona-Dascio zone, but these do occur (Fumasoli, 1974) in other TAC zones adjacent to the north (e.g. Mergoscia-Arbedo zone; cf. 6th day of excursion), and in southern parts of the Adula thrust sheet to the east (Monte Duria).

2. Hike to Passo S. Jorio

Start: Swiss coord. 729.9/115.9/1775 m

From Alpe Albion, we take the steep trail up to the crest just north of Corno di Gesero, follow the exposed ridge to Cima da Cügn, and then descend to Passo San Jorio; stops are not numbered, since observation may be continuous along the path. The heterogeneous Bellinzona-Dascio zone is in steep contact with the Jorio tonalite body. The fabric in this Oligocene intrusive is rarely magmatic, much more typically gneissic and banded the mineral quartz is banded (at the microscope of course) oligoclase / andesine, dark green hornblende, and biotite dominate, with minor magmatic epidote (±allanitic core), titanite, and zircon. Hornblende barometry indicates pressures of ~8.5 kbar (Schmidt, 1989), some 2.5-3 kbar higher than documented for the regional metamorphic overprint (Todd & Engi, 1997), which reached its peak temperatures in the SSB ~28±1.5 Ma ago (Engi et al., 1995). Hence, the Jorio tonalite entered the TAC at a time when the southern Lepontine belt was undergoing prograde metamorphism while decompressing. It is likely that migmatite formation in the Arbedo and Bellinzona zones also peaked in that interval, although a few aplites and tonalites crosscut the tonalite. Syn- and postmagmatic deformation is evident in the tonalite along the path up to Cima da Cügn, as is some hydrothermal veining and greenschist facies overprint.

As in the adjacent gneisses, numerous aplite, pegmatite and granite dikes cross the Jorio tonalite. Mylonites and other high-T strain effects are common, but low-T cataclastic effects occur as well. The southernmost band (Melirolo augengneiss: dark and pervasively foliated, with porphyroclasts of andesine), is in steep contact with the greenschist facies Tonale series, which comprises micaschist, retrogressed albie-epidote amphibolites, and very minor carbonates.

The surface expression of the major tectonic contact with the Southern Alps is strongest at the margin between the Tonale series, and the virtually non-metamorphic Triassic carbonates, hence this is where the classic Jorio-Tonale line has been mapped. However, the Apulian plate margin is strongly affected by cataclastic deformation, with a complex fault pattern, cutting up both the Hercynian basement and its sedimentary cover, producing a chaotic series in a belt of 1-2 km width (Reinhard, 1939). The Triassic (Anisian-Norian) is poorly exposed near Passo San Jorio; lower parts of Val Morobbia offer better exposures, also of the deformation associated with the late-Alpine exhumation of the Central Alps along the Jorio-Tonale line.

Return from San Jorio to Capanna Gesero for dinner and rest. Overall, the intensity of deformation diminishes, and the strain becomes more localized as we move away from the Insubric Line. A system of Riedel shear bands is oriented some 20-30° to the pervasive banding and foliation in the tonalite. Hydrothermal alteration under greenschist facies conditions is closely linked to these discrete deformation zones, in which epidote, chlorite, albite, sericite, and minor carbonate occur.

DAY 6

Emplacement of Eocene high-pressure rocks (eclogite, garnet, peridotite), and calc-silicate marbles in the Southern Steep Belt; decompression history and Oligocene Barrovian overprint, formation of orogenic migmatites during transpression.

By minibus from Alpe Gesero via Val d'Arbedo to Castione, Gorduno and Alpe Arami, then return to Arbedo. Mid-afternoon transfer to Breuil-Cervinia (Italy) by bus.

Problems linked to the formation, characteristics, and role of the TAC (Tectonic Accretion Channel), as introduced on the 5th day, remain a focal point of today's program.

Regional geologic setting

The emplacement of *HP fragments* into collisional orogens is not well understood, despite the significance commonly attributed to the occurrence of eclogites. In the Central Alps it has long been clear that this orogen has not, as a whole, undergone eclogite facies metamorphism. HP relics appear to be restricted to localities in tectonic mélange units, such as the Adula thrust sheet (e.g. Jenny et al., 1923; Heinrich, 1986; Trommsdorff, 1990; Meyre & Frey, 1998; Meyre et al., 1999), the Cima Lunga unit (e.g. Evans & Trommsdorff, 1978; Pfiffner & Trommsdorff, 1998), certain zones in the SSB (Southern Steep Belt), such as the Mergoscia-Arbedo zone, and equivalent zones further west, such as the Someo zone (Figure 5.1). Taken as a whole, the TAC fragments form a spatially coherent belt at the present erosion level of the Central Alps. However, this belt is imbricated internally, with an enormously variable spectrum of lithotypes. Metasedimentary, ophiolitic as well as continental basement rocks occur, but supracrustal rocks (orthogneiss, garnet-micaschist) are volumetrically dominant. Individual TAC zones, consisting of particular associations of rock

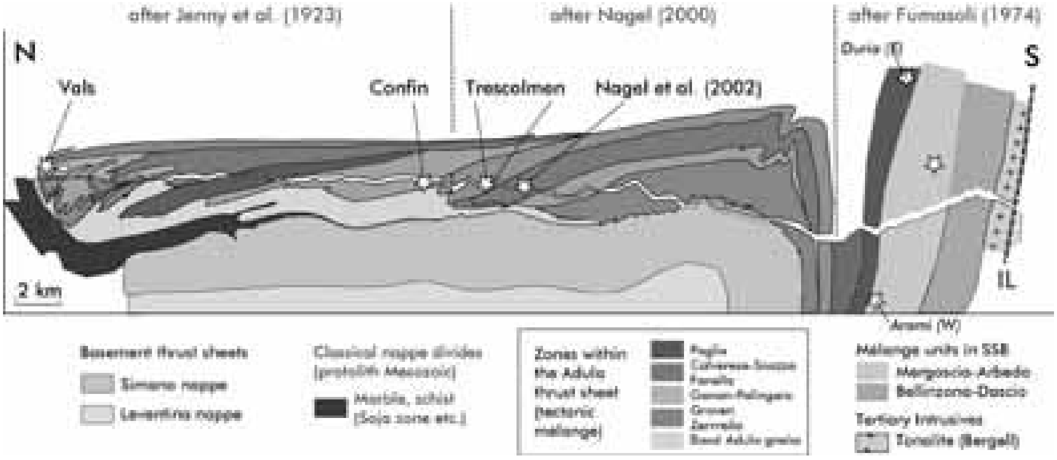


Figure 6.1 - Cross-section through the Adula thrust sheet and TAC-zones in the SSB, showing imbricate structure. Asterisks denote principal locations of HP relics (mostly eclogite).

types, have classically been mapped (as reviewed by Trommsdorff, 1990), and such zones may form imbricated slices, as in the Adula nappe (Figure 6.1). HP relics within and between such slices commonly occur as stringers of lenses or boudins, enveloped by gneissic and schistose members. Since it is the sum total of these that are viewed here as remnants of the Alpine TAC, and because the Barrovian overprint of the entire Lepontine has lead to the substantial reequilibration of HP rocks under medium-pressure conditions, it is not always easy to delimit TAC units from neighbouring tectonic units, i.e. the crystalline basement nappes.

Most prominent among the HP occurrences in the Central Alps is *Alpe Arami* (e.g. Grubenmann, 1908; O'Hara & Mercy, 1963; Moeckel, 1969; Evans & Trommsdorff, 1978; Ernst, 1977, 1978, 1981), a garnet peridotite body with a partial eclogite rim, located within the SSB. There has been a heated debate over the significance of the mineralogical remnants discovered by Dobrzhinetskaya et al. (1996), the validity of various barometers (estimates from ~80 to >300 km having been forwarded for the depth of equilibration), and the speed of exhumation (e.g. Green et al., 1997; Hacker et al., 1997; Brenker & Brey, 1997; Bozhilov et al., 1999; Nimis et al., 2000; Trommsdorff et al., 2000; Risold et al., 2001; Paquin & Altherr, 2001; Risold et al., 2003; Olker et al., 2003). The overall significance to the evolution of the TAC is not yet clear, but a two-stage process is conceivable, by which the Alpe Arami body was first emplaced from the (Asthenospheric) mantle into a deep portion of the TAC, and that extrusion along the suture set in after that. Slab-breakoff (von Blanckenburg & Davies, 1995) has been proposed as a mechanism that may have triggered such a scenario (Olker et al., 2003).

The interpretation of the HP localities known in the Lepontine has long been hampered by the uncertainty regarding their age. Until recently, evidence of HP metamorphism between ~43 and 37 Ma has been restricted to Alpe Arami and Cima di Gagnone (Gebauer, 1996; Becker, 1993), but a systematic Lu-Hf study, undertaken to date eclogite remnants from several other TAC localities, confirms Eocene HP conditions (Brouwer et al., 2003).

The widespread occurrence of migmatites, including the classic "Injektionsgneiss", within the SSB – in a belt shaped by strong transpressional deformation – poses several important questions: What is the dominant mechanism leading to partial melting (e.g. dehydration or fluid-assisted melting)? What mechanical and thermal effects are evident? What spatial-temporal relation is there to the regional Barrovian metamorphism in the Lepontine? These shall be addressed in the first part of today's field trip.

Base maps: See 5th day. Guidebook for Alpe Arami: Pfiffner & Trommsdorff (1998).

Field itinerary

1. Roadside outcrops in Valle d'Arbedo

Start at Swiss coord. 729.9/115.9/1775 m

Descending from Capanna Gesero towards the town of Arbedo (NE of Bellinzona), the private road offers sections through two zones of the SSB, both interpreted as TAC remnants, i.e. the Bellinzona-Dascio zone, and the Mergoscia-Arbedo zone. Stops at good outcrops in both zones to study orogenic migmatite (not numbered).

Leucosomes typically make up 20-30% in metaclastic and metagranitoid rocks, and much smaller fractions of quartz-feldspar veining occur in amphibolitic gneiss and biotite-plagioclase gneiss of basic-to-intermediate composition. Leucosomes range from concordant and folded together with their host rocks, to slightly discordant and either massively or weakly foliated, to completely undeformed types which may be weakly discordant or crosscutting the steep, regional E-W banding and foliation. Locally-generated veinlets predominate, but minor coalescence phenomena are common, as are quartz-feldspar veinlets a few cm across, and dikes up to 2-3 m in width. The geometry and abundance of leucosomes, their paucity in aluminous phases (chiefly sillimanite), and microstructural observations, all indicate that dehydration melting accounts for but a small fraction of the leucosomes. Partial melting must have been triggered to a major extent by fluid-assisted melting. The integrated flux of hydrous fluid required to explain the observed leucosome volume fraction is estimated as 25±10 m^3/m^2. Feedback mechanisms of enhanced fluid migration, transpressional deformation, partial melting, and melt separation are likely to have been important during protracted tectonic activity at mid-crustal conditions. Examples of repeated fluid access, formation of local melts, and variable deformation of earlier leucosomes (Figure 6.2), are abundant in several lithotypes. For example, quartz-rich tonalitic mesosomes are commonly crosscut by hornblende-bearing granitic dikelets, which required external fluid to drive the reaction

bio + plag$_1$ (An$_{\sim 35}$) + fluid –> hbl + Kspar + plag$_2$

Figure 6.2 - Migmatite outcrop in central Val d'Arbedo: Multiple formation of granitic partial melt, veining, and variable deformation of leuco-, mesosome, and restite stress the role of feedback mechanisms between fluid migration, partial melting, and deformation during mid-crustal extrusion of TAC units in the SSB.

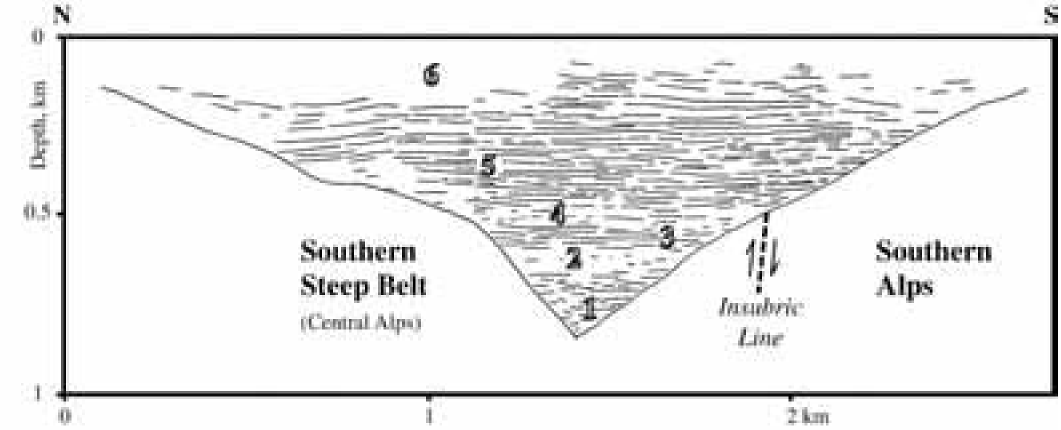


Figure 6.3 - Incision and backfilling in the central Magadino plain. Results of NRP 20 (Pfiffner et al., 1997). Sediment types: 1 Fluviatile deposits; 2 Coarse fluviatile sediments; 3 Fine grained lacustrine deposits; 4 Coarse fluviatile sediments; 5 Lacustrine sediments (Lago Maggiore); 6 Recent alluvial deposits.

Incision and backfilling in the central Magadino plain. Results of NRP 20 (Pfiffner et al., 1997). Sediment types: 1 Fluviatile deposits; 2 Coarse fluviatile sediments; 3 Fine grained lacustrine deposits; 4 Coarse fluviatile sediments; 5 Lacustrine sediments (Lago Maggiore);6Rec entalluvial

(An$_{\sim 7}$)

Thermobarometry on restites and *in situ* leucosomes indicates 9-5 kbar for migmatites in the SSB, i.e. a depth interval of 28-16 km for partial melting. As monazite age data from restites consistently yield ~29 Ma, and uplift in the southern Lepontine is known to have been particularly rapid in the Oligocene (Hurford, 1986), partial melting appears to be linked and indeed restricted to that period of active retro-thrusting (Pfiffner et al., 2000) and channel exhumation.

2. Castione quarry

Swiss coord. 723.60/121.41/240m

After traversing the floor of the overdeepened glacial valley (Figure 6.3) at the eastern end of the Magadino plain, we visit a series of quarries some 3 km to the north of Bellinzona, the proud capital of the canton (=Swiss province) of Ticino.

At Castione, a metacarbonate sequence is in subvertical position; classical maps position these metasediments between gneisses of the Simano nappe at their footwall (surfacing to the N), and the Adula unit in the hangingwall (to the S). Whereas the Simano nappe is a classic Pennine thrust sheet, the Adula unit is not, as it represents an internally imbricated stack of tectonic slivers (Fig 6.1) attributed to the Alpine TAC.

Three stops inside the quarry are planned (*and will be undertaken if we have time*):

- Stop A: Start at the north end of the Ambrosini quarries: A 150 m wide sequence of carbonaceous metaclastics is mined for road gravel in this quarry. The rock type here (named "Castione nero" for its dark color), is likely to be a highly metamorphic equivalent of *Bündnerschiefer* (a heterogeneous sequence of largely Jurassic sediments, predominant in variably clastic and carbonate contents). Thick sequences of Bündnerschiefer, comprising several units, form part of the Alpine accretionary prism in northern parts of the Central Alps; thin trails of these metasediments (and/or their Permotriassic base), can be followed over some 15-25 km southwards from the Pennine front, marking the tectonic contacts between flat-lying crystalline nappes. In some cases, such *nappe divides* show a fairly intact internal stratigraphy; indeed, in the northern part of the Lepontine the basal units are locally in stratigraphic contact with their pre-Alpine substrate. Further south, however, trails of metasediments cannot be linked with certainty to larger parts of the accretionary prism. This is the case for the Castione metasediments, for which no continuous connection to classic nappe divides exists. Nonetheless, regional correlation had lead earlier investigators to conclude that the "root zone of the Adula nappe" may be located between the two carbonate units found at Castione (Codoni, 1981; Bächlin et al., 1974). However, such correlations are hampered by discontinuous outcrops and strong polyphase deformation. Large isoclinal folds are visible, e.g. in amphibolite-marble intercalations, at the margin of the quarry.

Apart from its tectonic interest, Castione offers particularly rich *mineral assemblages*, notably in metapelitic and metamarly rocks. All three alumosilicates occur together in segregations with quartz. Textural evidence indicates the sequential overgrowth of commonly kinked blue kyanite by pink andalusite, with partial or complete replacement of both of these by greenish-grey sillimanite (fibrolite). Whereas andalusite occurs only in quartz-rich segregations, kyanite+sillimanite occur in the pelitic matrix as well, with fibrolite mats commonly growing at the direct margin of corroded kyanite laths. In dark marly host rocks garnet+diopside prevail next to calcite+quartz; scapolite is frequent, and large prisms occur in quartz-rich segregations in the "Castione nero", but without alumosilicates. Whereas the above segregations are aligned in the metamorphic foliation, a discordant variety (containing tourmaline, biotite books, muscovite, and very calcic plagioclase), can be found in large blocks at the south end of this quarry.

- Stop B: ~150 m to SE, at the N end of the next quarry, discordant pegmatites cut the calcsilicate rocks. The best quality "Castione nero" is mined here: It is of marly composition, more homogeneous, and coarser-grained than in the northern quarry. This variety makes an attractive building stone for interior use – its pyrite contents makes it unfit for outside applications.

- Stop C: ~150 m to SE, the southernmost quarry hosts the "Castione bianco", a white marble with darker bands rich in phlogopite. These bands commonly show isoclinal folding. Titanite, scapolite, muscovite, and quartz occur as accessories, locally concentrated.

The provenence of this last siliceous marble unit is controversial. If the "Castione nero" is indeed derived from Bündnerschiefer, the close association with the calcitic "Castione bianco" may suggest that these marbles are of Triassic origin. However, in the Central Alps, Triassic carbonate sequences are predominantly dolomitic, so one needs to explain what kind of metasomatism caused such Mg-loss in the "Castione bianco". Alternatively, spatial proximity does not necessarily imply a close stratigraphic or paleogeographic relation. For example, the spatial associations of different metasediments in TAC units of the Adula thrust is probably due to the tectonic juxtaposition of fragments. It does not seem possible to estimate the amount of total strain within and between the different bodies at Castione, but field relations in high-grade metamorphic terrains certainly indicate substantial tectonic mobility of carbonate-rich units. It thus seems possible that different marble and calcsilicate types found at Castione have been tectonically assembled in the TAC, and may not represent paleogeographic relatives.

The main thermal overprint in the southern Lepontine has been dated using a calcsilicate sample taken at Castione (Vance & O'Nions, 1992); these authors interpreted the Sm-Nd age of 26.7±1.7 Ma, measured in garnet, to be a growth age. This result is in conflict with earlier data by Jäger and coworkers (see Hunziker et al., 1993), but it agrees well with the U-Pb ages for monazite available in the southern Lepontine (Köppel & Grünenfelder, 1975, 1978; Köppel et al., 1981; Engi et al., 2002), and the U-Pb age of staurolite (Nagel, 2000). Also, P-T conditions estimated for that sample 600 ± 40 °C, and 8.6 ± 1.5 kbar, given by Vance & O'Nions (1992) for their Castione sample, are in agreement with the regional pattern (Engi et al., 1995; Todd & Engi, 1997). This indicates that the Castione section was equilibrated during the regional Barrovian metamorphic overprint, and that the climax in temperature was reached in the Miocene, following rapid exhumation (during the Oligocene).

End up at Swiss coord. 723.97/120.95/250m

3. Roadside outcrop above Gorduno

Swiss coord. 722.7/119.9/390m

A lens (ca. 120*30 m) of eclogitic garnet amphibolite surfaces in the open forest, just above the town of Gorduno, along the road to Bedretto and Alpe Arami. Engulfed by highly deformed leuco- to mesocratic quartz-two feldspar gneisses, this mafic lens shows partial hydration of eclogite, as it is commonly seen in the Mergoscia-Arbedo zone of the TAC. The formation of mm- to cm-size compositional domains reflect local equilibration volumes and retain mineralogical featuresyielding valuable clues the conditions of decompression and late heating associated with emplacement (Tóth et al., 2000).

In the main part of the body, very dark amphibolite preserves a weak foliation which lies almost perpendicular to the pervasive regional E-W fabric, that dominates the all-enveloping gneiss types. This latter foliation is not visible inside the lens, where the amphibolite retains many characteristics of its early high P-T evolution. Garnetiferous varieties prevail, except near the margins of the lens, and in bands that show evidence of higher plastic strain. The core region of the metabasite lens displays a dominant, symplectitic type of retrograded eclogite rich in garnet, whereas a continuous change from meta-eclogite to garnet amphibolite is recognized near and towards the rim of the body, within some 5-10 m from the contact. The rim of the body is totally devoid of garnet. Contacts with the encasing gneisses are poorly exposed; where visible, they do not appear tectonically disturbed.

The main part of the meta-eclogite consists of a fine to medium-grained symplectite matrix, with randomly distributed garnet porphyroblasts (with rutile±ilmenite), rimmed by a corona rich in plagioclase (An_{40-60}), and pale green hornblende. Omphacite relics are very rare, and low-Na salite is common. Some domains contain Al-rich phases (corundum, kyanite, hercynite, or staurolite), and pseudomorphs after lawsonite have been identified (Brouwer & Engi, 2004). Assemblages from this and adjacent mafic lenses indicate an evolution (Tóth et al., 2000; Brouwer, 2000; Grandjean, 2001) from HP-conditions, that differs from one locality to the next, within the Mergoscia-Arbedo zone of the TAC, but their final exhumation paths (Figure 6.4) for P < 7 kbar, are similar. This indicates that these bodies may have followed different HP histories, but became part of a coherent unit following extrusion to mid-crustal levels.

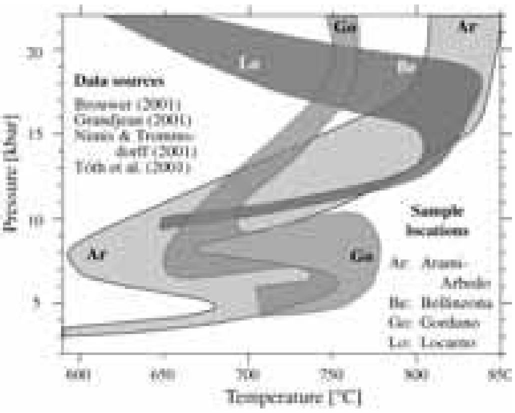


Figure 6.4 - P-T paths of ultramafic and mafic HP relics found in the SSB. Note the very different temperatures near P_{max} and in a first stage of decompression, converging to rather similar paths at mid-crustal levels. Although the low-T parts are poorly constrained, such a pattern is consistent with individual fragments having coalesced into a coherent(?) TAC only during extrusion. Data and P-T paths from (Brouwer, 2000; Nimis et al., 2000; Tóth et al., 2000; Engi et al., 2001a; Paquin & Altherr, 2001); conflicting thermobarometric results for Alpe Arami are under debate (see text).

4. Alpe Arami

The starting point of an easy 30 minutes hike to this classic location, known for its beautiful Mantle rocks, is the hamlet of Bedretto (Swiss coord. 720.15/120.8/1283m). The gravel road climbs gently to the S, then W and NW along outcrops of veined gneisses, fibrolite-garnet-biotite-Kspar schists (with cordierite in local biotite restite), and pyroxene amphibolite, with granitic dikes intruding the steeply S-dipping sequence.

At Alpe Arami, outcrops of garnet peridotite prevail, eclogite occurs principally at the poorly exposed margin of the lens (Figure 6.5). The HP assemblages are partially hydrated in some parts of the lherzolite, with garnet being rimmed by amphibole-spinel kelyphite, which in turn is progressively replaced by chlorite knobs. In other parts of the lens, porphyroclastic garnet grains are fresh and bright red (~66.5% pyrope, 19% almandine, 13.7% grossular). Garnet coexists with grass-green chromian diopside, minor grey enstatite (locally kinked) and amphibole (pargasit-edenite), and two generations of olivine (~90% forsterite), one of them porphyroclastic (Ø 2-3 mm), the second one recrystallized to small subhedral grains. It is in the earlier type of olivine that topotactic chromite and ilmenite ($FeTiO_3$) rods were discovered by Dobrzhinetskaya et al. (1996), who interpret b-$FeTiO_3$ to be the result of exsolution from perovskite, which implies depths of ~300 km. These inferences and thence the ultrahigh pressure origin have been questioned by Risold et al. (2003), who explain the microstructural evidence differently and favor depth estimates based on multi-equilibrium thermobarometry, indicating

32±3 kbar, 833±34 °C, i.e. depths of just over 100 km. These rest on preserved thermodynamic equilibria, and are in conflict with disequilibrium considerations raised by Brenker & Brey (1997), Paquin & Altherr (2001), and Olker et al. (2003), who conclude that subduction reached depths of 180 km (59±3 kbar, 1180±40 °C), and that extrusion rates for an initial phase (to ~800°C) were B1.5 cm/a. Consensus among the various proponents does not appear immanent, but the data sets, taken at face value, seem compatible with Alpe Arami being a sliver of subcontinental mantle which was tectonically incorporated into the Alpine TAC, following slab breakoff between 43 and 36 Ma ago, based on zircon SHRIMP data by Gebauer (1996; 1999). After amalgamation with subducted supracrustal TAC fragments, extrusion to mid-crustal levels followed along the subduction fault system. Quite conceivably, accretion into what is now observed as the Mergoscia-Arbedo zone continued during this phase, though the flow mechanisms are not well constrained. The final phase involved retrothrusting (Pfiffner et al., 2000) along a Proto-Insubric Line, and rapid tectonic denudation of the Central Alps (e.g. along the Simplon detachment, Merle, 1994), during the Oligocene and arly Miocene a loose use of stratigraphic terms is compulsory in the crystalline basement Stratigraphy in the foreland and hinterland basins of the Alps (Schlunegger et al., 1997) correlates well with such erosional fluxes from the evolving orogen.

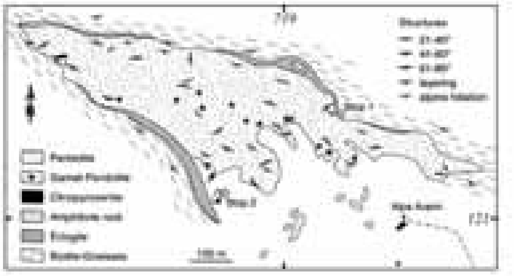


Figure 6.5 - Simplified geological map of Alpe Arami (from Moeckel, 1969)

Field itinerary

1. Fresh garnet peridotite

Swiss coord. 719.15/121.22/1460m

By following a small trail from the huts of Alpe Arami, ~250 m to the NNW into a steep, narrow valley, the northern margin of the ultramafic lens is reached. Buff weathering blocks and outcrops of fresh garnet peridotite can be sampled. Bright green Cr-diopside occurs frequently near garnet porphyroclasts. In many samples, garnet is rimmed by kelyphite, a fine symplectic intergrowth of amphibole and spinel, and further hydration may have converted these into silver-grey chlorite. Minor serpentine occurs principally along brittle fractures and shear planes in this peridotite.

1. Variably retrogressed peridotite and eclogite

Swiss coord. 718.85/121.1/~1700m

After returining to the huts of Alpe Arami, climb gently WNW along a fading trail through the open timber of Pianca Grande. Towards the western margin of the lens, observe blocks and outcrops of peridotite, with spinel-amphibole preudomorphs after garnet and with opx+sp+hbl replacing cpx. Occasional layers of garnet pyroxenite are found, and eclogite at the margin occurs both fresh and progressively hydrated to garnet amphibolite. Garnet-free black amphibolite is found in contact with biotite-plagioclase gneiss surrounding the peridotite lens, much the same as the eclogite lens above Gorduno.

A more massive band of clinopyroxenite outcrops at ~1650 m, and marks the SW border of the Alpe Arami lens.

Conclusions, Outlook

The two days in the Southern Steep Belt of the Central Alps have focussed on the role and significance of the TAC. While far from fully understood, three aspects appear pivotal to the evolution of the Alpine collisional orogen:

(1) Made up of highly diverse fragments, comprising rocks from continental to oceanic to Mantle origin, the TAC acted as a conveyer belt along the convergent plate boundary. In view of the strong internal reworking, it seems unlikely that the paleogeographic origin of the fragments can be reconstructed.

(2) In its evolution over a period >20-25 My, this mélange unit underwent dramatic changes. Its thermal state, rheological properties, and fluid budget were crucial to such processes such as the extrusion of HP fragments, partial melting, calcalkaline magmatism, and orogenic exhumation.

(3) Accretion of dominantly upper crustal TAC-fragments, rich in radioactive components, added a substantial source of heat (2.6 μWm^{-3}) along the base of the upper plate (i.e. the Apulian continental margin). Combined with the crustal material accumulated at mid-crustal depth upon collision with the Briançonnais microcontinent, the extruded TAC-units (Figure 5.1) contributed heat essential to generate the Barrovian overprint in the Lepontine dome.

Recent reports indicate that a TAC has played a critical role not only in the Central Alps, but that a similar tectonic element has developed in other collisional orogens (e.g. Ábalos et al., 2003; López Sánchez-Vizcaíno et al., 2003), and perhaps beneath introceanic fore-arcs as well (Cluzel et al., 2001).

Acknowledgments

We thank Fraukje Brouwer, Tom Burri, Igor Villa and Volkmar Trommsdorff for discussions, Capanna Gesero for hospitality, and the Swiss Nationalfonds for support of our research on metamorphic evolution (grant 20-63593.00).

DAYS 7 - 8

Geology of the dent blanche, mesozoic ophiolites and sediments (monte cervino) and the eclogitised continental crust of sesia lanzo zone (lower val d'aosta)

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2.1. The austroalpine system

Seventh and eighth days – *An overview into the structure, lithostratigraphy and petrology of the western Austroalpine tectonic system (Dent Blanche nappe) and underlying Mesozoic meta-ophiolites (Piemonte zone) and sediments (Combin z.) in the Monte Cervino (Matterhorn) area, and a section of the middle Aosta valley (Italian side of the Western Alps). In this region of the Alps, a significant progress in the kinematic interpretative syntheses has been developed in the last few decades.*

The main tectonic blocks that are interpreted to form the central-western Alpine belt in a lithosphere-scale cross-section, are represented in Figure 7.1 (from Dal Piaz et al., 2003). The oceanic suture zone, recording subduction metamorphism, involves the so-called Penninic domain and the Austroalpine.

The Western Austroalpine system consists of the internal Sesia-Lanzo zone (nappe) and the external Dent Blanche nappe, the latter subdivided by the Aosta-Ranzola fault running along the middle Aosta valley into northern (Dent Blanche, Mont Mary, Pillonet, Etirol-Levaz) and southern klippen (Glacier-Rafray, Tour Ponton, Emilius, Santanel, Chatillon), Figure 7.2 (A) and (B). The Austroalpine system was deformed and metamorphosed from the Cretaceous-

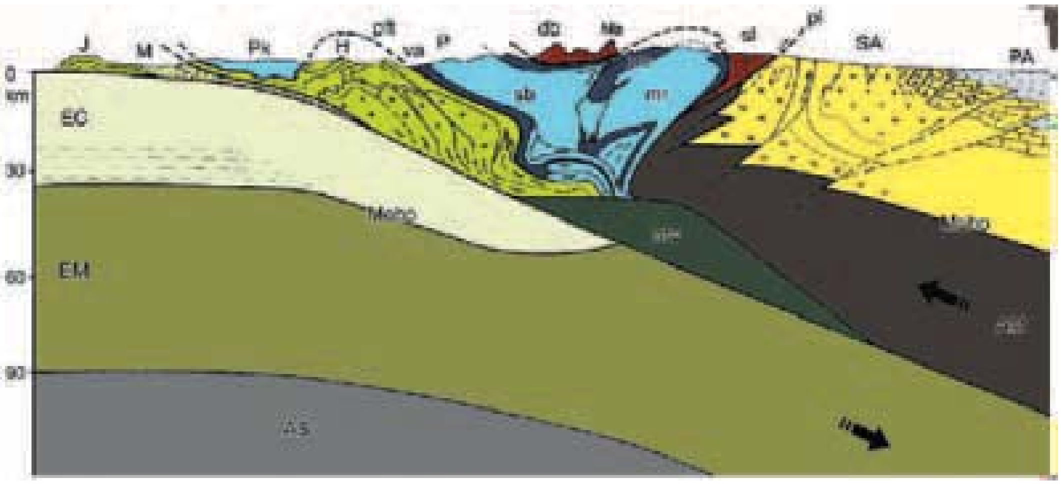

Figure 7.1. Lithospheric section of the central-western Alps (after 150 years of field geology and 35 years of geophysical investigations; no vertical exaggeration) - 1) Western Austroalpine nappe system: Sesia-Lanzo inlier (sl) and Dent Blanche nappe s.l. (db), including Matterhorn (Ma); 2) Penninic domain (P): Piedmont ophiolitic units (po), Monte Rosa (mr) and Grand St. Bernard (sb) nappes, underlain by lower Penninic and outer Penninic Valais zone (va), Penninic klippen (Pk), Penninic frontal thrust (pft); 3) Helvetic basement slices and cover nappes (H); 4) Molasse foredeep (M); 5) Jura belt (J); 6) buried wedge (BW) of European mantle or eclogitized crustal units; 7) European lithosphere: continental crust (EC) and mantle (EM); asthenosphere (AS); 8) Adriatic lithosphere: antithetic belt of Southern Alps (SA) and mantle (AM); Periadriatic Tonale-Insubric-Canavese fault system (pl); 9) Padane-Adriatic foreland (PA). From Dal Piaz et al., 2003.

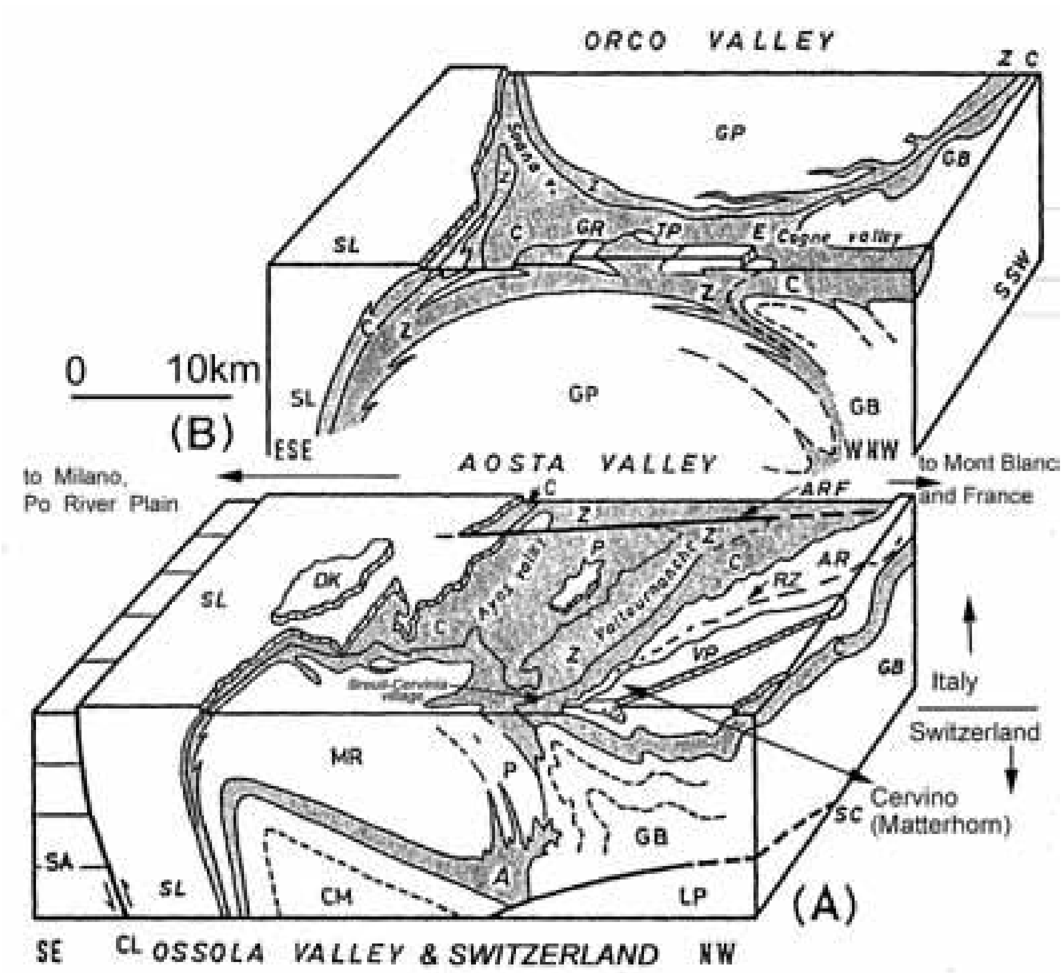

Figure 7.2
Block diagrams of the central-western Alps, across three main Alpine valleys, viewed from Switzerland (=from the North) and displaying the tectonic relationships between the sheets (nappes) of pre-Alpine continental crust and the Mesozoic oceanic crust or Mesozoic sediments of oceanic or continental margin affinities. Compare with Figure 7.1 and 1a (making the effort of reversing east with west); utilize this 3-D diagram to understand the three-dimensional structure of the western Alps, while looking south from the panoramic Stop 7.1 at Plateau Rosa.
Sheets (nappes) of pre-Alpine continental crust: SL=Sesia-Lanzo - Dent Blanche system, DK=II Diorite-Kinzigite zone, MR=Monte Rosa, GP=Gran Paradiso, P=Portjengrat, GB=Grand Saint Bernard, CM=Camughera-Moncucco, LP=Lower Pennine, VP and AR=Valpelline and Arolla series of the Sesia-Lanzo-Dent Blanche system, with infolded RZ=Roisan Zone Mesozoic cover, GR, TP, E, P =Glacier-Rafray, Tour Ponton, Emilius, and Pillonet klippen of the Sesia-Lanzo-Dent Blanche system. Traditionally, as in the rest of the Alps, the continental sheets underlying the Mesozoic oceanic rocks are called Pennine nappes, and the overlying ones Austroalpine.
Sheets (nappes) of Mesozoic oceanic crust or Mesozoic sediments of oceanic or continental margin affinities: Z and A= Zermatt-Saas and Antrona ophiolites, with thin oceanic sedimentary covers; C=Combin Mesozoic covers of continental margin-to slope affinity, including the Frilihorn-Tsaté and Pancherot-Cime Bianche trench sediments.
SA=Southern Alps: a south-verging thick-skin Alpine thrust system located south of the Tonale-Insubric-Canavese tectonic exhumation fault system. SC, ARF =Simplon-Centovalli and Aosta-Ranzola tectonic denudation fault systems.

Paleogene (eoalpine) to the Eocene-Lower Oligocene (mesoalpine) under eclogitic and greenschist facies conditions; the geological history of this unit ends in the Neogene with ductile-brittle deformation of the nappe pile (Dal Piaz et al., 1972, 1983; Hunziker, 1974; Compagnoni et al., 1977; Oberhansli et al., 1985; Ballèvre et al., 1986; Pognante et al., 1987; Vuichard, 1989; Droop et al., 1990; Polino et al., 1990; Lardeaux and Spalla, 1991; Venturini et al., 1994).

The pre-Alpine protoliths are represented by Variscan paragneisses of high metamorphic grade (kinzigite, felsic granulites), with interbeddings of mafic granulite, amphibolite, and marble, by Permian intrusive granitoids and gabbros, and by minor Mesozoic covers (mainly platform carbonates, rift sedimentary breccias, and flysch; Mont Dolin, Roisan zone, internal Sesia-Lanzo zone) (Compagnoni et al., 1977; Dal Piaz, 1993; Venturini et al., 1994).

The eoalpine subduction metamorphism is largely preserved in the Eclogitic Micaschists complex of the internal Sesia-Lanzo zone (Ballèvre et al., 1986; Droop et al., 1990; Dal Piaz et al., 1993), in the southern Austroalpine klippen as a whole, and in the Etirol-Levaz thrust sheet; peak P-T-conditions of the eclogitic metamorphism are estimated at around 550°C and 1.5-1.8 GPa. With the exception of the Etirol-Levaz sheet (Kienast, 1983), the other northern klippen are eclogite-free, displaying only a few mineral relics of relatively high pressure (aegirine, sodic amphiboles, garnet, and white mica with high Si contents) below a pervasive greenschist facies overprinting (Gneiss Minuti complex, Arolla Gneisses; Dal Piaz, 1976; Ayrton et al., 1982; Pennacchioni and Guermani, 1993). Greenschist-facies-dominated Gneiss Minuti also outcrop along the external side of the Sesia-Lanzo zone, where they locally preserve eclogitic mineral relics (Spalla et al., 1991). The Dent Blanche-Mt.Mary klippen, and the Sesia-Lanzo zone, are structurally composite, both displaying a top unit (known as the Valpelline Series and 2nd Diorite-Kinzigite zone, respectively) formed by lower continental crust rocks with a few slices of mantle peridotite. These lower continental crust rocks are closely similar to lithologies occurring in the Southalpine kinzigitic complex of the Ivrea zone (Stutz and Masson, 1938; Diehl et al., 1952; Dal Piaz et al., 1971, 1972; Compagnoni et al., 1977; Cesare et al., 1989; Vuichard, 1989; Canepa et al., 1990).

2.2. Ophiolitic units

The Alpine ophiolitic units are slices of a Upper Jurassic oceanic lithosphere, generally coupled with Cretaceous trench-derived flysch sequences, and minor mélanges (Bernoulli and Lemoine, 1980; Lagabrielle, 1987; Ziegler, 1988; Dal Piaz and Polino, 1989; Dercourt et al., 1990; Polino et al., 1990; Martin et al., 1994). These units occur as thin sheets, never exceeding 1-2 km in thickness. The thickest units generally consist of tabular bodies of metagabbro and/or serpentinized mantle peridotite, in places directly covered by oceanic metasediments. In other words, the Alpine ophiolites never preserve a complete section of normal oceanic crust (Lombardo and Pognante, 1982; Auzende et al., 1983; Polino et al., 1990), and probably represent slices of topographic highs of the oceanic floor (horst, fracture zones, seamounts, etc.), which were delaminated and scraped off when the ocean floor entered the trench and collided with the active margin. In this view, Alpine ophiolites are fragmented records of the subducting ocean, transferred tectonically to the overriding plate; they were made free to interplay tectonically within the subduction channel, after episodical decoupling from the Tethyan lithosphere consumption at depth. In the Northwestern Alps, the following ophiolitic units are recognized:

1) The Piedmont ophiolitic zone,

a structurally-composite nappe system, sandwiched between the Austroalpine nappes and the underlying Upper and Middle Penninic nappes. From contrasting lithological settings and metamorphic imprints, the Piedmont zone of Aosta Valley and southern Valais is currently divided into two ophiolite-bearing units (Figure 7.1): the overlying greenschist facies-dominated Combin (Tsaté) unit, and the underlying eclogitic Zermatt-Saas unit (Bearth, 1967; Dal Piaz, 1974, 1988, 1992; Dal Piaz and Ernst, 1978; Dal Piaz et al., 1979, 1985; Ballèvre et al., 1986; Sartori, 1987; Vannay and Allemann, 1990).

North of the Aosta-Ranzola fault, the two units are separated by a thin ophiolite-free décollement unit (Pancherot-Cime Bianche-Bettaforca unit: PCB; Figure 7.1), and locally by the Austroalpine Etirol-Levaz eclogitic slice (Ballèvre et al., 1986; Dal Piaz, 1988, 1992). The PCB consists of Permian-Cretaceous cover sequences deriving from a continental basement.

The Combin ophiolitic unit is the tectonic sole of the northern Austroalpine Dent Blanche, Mt. Mary and Pillonet klippen, altogether forming a tectonic multilayer which experienced the same blueschist to greenschist facies metamorphic evolution, whilst southern homologues of the Zermatt-Saas nappe are the tectonic sole of the southern Austroalpine eclogitic klippen (Ballèvre et al., 1986; Polino et al., 1990). As shown in Figure 7.1 and 7.2, the Zermatt-Saas unit and southern homologues lie directly over the Monte Rosa and Gran Paradiso continental nappes, disappearing to the northwest beneath the inner Gran St. Bernard back folds and back thrusts (from Mischabel, near Zermatt, to Grand Nomenon in the Aosta-Cogne area); by contrast, the Combin zone extends much more externally, being thrust over the outer Grand St. Bernard nappe system (Elter, 1960; Escher et al., 1986).

The Combin ophiolitic sequence consists of carbonate to terrigenous flysch-type metasediments (calcschists *sensu lato*), commonly including multiple interleavings of tabular greenschist facies metabasalts (prasinites), and minor serpentinite slices (Dal Piaz, 1965, 1988; Vannay and Allemann, 1990). Major ophiolitic bodies, with a cover of manganiferous quartzite and other oceanic metasediments, may locally predominate in the upper section of the Combin nappe. They display a peculiar greenschist facies imprint of mid-Tertiary (mesoalpine) age, that predates the transecting Oligocene (31-30 Ma) andesite-lamprophyre dykes of the Periadriatic magmatic activity (Dal Piaz et al., 1979; Venturelli et al., 1984; Diamond and Widenbeck, 1986). In addition, relatively high-P relics locally occur in metabasalts, metagabbros, and metasediments (blue amphiboles, paragonite, phengite, garnet, and rutile; Dal Piaz, 1976; Ernst and Dal Piaz, 1978; Ballèvre et al., 1986; Polino et al., 1990). These relics may be related to a subduction event of unknown age, probably Late Eoalpine (Paleocene) or Early Eocene.

The Zermatt-Saas ophiolites consist of huge mafic and ultramafic bodies, with minor metasedimentary remnants of the oceanic cover and orogenic deposits (Bearth, 1959, 1967; Dal Piaz and Ernst, 1978). Alpine transposition and metamorphic reworking have pervasively effaced most of the original stratigraphic relations and primary features. Therefore, the reconstruction suggested here is only tentative, being essentially inferred from low strain domains described elsewhere in the Alpine-Apenninic domain, and from present-day oceanic lithosphere. The Zermatt-Saas unit displays this lithological setting:
i) thick basal titanclinohumite-bearing antigorite serpentinites (formerly mantle peridotites), cut by numerous rodingitic gabbro dykes (Dal Piaz, 1969; Dal Piaz et al., 1980) and locally mantled by ophicarbonate breccias (ophicalcites; Driessner, 1993); gigantic ultramafic bodies occur in both sides of the Aosta valley (Monte Avic and Monte Rosso di Verra-Breithorn massifs); ii) Mg-rich and minor Fe-Ti-rich metagabbros and related cumulus ultramafics; iii) metamorphosed massive basalts, pillow lavas, pillow breccias, and hyaloclastites; iv) quartzites and piemontite-spessartine-rich manganiferous metacherts (Dal Piaz et al., 1979; Mottana, 1986), capped by marbles and minor calcschists, a sequence which roughly recalls the supraophiolitic cover (Callovian-Oxfordian radiolarian cherts-Calpionella limestones), capping the Ligurian ophiolites of the Northern Apennines; v) orogenic metasediments and an eclogitic subduction mélange (Riffelberg-Garten complex) consisting of rounded to faceted blocks of eclogitic metabasalts within ankerite-bearing garnet micaschists (Bearth, 1967; Dal Piaz and Ernst, 1978). A transitional to normal-MORB geochemical affinity is reported for the Combin, Zermatt-Saas and Antrona mafic rocks (Dal Piaz et al., 1981; Beccaluva et al., 1984; Pfeiffer et al., 1989). On the basis of lithological association and geochemical signature, these ophiolites have been so far univocally interpreted as slices of oceanic lithosphere.

The Zermatt-Saas nappe displays an eclogitic imprint of Cretaceous age (90 Ma; Bocquet et al., 1974; Hunziker, 1974; Hunziker et al., 1992). The eclogitic assemblage is particularly well-preserved in the classic Allalin body (Bearth, 1967; Droop et al., 1990), and in minor Fe-gabbro bodies from the Italian side (Baldelli et al., 1985; Benciolini et al., 1988), as well as in some massive and pillow metabasalts. Mineral equilibria in eclogitic gabbros suggest metamorphic conditions of T=450°-650°C for minimal pressures of 1.0-1.5 GPa (Chinner and Dixon, 1973; Ernst and Dal Piaz, 1978; Benciolini et al., 1988; Martin and Tartarotti, 1989; Droop et al., 1990; Dal Piaz et al., 1993). In the northern Aosta valley, temperatures for the eclogitic peak seem to have attained higher values than those for the southern ophiolites (Ernst and Dal Piaz, 1978; Oberhänsli, 1986). Coesite has been recently found within Mn-Mg-rich garnets from the Cignana (Valtournanche) metacherts of the Zermatt-Saas unit, recording peak conditions of T=590°-630°C and P=2.6-2.8 GPa (Reinecke, 1991). The post-eclogitic evolution of the Zermatt-Saas ophiolites is characterized by multiple re-equilibration under decreasing pressure, at first under high-T/blueschist facies conditions (glaucophane-garnet-bearing assemblages), and later, under Ab-amphibolite and greenschist facies conditions (Bearth, 1967; Ernst and Dal Piaz, 1978; Kienast, 1983; Ballèvre, 1988; Martin and Tartarotti, 1989; Reinecke, 1991).

2.3. The penninic basement and cover nappes

1) The Upper Penninic Monte Rosa and Gran Paradiso nappes.

The Monte Rosa and Gran Paradiso nappes occur at the same structural level within the present nappe pile (Figure 7.1 and 2). They consist of Variscan garnet-biotite-sillimanite paragneisses and cordierite-bearing migmatites, with mafic bodies and some marble interbeddings (pre-granitic complex), intruded by Upper Carboniferous porphyritic granites (310 Ma; Hunziker, 1970) and aplite-pegmatite dykes; these rock units are partly preserved at all scales in domains of low strain (Bearth, 1952; Dal Piaz, 1993). The predominating alpine derivatives are represented by various kinds of garnet micaschists, often albite-bearing (Gneiss minuti), and by metagranites to augengneisses, that record an eoalpine eclogitic imprint (400-530°C, 1.0-2.0 GPa), and a mesoalpine greenschist to amphibolite facies overprint (Bearth, 1952; Dal Piaz, 1971; Compagnoni and Lombardo, 1974; Compagnoni et al., 1974; Chopin and Maluski, 1980; Dal Piaz and Lombardo, 1986; Ballèvre, 1988; Biino and Pognante, 1989). Note that the Dora-Maira nappe - the southern homologue of Monte Rosa and Gran Paradiso - displays the first occurrence of coesite found in the Alps (Chopin, 1984). The Monte Rosa and Gran Paradiso basement is locally mantled by décolled remnants of Permian-Mesozoic cover sequences (quartzites, dolostones, marbles, and calcschists). As shown in (Figure 7.1 and 7.2), the Monte Rosa nappe is a huge recumbent fold (post-nappe deformation), resting over the Antrona ophiolites and narrowing down, to the southeast, into the inner steep belt occurring along the Ossola valley (Milnes, 1974; Klein, 1978; Milnes et al., 1981), i.e. into Argand's root zone of the Penninic nappes. By contrast, the tectonic sole of the Gran Paradiso and Dora-Maira nappes, located out of the Ossola-Tessin culmination, is not exposed at the surface.

2) The Middle Penninic Grand St. Bernard nappe system. The Grand St. Bernard system continuously extends from the Gulf of Genoa to the Valais and the Ossola valley; Bigi et al., 1990). From Valais to the northern Aosta valley (Figure 7.2), it is represented by a huge tectonic multilayer, consisting of the capping Mont Fort unit, the Siviez-Mischabel and Ruitor units, the Pontis unit and the basal and external "zone houillère", a thick décollement unit made up of Upper Carboniferous-Permian metaclastic deposits with coal interbeddings (Ellenberger, 1958; Elter, 1960, 1972; Caby et al., 1978; Escher et al., 1987; Escher, 1988). The Grand St. Bernard system displays a penetrative mid-Tertiary metamorphic imprint, ranging from blueschist to later greenschist facies. A pre-Westfalian basement (paraschists with associated igneous bodies generated by a bimodal magmatism), is preserved in the Siviez-Mischabel, Ruitor, and Pontis units. The basement is characterized by a Variscan amphibolite facies regional metamorphism (biotite, garnet, staurolite, kyanite; Frey et al., 1974; Desmons, 1992), and by older (eo-Variscan ?) relict eclogites (Thelin et al., 1993). The Variscan basement was intruded by Paleozoic granites and subvolcanic bodies, and is unconformably covered by Carboniferous-Triassic clastic deposits and volcanics, followed by Middle Triassic-Eocene platform- to deep-water carbonate and clastic deposits (Briançonnais sedimentary cover; Ellenberger, 1958; Marthaler, 1984; Escher, 1988). Basin analysis suggests that the Briançonnais domain operated as a structural high during the early stages of Mesozoic rifting.

DAY 7

Geology of the dent blanche, mesozoic ophiolites and sediments (monte cervino)
(Warm clothes and mountain shoes)

Stop 7.1:

Tectonic view from the terraces of the Plateau Rosa, the uppermost station of the cable car from Breuil-Cervinia. Comments will be made from two outstanding vantage points on the 3-D structure of the ophiolites and Dent Blanche nappe, and on their correlated sedimentary covers, according to the

Figure 7.3
View, from Plateau Rosa, of the Pancherot-Cime Bianche unit on the northern slope of Motta di Pleté (to be connected with 7.4 and 5.)

geologic relationships as described above. These vantage points are as follows: to the west on the Dent Blanche nappe, Combin and Zermatt-Saas zones (Figure 7.3, 4, 5 and 6); and to the north, on the backfold of the Gd. St. Bernard nappe (Figure 7.7, 8 and 9). The significance of the gabbro of Monte Cervino-Collon, and the tectonic implications of mesozoic covers in the partially-rejuvenated pre-Alpine continental crust will be discussed.

Figure 7.4
View of the Mont Blanc du Creton- to Dent d'Hérens chain (=Grandes Murailles) with Dent Blanche (Arolla metagranitoids and Valpelline series-metapelites, marbles and amphibolites. Mesozoic meta-ophiolites and calcschists in the lowermost part of the valley.)

Figure 7.5
Southeastern slope of Monte Cervino (the Swiss Matterhorn). =For explanation see captions for Figure 7.6.

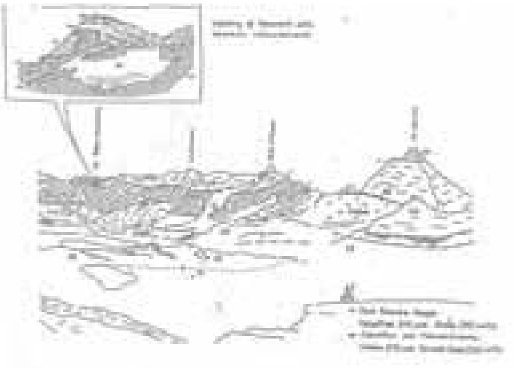

Figure 7.6
Explanatory tectonic scheme of Grandes Murailles and Monte Cervino southeastern slope geology (from a previous sketch by Giorgio V. Dal Piaz). See enclosed legend.

Figure 7.7
View of the Zermatt valley from the north (Plateau Rosa, to be combined with 7.8 and 9). Mischabel backfold of the Gd. St. Bernard nappe on the left slope of the valley.

Figure 7.8
Right flank of the Zermatt valley

Figure 7.9
Piccolo Cervino (Lesser Matterhorn) metaophiolites.

Stop 7.2:

Manganiferous metacherts north of Plan Maison. North of the Plan Maison cable-car station, the top of the eclogitic Zermatt-Saas unit consists of partly retrogressed eclogitic metabasalts, with normal-MORB affinity, and with an overlying bed of Mn-rich quartzite, which may be referred to as the Middle-Upper Jurassic base of the supraophiolitic oceanic covers. Metabasalts are characterized by the occurrence of lozenge-shaped aggregates of zoisite-epidote and white micas, replacing pre-eclogitic (prograde) lawsonite, glaucophane omphacite-almandine peak assemblage, and greenschist facies retrogression. The overlying metasediments consist of garnet-phengite quartzites, including thick bands and nodules rich in manganiferous and other minerals, such as piemontite (reddish), spessartine and alurgite (pink), brownite (black), and epidote (yellow). This mineralisation is representative of Alpine polyphase (eclogitic and greenschist facies) recrystallisation of ocean-floor hydrothermal deposits developed during the Mesozoic spreading of the Tethyan Ocean.

Field itinerary

Stops 7.3, 7.4:

“Riffelberg-Garten” Unit. Rocks exposed from the Testa Grigia (Plateau Rosa; see Stop 7.1, 7.2) - Ventina Glaciers to the town of Cervinia are part of the upper Zermatt-Saas ophiolitic unit. The outcrops, mostly covered by moraine deposits, consist of eclogitic metabasalts, serpentinites, and calcschists. At Stop 7.3 (close to the “Cime Bianche” station of the cable railway), boulders polished by the glacier (roche moutonée), expose marble and calchscists, including dm-scale layers and boudins, and cm to dm-scale subspherical to roughly-faceted clasts of metabasalt (Figure 7.10). These rocks make up the so-called “Riffelberg-Garten” sub-unit (Dal Piaz 1965; Bearth, 1967), which extends for a few km^2 between the “Cime Bianche” and “Plan Maison” cable car stations. It also outcrops in the upper part of the Ayas Valley (East of the Valtournanche Valley), and in Switzerland. In the Cime Bianche-Plan Maison area, the host rock of the Riffelberg-Garten sub-unit consists of either calcschist *s.s*, calcschist *s.l.* (micaschist interbedded with micaceous marble), quartz-rich calcschist, micaschist, marble, or carbonate-rich mafic rock (impure basalt? see Stop 7.3). Mafic boudins and clasts show homogeneous mineralogy, and consist of carbonate-rich eclogite. At Stop 7.4, near the Goillet lake (see figure7.10), the Riffelberg-Garten sub-unit is mostly represented by marly calcschists, including mafic boudins of various sizes and shapes.

Figure 7.10 - Eclogitic mafic layers and boudins included in calcschists of the Riffelberg-Garten sub-unit (Stop 7.3).

The origin of these uncommon rocks still remains controversial, altough in the past they have been interpreted as a possible eo-alpine subduction mélange (Dal Piaz, 1965).

Geological Maps

Geologischer Atlas der Schweiz 1:25.000, Blatt 1347 Matterhorn. Office fédéral des eaux et de la géologie.

DAY 8 (morning)

The eclogitised continental crust of Sesia Lanzo Zone and its implications with the Mesozoic oceanic units (Lower Aosta Valley).

In the Western Alps, high-pressure low-temperature (HP-LT) metamorphic imprint widely affects not only the ophiolites and related sedimentary sequences, but also large volumes of the pre-Alpine continental crust. The Sesia-Lanzo Zone (SLZ; Figure 8.1) is the widest portion of the continental crust affected by eo-Alpine eclogite-facies metamorphism of this sector of the chain; its Alpine tectonic evolution, with eo-Alpine ages (130-70) proposed for the HP-LT metamorphic imprint (e.g: Hunziker, 1974; Oberhaensli, 1985; Stockhert, 1986; Rubatto, 1998; Rubatto, 1999), is characterised by a LT eclogite imprint followed by blueschist re-equilibration (Castelli, 1991; Pognante, 1991) and references therein), and a successive LP-greenschist retrogradation. This evolution is compatible with an uplift during active oceanic lithosphere subduction (Spalla, 1996, Zucali, 2002). The characteristic low T/P ratio facilitated preservation of relict assemblages in rocks, undergoing several successive Alpine re-crystallizations. The pre-Alpine metamorphic evolution of this portion of Austroalpine continental crust, from granulite to greenschist facies conditions, is variably preserved in marbles, meta-pelites, meta-granitoids, meta-gabbros, granulites, and amphibolites (Compagnoni, 1977; Lardeaux, 1991; Rebay, 2001 and references therein). The granulite to amphibolite PT path has been considered to be the result of an extension-related uplift during Permo-Triassic times of the pre-Alpine lower crust (Lardeaux, 1991; Dal Piaz, 1993), an event similar to the one described in the Ivrea Zone (e.g. (Schmid, 1976; Sills, 1984; Mayer, 2000). Relics of the pre-Alpine history are preserved through the three main lithologic complexes of the SLZ (Figure 8.1): i) Gneiss Minuti complex (GMC), ii) Eclogitic Micaschists complex (EMC) and iii) II Dioritic-Kinzigitic Zone (IIDK). IIDK consists of kilometric lenses not recording the eclogitic re-equilibration; EMC and GMC, both pervasively eclogitised, strongly differ in the volume

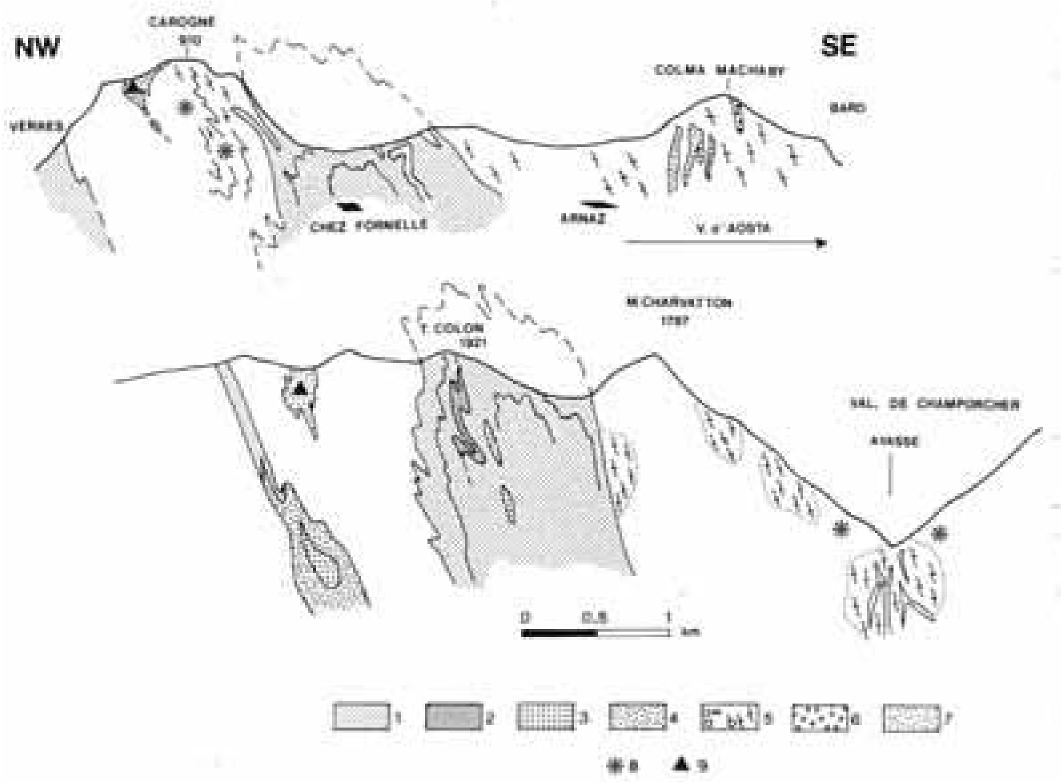

Figure 8.1- Cross section, seen in the natural exposure, of the implication of the external margin of the Sesia-Lanzo zone and the Mesozoic calcschists of the Combin unit. 1=calschists, 2=metabasics, 3=metagabbros, 4=serpentinites, 5=high grade pre-Alpine metapelites with blueschist Alpine overprint, 6=high grade amphibolites associated with 5, 7=quartzites, marbles, and high grade metapelites, 8=eclogites, 9=pre-Alpine granulites.

percentage of greenschist re-equilibration. GMC is widely reequilibrated under greenschist conditions, and marks the continent-ocean tectonic boundary, active during subduction-exhumation processes of the SLZ and the meta-ophiolites of the Piemontese Zone. In GMC, the greenschist imprint is generally associated with mylonitic textures (Stuenitz, 1989; Spalla, 1991). The EMC constitutes the innermost part of the SLZ; here the greenschist overprint is confined to discrete shear zones, more pervasive towards its inner boundary with the Southern Alps. The Alpine syn-metamorphic structures of Sesia-Lanzo Zone are intruded by calc-alkaline and ultrapotassic dikes during Oligocene (Dal Piaz, 1973; Dal Piaz, 1977).

The lower Aosta valley (Figure 8.1), from Borgofranco to Verres, offers a complete section across the Sesia-Lanzo zone, from the EMC (mainly eo-alpine eclogite facies rocks), to the GMC (mainly greenschist facies mylonites).

Stop 8.1:

Locality: Arnad, along highway A5, from Aosta to Torino.

Topics: Panoramic view over kilometer scale isoclinal folds of tectonic contact between GMC continental rocks and the metasediments of the Piedmont ophiolite zone.

The first stop of the eighth day is reached by following the Aosta-Torino highway (A5). The stop is some hundred meters after the Bard gate, in a parking area. The excursion stop is illustrated in Figs. 8.1 and 8.2.

In the natural cross section between Verres and Bard, the continental unit of the external SLZ (GMC) displays an historically known tectonic implication (by a several kilometer-scale fold) with the underlying Mesozoic calcschists and ophiolites. Analysis of

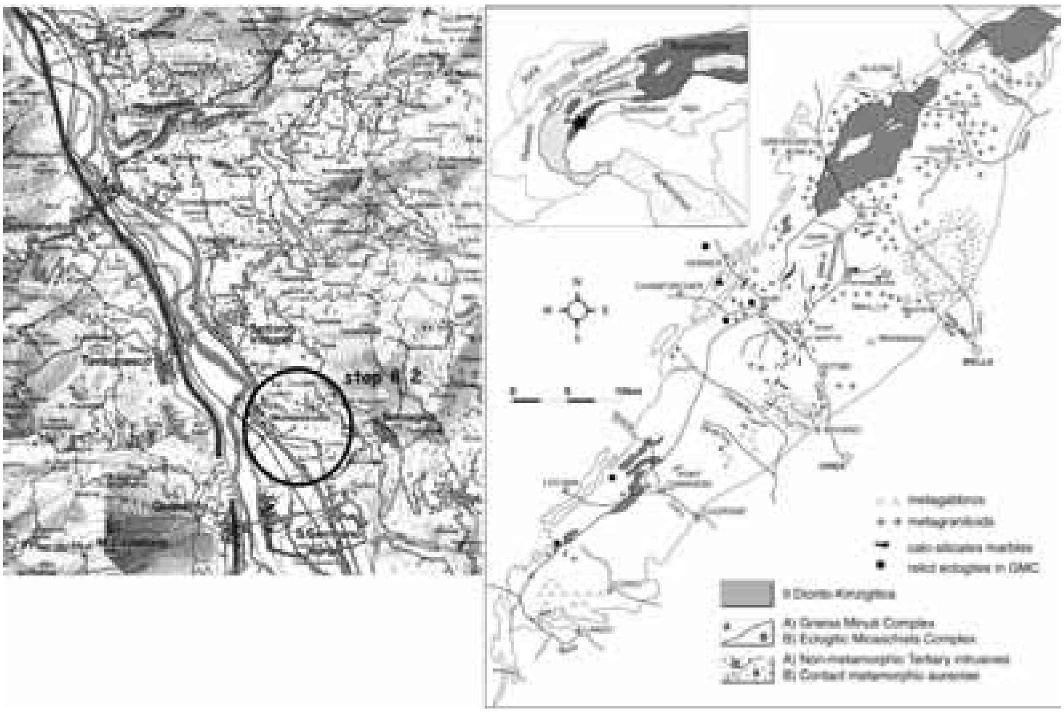

Figure 8.2 - General map of the Sesia-Lanzo zone, and location of Stop 2.
schema Sesia: (B) Simplified geological map of the Sesia-Lanzo-Zone. Legend: 1 = II Dioritic- Kinzigitic zone; 2A = Gneiss Minuti complex; 2B = Eclogitic Micaschists complex; 3A = non-metamorphic Tertiary intrusives; 3B = contact metamorphic aureole; Symbols: a) = metagabbros; b) = metagranitoids; c) = calc-silicate marbles; d) = relict eclogites in the Gneiss Minuti complex. (C) E-W idealized cross-section, in which deformation and greenschist re-equilibration gradients from the Eclogitic Micaschists (East) to Gneiss Minuti (West) complexes are represented by the frequency of greenschist deformation zones (beards). Legend: 1) and 2) meta-ophiolites and calcschists of the Piemonte Zone, respectively; 3) Lanzo ultramafics; 4) Gneiss Minuti and Eclogitic Micaschists Complexes; 5) II Dioritic-Kinzigitic zone; 6) Tertiary intrusives; 7) Ivrea Zone; I.L. = Insubric Line.

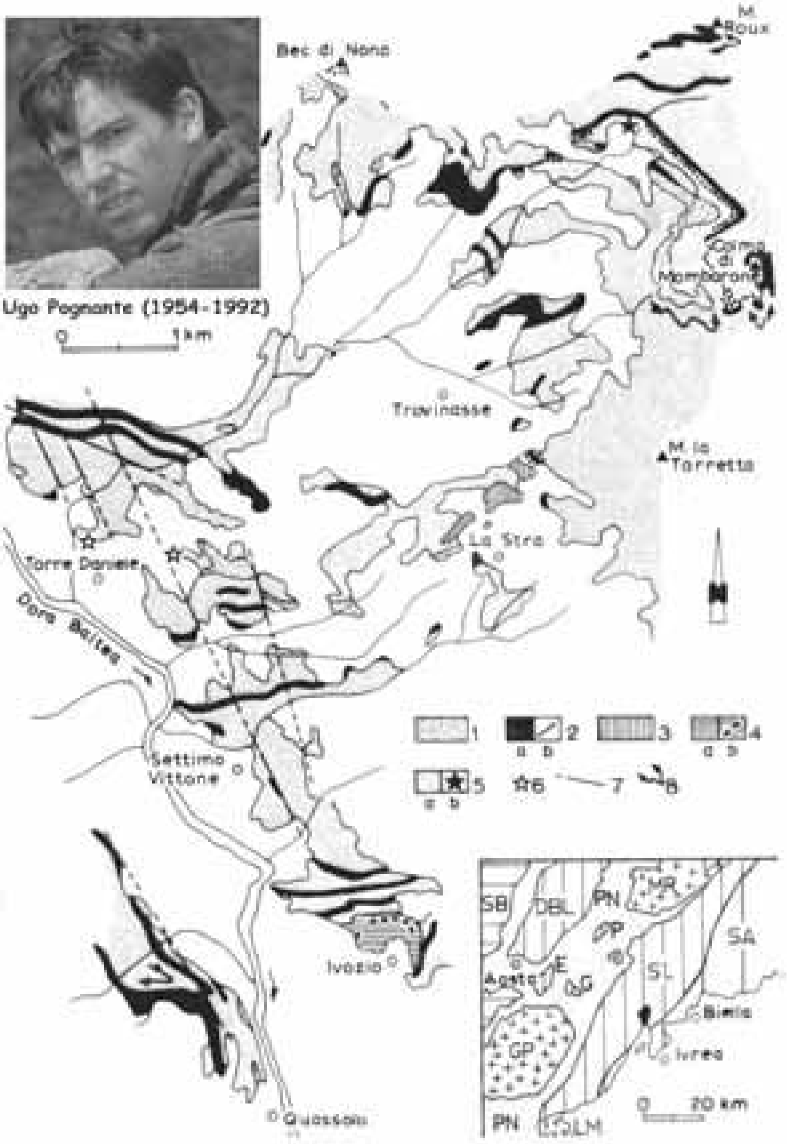

Figure 8.3 - Map of the internal part of the Eclogitic Micaschists complex along the lower Aosta valley (Colma di Mombarone, western slope), by Ugo Pognante (1980). 1) marbles and carbonate schists; 2a) metagranitoids; 2b) jadeite megablastic layers; 3) amphibole eclogites (La Stra); 4a) eclogitic metabasites (Ivozio); 5a) eclogitic micaschists; 5b) kyanite-chloritoid-garnet micaschists; 6) post-metamorphic lamprophyric dikes; 7) faults and fracture zones; 8) main D2 structures; 9) traces of cross sections (see Figure 2 in Pognante et al., 1980); SA=Southern Alps; LM=Lanzo Massif; SL=Sesia-Lanzo zone; DBL=Dent Blanche nappe; G=Glacier-Rafray klippe; E=M.Emilius klippe; P=Pillonet klippe; PN=Piemonte Ophiolite nappe; MR=Monte Rosa nappe; GP=Gran Paradiso nappe; SB=Saint Bernard nappe.

small scale folds and cleavages demonstrates that this fold belt, which is a dominant tectonic feature of the SLZ external margin, over several tens of kilometers, developed under greenschist facies conditions. In spite of the pervasive greenschist overprint, small relics of Alpine eclogite and pre-Alpine granulites are preserved both in the GMC (Figure 8.2), and in the metabasalts associated with the Mesozoic calcschists.

Stop 8.2:

Locality: Montestrutto area, at the boundary between the Valle d'Aosta and Piemonte regions, a few kilometers north of Ivrea.

Topics: coarse-grained polydeformed eclogite facies-rocks of EMC; deformation vs. reaction rate and the role of bulk chemistry.

The second stop of the eighth day is reached by following the highway Aosta-Torino to the Quincinetto exit and the main road for Ivrea (S.S. n° 20) to Montestrutto village. Stop in parking area along the main road, excursion stop is located in Fig. 8.1. Short walk (10 - 20 min.) along a foot-path in the wood.

The rocks of the region around Montestrutto belong to the EMC (Figure 8.1), and consist of micaschists and gneisses with Qtz, Phe, Grt, ± Na-Cpx, ± Gl, Pg, Zo, Ep, Rt, locally Ky, and Mg-rich Cld. Micaschists and gneisses include layers and lenses, up to 10 meters thick, of mafic rocks (eclogites, amphibole bearing eclogites, glaucophanites and hornblendites), folded or boudinaged during polyphase Alpine deformation, and showing different eclogitic assemblages, depending on their bulk composition and fabric evolution (Figure 8.4). Amphibole-bearing eclogites show the most common mineral assemblage: Omp, Grt, Rt, Gl/Ca-Na Amp, white mica, and Zo. Zo and Pg locally replace Lws in the eclogites of Ivozio (Figs. 8.3). Pure and impure marbles (Cal, Ank, Dol, ± Phe, Grt, Qtz, and Omp), interlayered within micaschists (Figure 8.3), locally show mylonitic texture (Castelli, 1991); leucocratic metagranitoid dykes (Qtz, Na-Cpx, Phe, ±Grt, Gl, and relict Kfs) are folded and transposed in micaschists.

Internal deformation of EMC manifests four generations of Alpine folds (Pognante, 1980; Williams, 1983): D_1 and D_2 developed under HP-LT conditions, as evidenced by Phe and Na-Cpx aligned in the S_1 foliation, and by the recovery sub-structure of the deformed HP minerals during D_2 micro-folding. A pre-eclogite fabric is preserved in the mafic rocks, where Amp, Zo/Czo, white mica, and Rt define a foliation overgrown by Na-Cpx, Grt and Zo (Pognante, 1980); similar patterns have been interpreted, in adjacent areas of SLZ (Valchiusella), as the mineral record of a subduction-related prevailing P-prograde trajectory (Reinsch, 1979). D_3 is synchronous with the re-equilibration under blueschist-facies conditions; D_4 mega-scale folds overprint the previous structures (Williams, 1983).

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