Migmatization and deformation in the Southern Steep Belt of the Central Alps

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Itinerary

Stop 1: Monte Verità → Amphibolites and partly molten metasediments of the Ivrea-Verbano zone

Stop 1B (depending on time, weather and opportunity): Arcegno → Garnet-bearing amphibolites of the Ivrea-Verbano zone

Stop 2: Maggia river by Tegna → Migmatitic ortho- and paragneisses of the Southern Steep Belt

Stop 3: Lavertezzo bridge → Strongly deformed paragneisses and orthogneisses of the Simano nappe

Stop 4: Verzasca "James Bond" dam → Spectacular folding in the metasediments of the Simano nappe

Stop 5: Bellinzona castle → Migmatitic paragneisses and orthogneisses of the Southern Steep Belt

General structure of the Alps

The Alps result from the convergence between the European and Adriatic paleo-margins, which led to the closure of two oceanic basins, the Piemont-Liguria Ocean to the south and the Valais seaway to the north (e.g. Milnes and Pfiffner 1980). South-dipping subduction of the European plate and subsequent continental collision with Adria produced the stack of the Penninic nappes in the Central Alps. Five paleogeographic domains are recognized (Figs. 1 and 2):

(i) the Leventina, Simano and Adula nappes are ascribed to the distal parts of the **European continental margin** (Trümpy 1960; Schmid et al. 1996);
(ii) the ophiolites of the Misox zone and Chiavenna are interpreted as remnants of the **Valais ocean** (Schmid et al. 1996; Steinmann and Stille 1999);
(iii) the Tambo and Suretta nappes represent slivers of the former **Briançonnais micro-plate** and other crustal fragments (Schmid et al. 1990) between the Piemont-Liguria and Valais oceanic domains;
(iv) the ophiolitic Malenco-Forno-Lizun Avers units are assigned to the **Piemont-Liguria ocean** (Staub 1946; Schmid et al. 1996);
(v) The Austroalpine units correspond to the **Adriatic continental margin** (Handy et al. 1993).

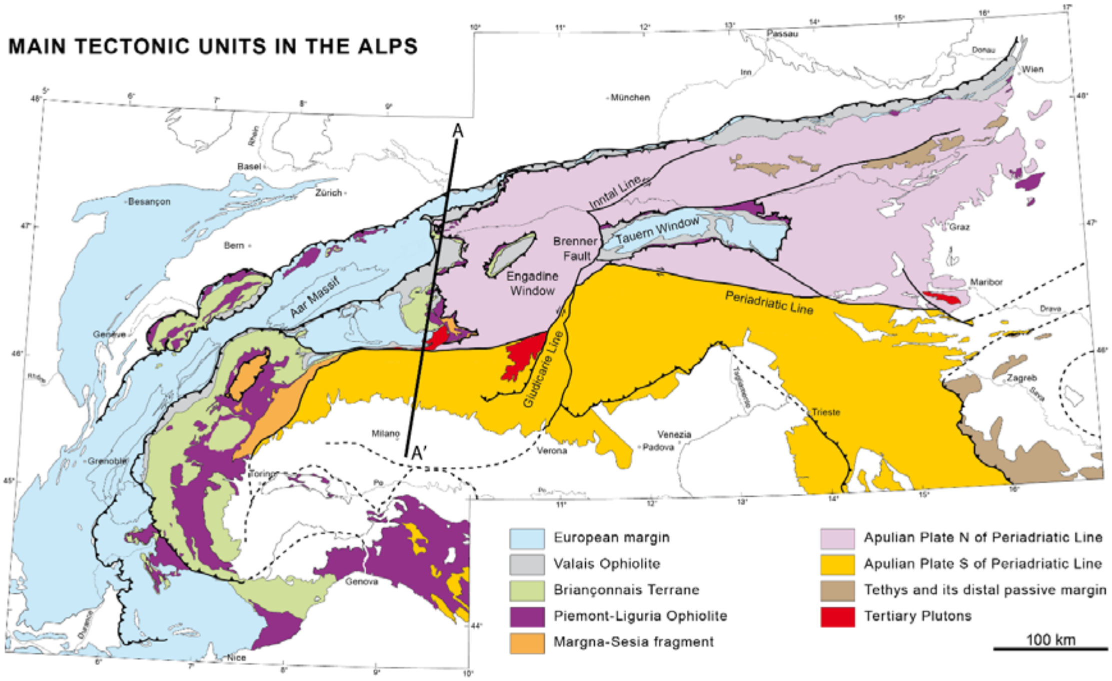


Fig. 1: a) Tectonic map of the Alps (modified after Schmid et al. 2004, 2009).

In this nappe stack, coherent allochthonous basement sheets such as the Leventina, Simano, Tambo and Suretta nappes of domain (iii) are accompanied by heterogeneous units such as the Adula-Cima Lunga nappe, the Gruf complex and the Bellinzona-Dascio units interpreted as parts of a ‘‘tectonic accretion channel’’ ((Engi et al. 2001). In the southernmost part of the Central Alps the entire nappe stack is bent from flat-lying to subvertical and even overturned southward into the so-called Southern Steep Belt. This belt contains the most convincing evidence of Alpine anatexis and intrusions. Pegmatite and aplite dykes, up to decameter-sized granitic bodies and in-situ migmatites are widespread along this E–W trending belt (e.g. Burri et al. 2005). To the south, the outhern Steep Belt is cut by the Insubric line, a major post-late Oligocene, ductile to brittle shear zone accommodating dextral transpression between the Adriatic and European plates (Schmid et al. 1989). The Insubric line is a ca. 1000 m thick fault zone with mylonites displaing complex movements between the Southern and the Central Alps. The latter are presently back-thrusted to the SE with a vertical component reaching 20 km in the Ticino area. Combined back-thrusting and strike-slip movements occurred between 35 and 20 Ma ago. Since then, dominantly dextral-slip took place along brittle faults (Schmid 1989).

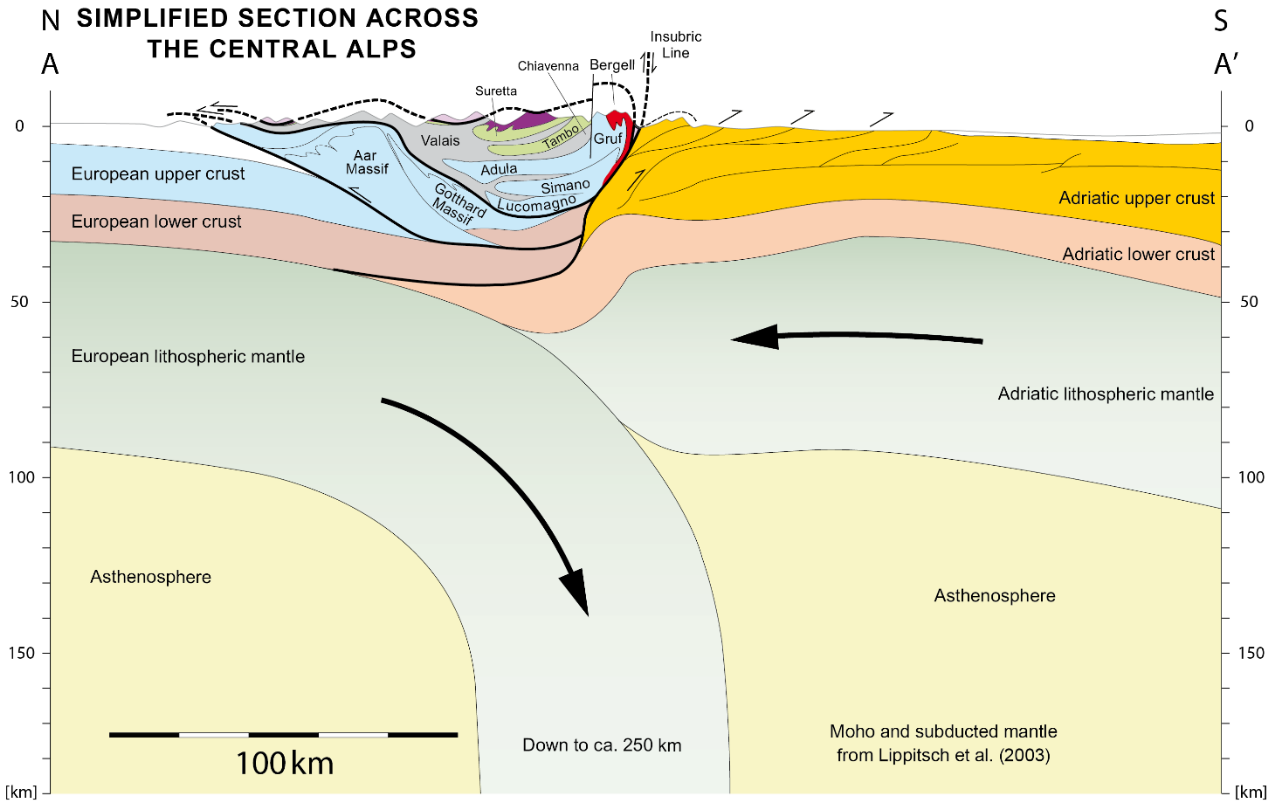


Fig. 1: b) simplified section across the Central Alps (modified after Pfiffner 2009 and Burg et al. 2002).

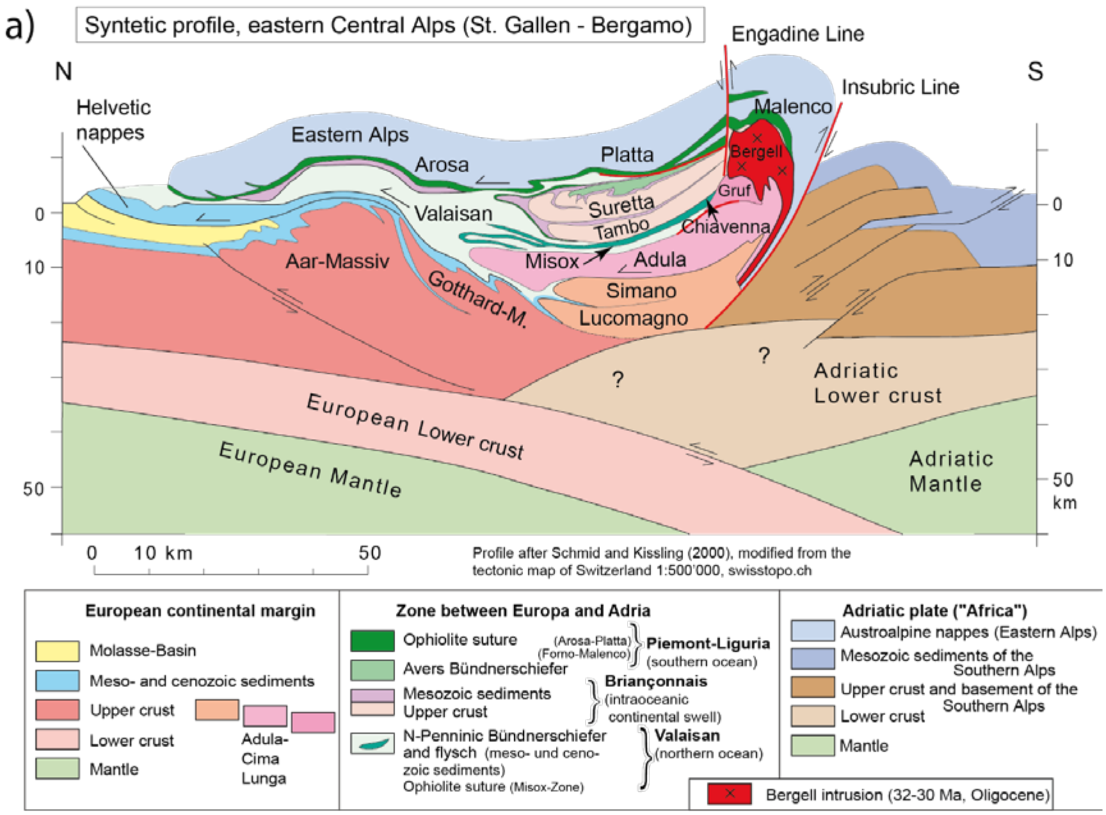


Fig. 2: a) Syntetic profile of the eastern central Alps (modified after Schmid and Kissling 2000)

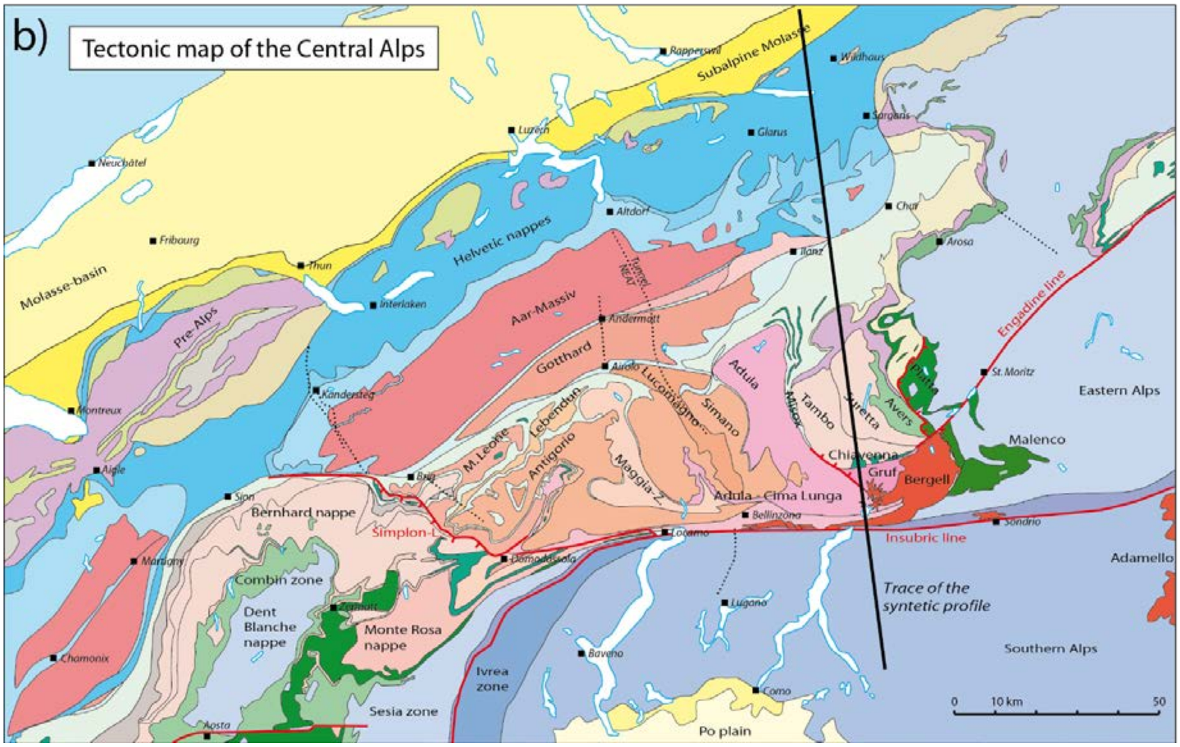


Fig. 2: b) tectonic map of the Central Alps (from many authors).

Metamorphic evolution of the Central Alps

The metamorphic pattern of the Central Alps is characterised by two major metamorphic events. An older low to medium-temperature, HP metamorphism is preserved as relics of blueschist- and eclogite-facies mineral assemblages in metasediments of domains (ii) and (iii) (Ring 1992; Baudin and Marquer 1993; Bousquet et al. 2002) and as eclogites of mainly metabasaltic and peridotitic composition in the Adula-Cima Lunga nappe (Heinrich 1986; Meyre et al. 1999; Nimis and Trommsdorff 2001; Dale and Holland 2003; Brouwer et al. 2005). This first metamorphic event is related to subduction and has been dated by Sm/Nd in garnet at 38-42 Ma (Becker 1993) and by SHRIMP on zircon at 35-43 Ma (Gebauer 1996). It was followed by a Barrow-type event, which strongly overprinted pre-existing mineral assemblages. Concentric isograds, isotherms and isobars (Fig. 2) define the ‘‘Lepontine Metamorphic Dome’’ (Wenk 1955; Todd and Engi 1997). This pattern cuts across nappe boundaries (Fig. 3), implying that the Barrow-type peak-metamorphic conditions were reached after nappe emplacement (Niggli and Niggli 1965; Wenk 1970; Trommsdorff 1966; Todd and Engi 1997). Barrow-type metamorphic conditions increase southwards from upper greenschist- to upper amphibolite-facies. In the southern central part, the metamorphic dome is characterized by migmatisation (Burri et al. 2005) that took place through fluid-assisted melting (Berger et al. 2008) at about 700 °C and 6-8 kbar (Burri et al. 2005; Galli et al. 2013) between 32 and 22 Ma (SHRIMP ages on zircon, Rubatto et al. 2009; Galli et al. 2012). Further to the south, the Lepontine dome is truncated by the Insubric line (Fig. 1 and 2). Instead, the Southern Alps recorded only low grade Alpine metamorphism.

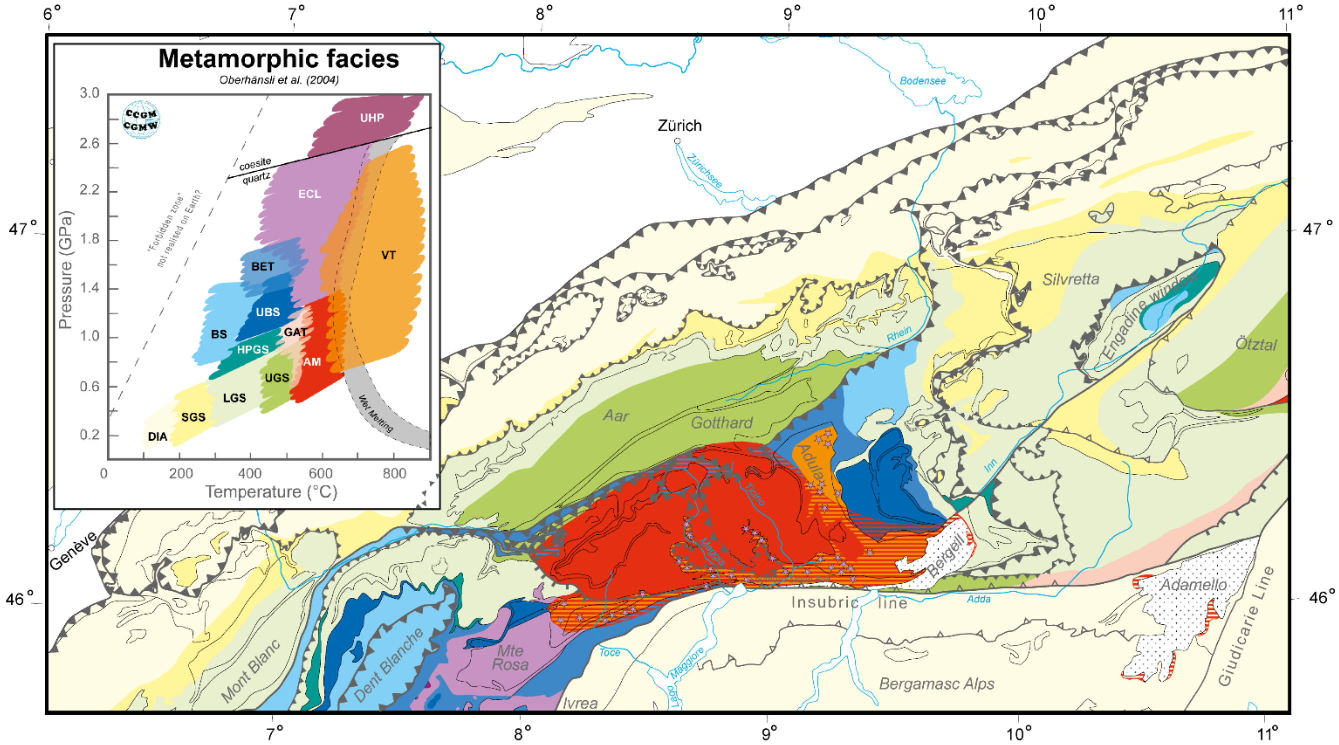
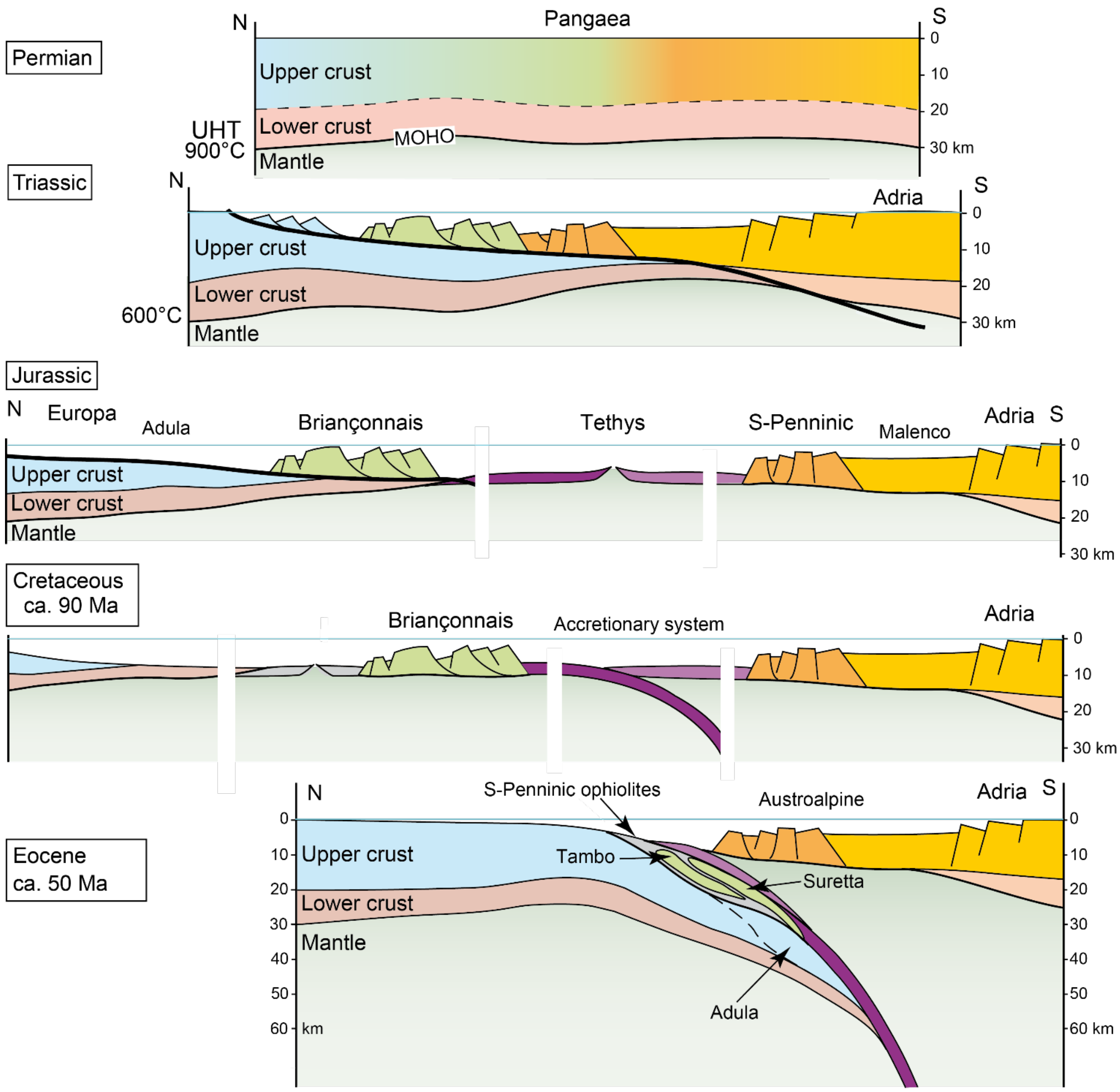


Fig. 3: Map of the metamorphic structure of the Alps (after Oberhänsli et al. 2004).

Tectonic interpretation

Spreading of the Piemont-Liguria, Tethys-related Ocean started in the Mid-Jurassic (oceanic crust covered by Jurassic, deep sea radiolarites), after Permian-Triassic crustal extension (Fig. 4); opening of the Valais oceanic zone may have been delayed until the Early Cretaceous (ca. 93 Ma old gabbros, Liati et al 2003). Both passive continental margins of Europa, to the north and Adria (a Gondwana-related subcontinent), to the south, had been teared up into several continental pieces. These crustal pieces or rafts (e.g. Briançonnais, Cervigna) are now stacked into the Helvetic nappes. They were possibly separated by seaways such as the Valais, which make the "ophiolitic" slices identified in the imbricate system. The start of tectonic inversion from spreading to convergence started is not clearly dated. Ca 100 Ma is an accepted figure, which is more or less the time when sinistral wrenching between "Gondwana" and "Eurasia" became almost head-on convergence (Savostin et al. 1986). Pieces of the margins were subducted to eclogites facies (13-27 kbar and 520-750 °C) at 90 Ma, as indicated by the Sm-Nd, Lu-Hf, U-Pb and Rb-Sr systems (review in Thöni 2006), while the nappe stack built up and evolved into the "subduction channel" until ca. 65 Ma (zircon SHRIMP age, Rubatto et al. 1999). South-dipping subduction closed all oceanic domains in the Paleogene or early Eocene times, full closure being achieved in the Eocene (45-40 Ma), when continental sedimentation started in the forelands (Kempf and Pross 2005). Continental collision generated the foreland-ward propagating thrust system sealed by the Barrovian isograds. A major orogenic event occurred at 35-30 Ma, with plutonism and exhumation of the deep rocks. This plutono-tectonic event is linked to slab break-off (Von Blanckenburg and Davies 1995), the isostatic consequences of which would have produced the highest Alps, with dramatic erosion witnessed in huge deltas with coarse conglomerates in the foreland (molasse) basin (Kempf and Pross 2005). Fission track ages indicate that low temperature conditions were passed by exposed rocks at about 15 Ma (review in Hansmann 1996). The Younger Jura Mountains are the outward propagating deformation front of the Alps.


Permian
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Lower crust
600°C
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Jurassic
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Europa
Adula
Briançonnais
Tethys
S-Penninic
Malenco
Adria
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Upper crust
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Mantle
Cretaceous
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Briançonnais
Accretionary system
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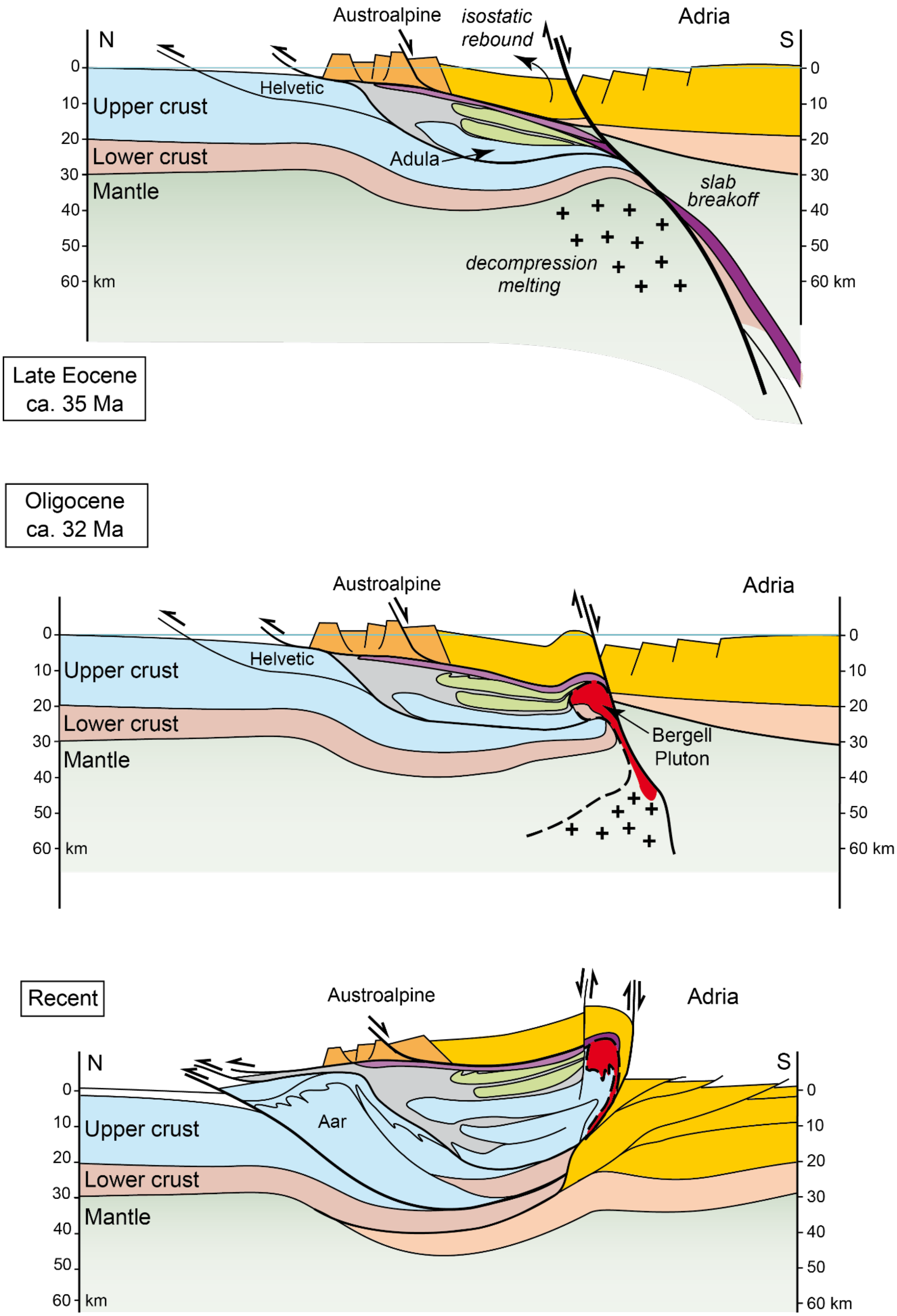

Fig. 4: Tectonic evolution of the Alps.

Excursion – Outcrop descriptions

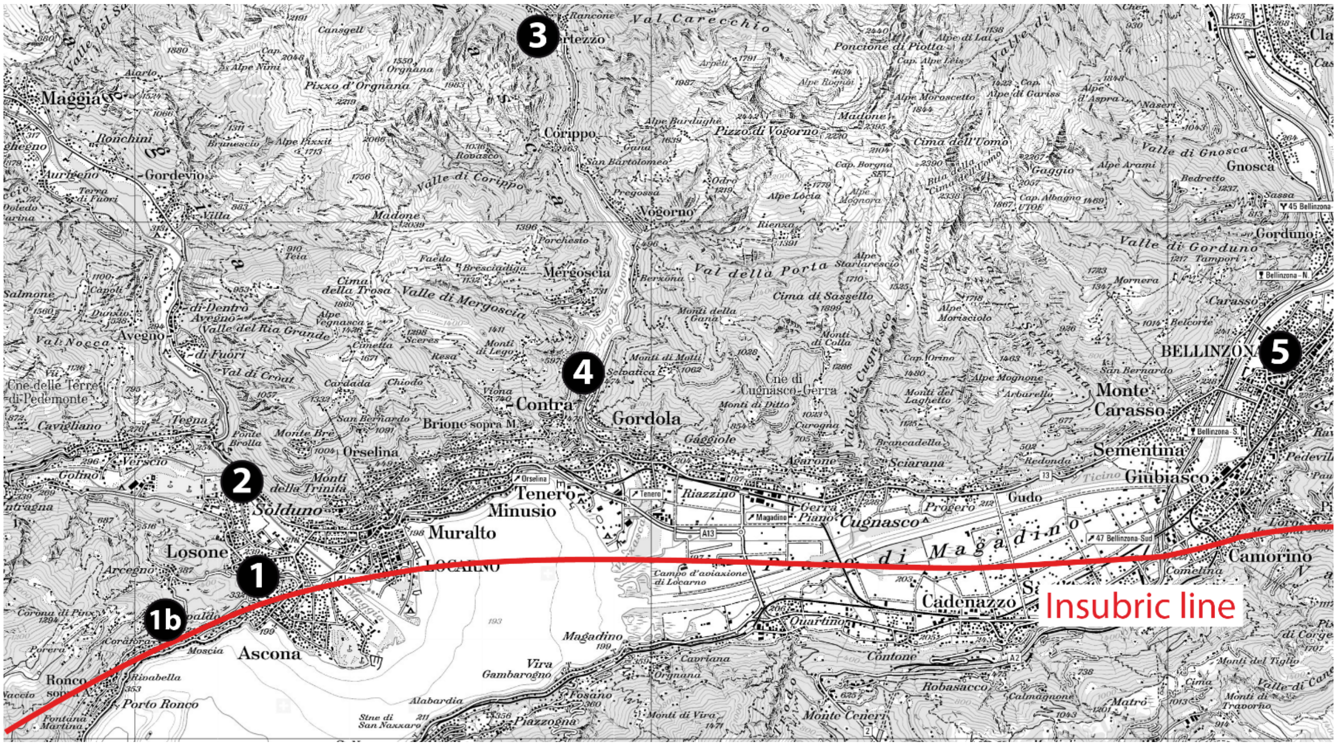

Fig. 5: Geographic map of the visited area with stop locations and position of the Insubric line (in red) as reference.

STOP 1: Monte Verità (46°09'28.1"N; 008°45'47.4"E, ca. 1 hour)

Rocks of the Southern Alpine Ivrea-Verbano zone (IVZ) are exposed close to the entrance of Monte Verità,
One can observe the contact between migmatitic paragneisses, micaschists and amphibole-rich rocks (Fig. 6a). Anatexis is Permian in age (ca. 270-295 Ma, SHRIMP ages on zircon, Vavra 1996). Migmatitic paragneisses and micaschists are characterized by milli- to centimetric, granoblastic bands and lenses of quartz, plagioclase ± alkali feldspar constituting a leucosome. Millimetric, melanocratic lepidoblastic bands consisting mainly of biotite, fibrolitic sillimanite, rare muscovite and garnet represent the residual melanosome to mesosome. Leucocratic and melanocratic bands are parallel to the main foliation. Few cm-sized pockets of leucosome cut across the main planar fabric.

STOP1B: 46°09'08.7"N; 008°44'35.2"E

In the north, the Mafic complex is composed of dark, foliated amphibolites, mostly constituted of hornblende and plagioclase. Amphibolites are locally garnet-rich (Fig. 6b). The contact between the mafic complex and the previously seen gneisses is defined by an up to 100 m thick zone, where meter-sized lenses of amphibolite occur within paragneisses and micaschists. Size and frequency of these lenses increases to the north towards the Mafic complex suggesting that the contact is magmatic.

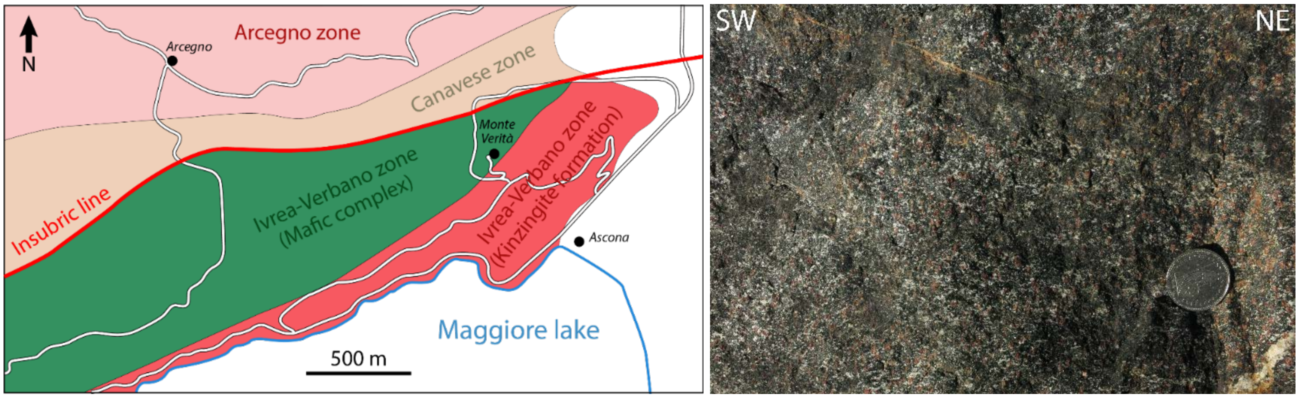

Fig. 6: Situation around Monte Verità (left, modified after Walter, 1950); Grt-rich amphibolite of the Mafic complex (right).

The geological interpretation of the IVZ involves underplating of voluminous, mantle-derived mafic magmas (Mafic complex) into the amphibolite- to granulite facies metamorphic basement of the Southern Alps (Kinzingite formation) in Permian time. The mafic-ultramafic Ivrea body is responsible for a large magnetic and high-velocity anomaly observed along the Western Alps from Locarno to Turin (Lanza 1982; Paul et al. 2001; Vernant et al. 2002). Gravity and seismic reflection data suggest that the IVZ dips steeply to the southeast near the surface but flattens into a sub-horizontal orientation at a depth of 20 to 30 km beneath the Po plain (Nicolas et al., 1990; also see Berckhemer, 1968).

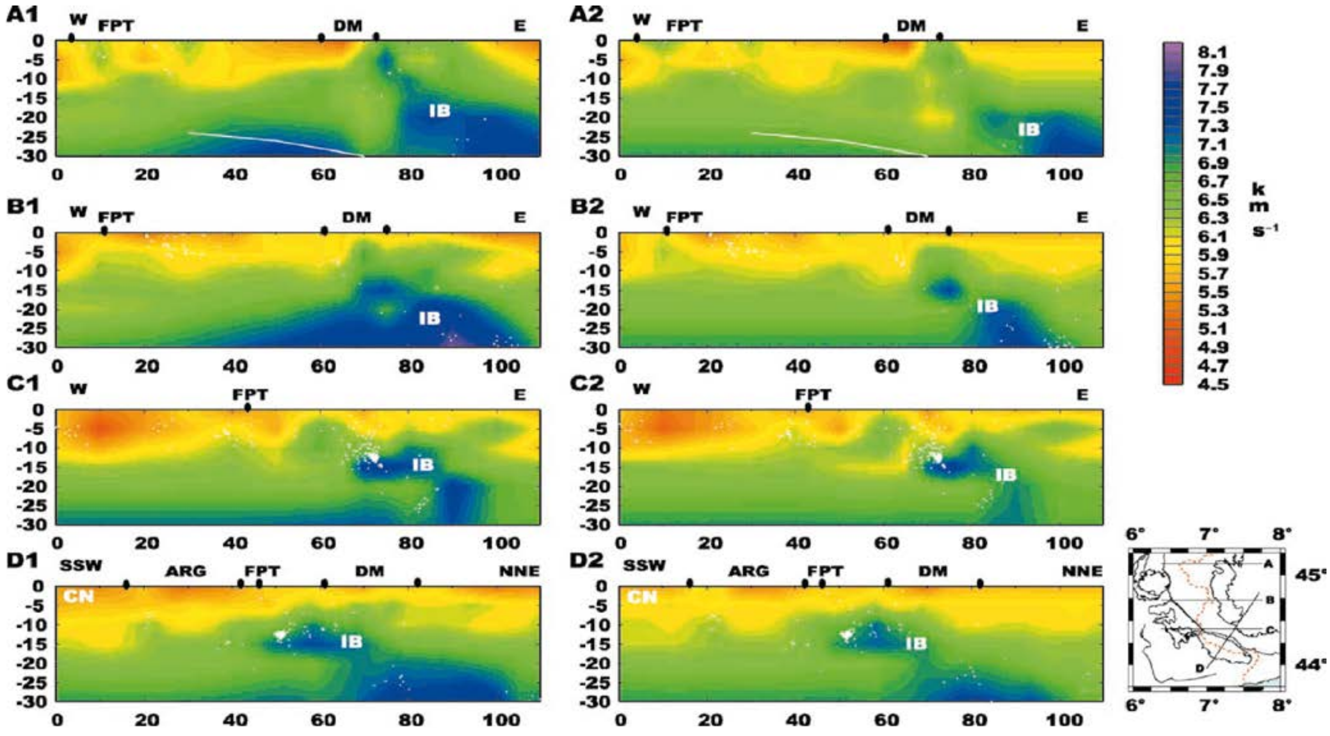

Fig. 7: Vertical cross-sections along lines A, B, C and D of the map. A1, B1, C1 and D1 correspond to the sequential model (gravity seismology) while A2, B2, C2 and D2 correspond to the LET model (seismology). The white line indicates the location of a deep reflector imaged by the ECORS-CROP wide-angle experiment. FPT, Frontal Penninic Thrust; DM, Dora Maira; ARG, Argentera; IB, Ivrea Body; CN, Castellane Nappe.

STOP 2: Maggia river by Tegna (46°10’40”N; 008°45’43.5”E, ca. $1^{1/2}$ hour)

We moved from the Southern Alps (Stop 1, Ivrea-Verbano zone) to the Central Alps.The Insubric line, which defines the contact between Southern and Central Alps (Fig. 1a), is located between the village of Arcegno and the town of Giubiasco, following the Magadino plain (Fig. 5). Along the Maggia river, a series of migmatitic orthogneisses and paragneisses allows discussing the relations between anatexis and deformation in the Southern Steep Belt. Anatexis to the north of the Insubric line is Alpine. Geochronological studies (U-Pb SHRIMP zircon ages) suggest that crustal melting was protracted between 32 and 22 Ma ago (Rubatto et al., 2009).

The rocks display a penetrative, steeply-dipping foliation (060-070/ca. 80N), characteristic for the general geometry of the Insubric line. Up to 50 cm thick, quartzo-feldspatic leucocratic bands interpreted as products of anatexis are common. Leucosomes are usually boudinaged, foliated, sheared or folded (Fig. 8). The main foliation is mostly a migmatitic banding. Late veins cutting across foliations attest for the syn-migmatitic character of the regional foliation. Anastomosing ductile shear zones are abundant. The typical S shape of the foliations on both sides of the planar mylonite zones indicates that the rock was still ductile at the time of dextral shearing, and mineral assemblages across such shear zones (e.g. recrystallised biotite, quartz and feldspars) document that shearing took place under upper amphibolite facies conditions. These shear zones are commonly accompanied and intruded by relatively less sheared leucosomes, indicating syn-migmatitic shearing in the presence of melt at around 650-700 °C and 6-8 kbar. The geometry of the ductile shear zones and the presence of asymmetric leucosome lenses indicate dextral sense of shear.

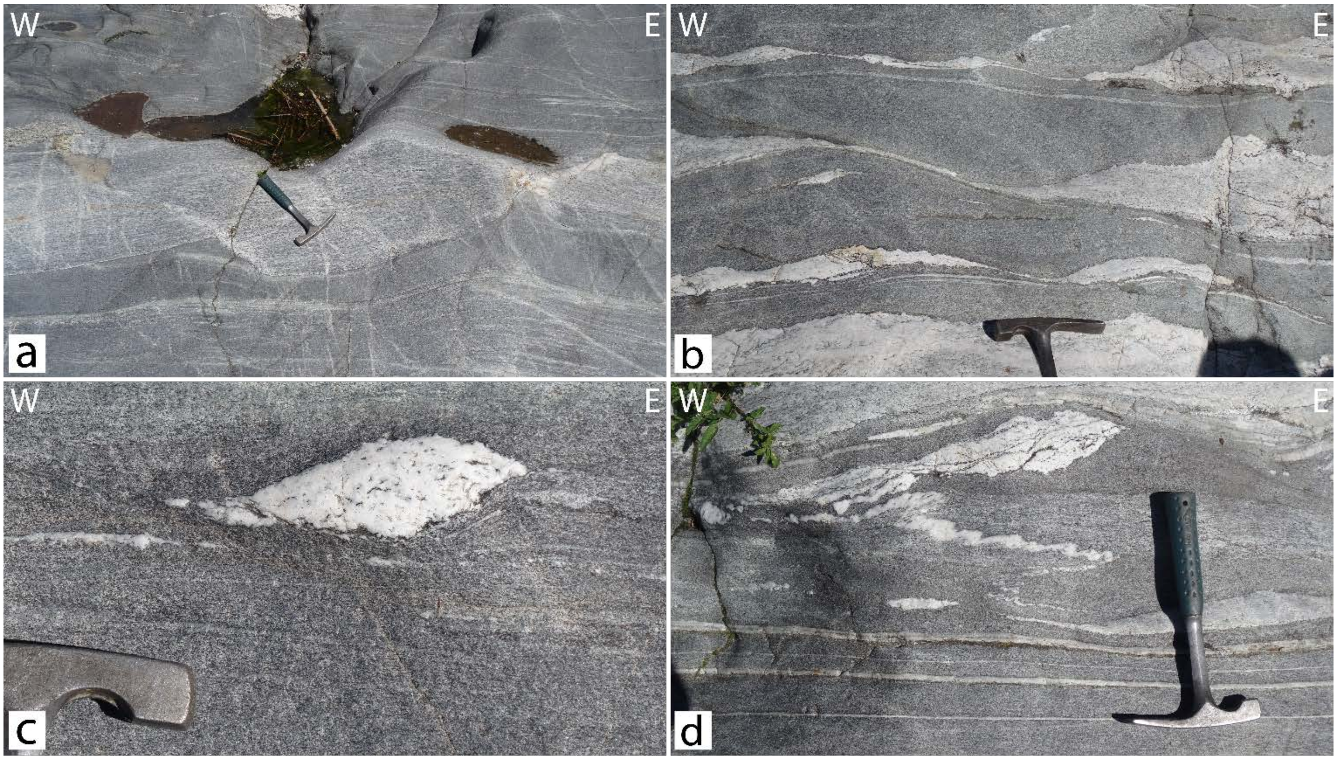

Fig. 8: a) Shear bands between boudins of orthogneisses; b) Melt-filled shear bands; c) Asymmetric melt pocket within partly molten paragneisses; d) Folded leucosomes within paragneisses.

STOP 3: Lavertezzo old bridge (46°15’35.6”N; 008°50’10.4”E, ca. $1^{1/2}$ hour)

Orthogneisses and biotite-garnet-kyanite-bearing paragneisses of the Simano nappe are exposed next to the medieval bridge of Lavertezzo (Fig. 9a). Orthogneiss intruded after the Variscan orogeny (ca. 305 Ma, U-Pb zircon LA-ICP-MS age, Bussien et al. 2011) into paragneisses. The original intrusive relationships are locally preserved (Fig. 9b). Ortho-and paragneisses have been strongly folded during the Alpine orogeny. The general geometry is characterized by a NW-SE striking, almost vertical main foliation and a sub-horizontal stretching lineation parallel to fold axes. If there are not too many tourists lying on the rocks, one may be able to observe lobate-cuspate structures indicative of contrasting viscosities across lithological boundaries, interference pattern between folds, ductile shear zones, S-Z-M vergence of secondary folds, boudinaged and folded pegmatite dykes dated at ca. 20 Ma (zircon age, Romer et al. 1996), en-échelon faults, metasomatic halos between chlorite veins and host gneisses and more.

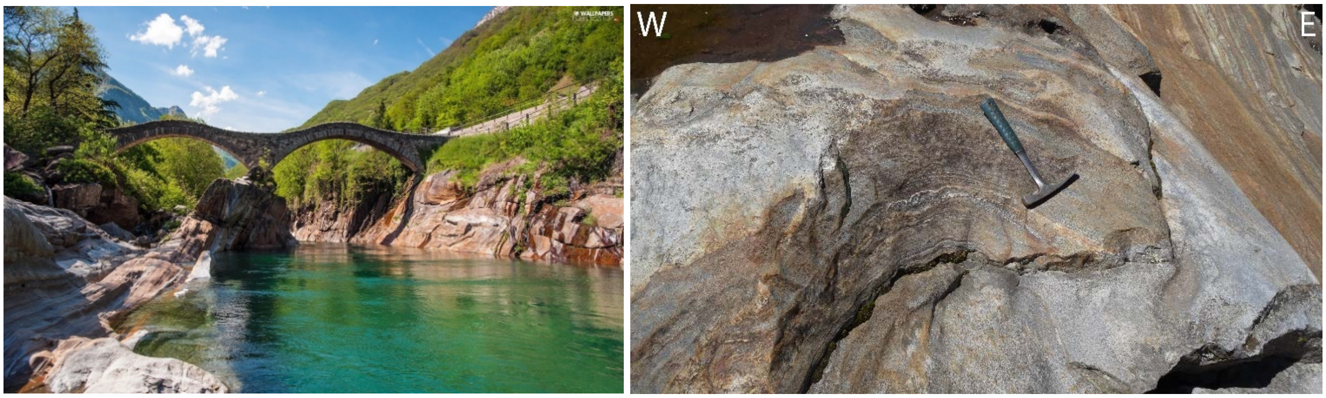

Fig. 9: Old bridge by Lavertezzo (left); intrusive relation between greyish orthogneiss and brownish paragneiss (right).

STOP 4: Verzasca “James Bond” dam (46°11’48”N; 008°50’50”E, ca. ½ hour)

Upper amphibolite facies paragneisses and marbles of the central Alpine Simano nappe are strongly folded about upright folds (Fig. 10). Fold axes plunge steeply to the north. Looking at the landscape northward, one can see that the main foliation progressively changes orientations from steeply dipping to almost horizontal. This is the large flexure that characterizes the general cross section (Fig. 1b).

Technical data:	constructed between 1961 and 1965 production per year: 227 * 10^6 kWh height: 220 m (4th highest in Switzerland) lengths: 380 m volume of concrete: 660’000 m^3
Verzasca lake:	maximal filling: 105 * 10^6 m^3 (9th biggest in Switzerland) surface: 168 ha length: ca. 5.5 km catchment area: 233 km^2

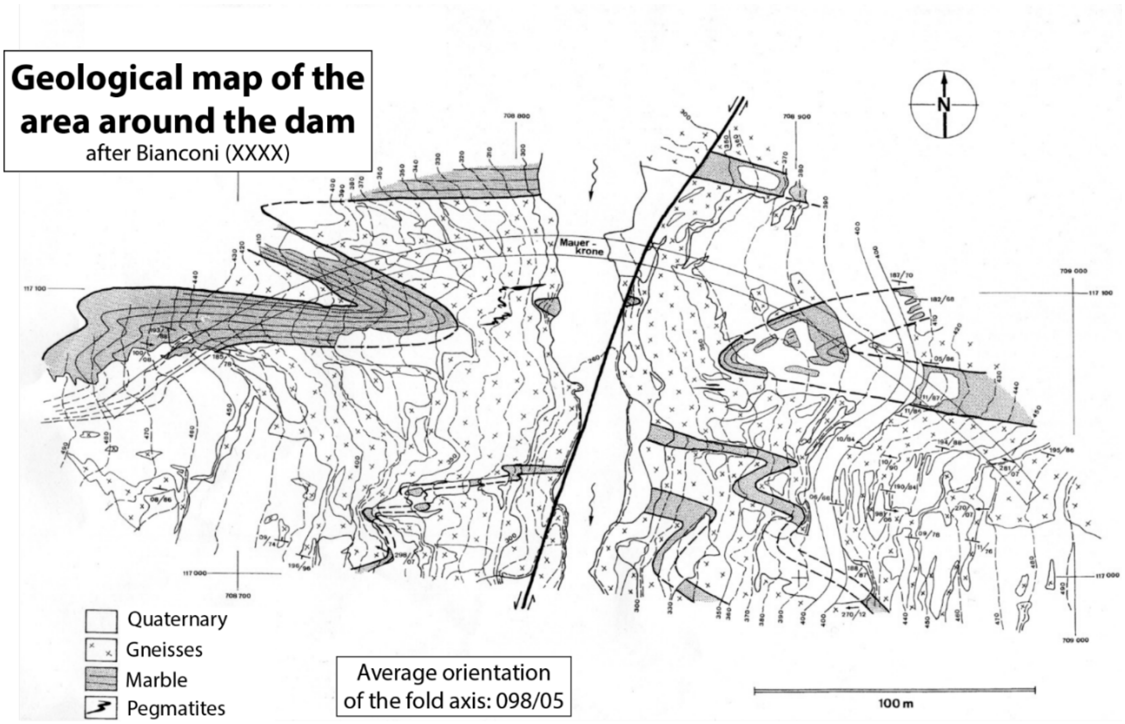

Fig. 10: Geological map around the Verzasca dam (after Bianconi, 1971).

STOP 5: Bellinzona castle (Castello di Monte Bello) (46°11’29”N; 009°01’36”, ca. ½ hour)

The main castle of Bellinzona (Fig. 11) was built on a series of partly molten quartzo-feldspathic orthogneisses and biotite-garnet-bearing paragneisses of the Southern Steep Belt. The rocks display a penetrative foliation and gneissic banding steeply dipping to the north. Generally, quartz-feldspars-rich leucosomes and biotite-rich melanosomes are parallel to the main fabric (Fig. 11). Locally, melt-filled shear zones and centimeter-sized melt pockets and bands cut across the main foliation suggesting syn- to post-tectonic anatexis and indicating that deformation ceased while melt was still present in the system. U-Pb SHRIMP ages on zircon grains separated from leucosomes parallel to the main foliation and leucosomes intruding the planes of shearing yielded 23-31 Ma, suggesting a protracted melting event (Rubatto et al. 2009).

Fig. 11: Steeply dipping, migmatitic, quartzo-feldspathic orthogneisses of the Southern Steep Belt (left) close to the Bellinzona castle (right).

LIST OF REFERENCES

Baudin, T., Marquer, D. (1993). Metamorphism and deformation in the Tambo nappe (Swiss Central Alps): evolution of the phengite substitution during Alpine deformation. Schweizerische Mineralogische und Petrographische Mitteilungen, 73, 285–299.

Becker, H. (1993). Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine some (Swiss Alps): New evidence for Eocene high-pressure metamorphism in the central Alps. Geology, 21, 599–602.

Berckhemer, H. (1968). Topographie des Ivrea Körpers abgeleitet aus seismischen und gravimetrischen Daten. Schweizerische Mineralogische und Petrographische Mitteilungen, 48, 235–246.

Berger, A., Mercolli, I., Engi, M. (2005). The central Lepontine Alps: explanatory notes accompanying the tectonic-geological map sheet Sopra Ceneri (1:1000000). Schweizerische Mineralogische und Petrographische Mitteilungen, 85, 109–146.

Berger, A., Burri, T., Alt-Epping, P., Engi, M. (2008). Tectonically controlled fluid flow and water-assisted melting in the middle crust: an example from the Central Alps. Lithos, 102, 598–615.

Bianconi, F. (1971). Geologia e petrografia della regiona del Campolungo. Beiträge zur Geologischen Karte der Schweiz, vol. 142, Kümmerly and Frey, Bern.

Bousquet, R., Goffé, B., Vidal, O., Oberhänsli, R., Patriat, M. (2002). The tectono-metamorphic history of the Valaisan domain from the western to the Central Alps: new constraints on the evolution of the Alps. Geological Society of America Bulletin, 114, 207–225.

Brouwer, F. M., Burri, T., Engi, M., Berger, A. (2005). Eclogite relics in the Central Alps: PT-evolution, Lu-Hf ages and implications for formation of tectonic mélange zones. Schweizerische Mineralogische und Petrographische Mitteilungen, 85, 147–174.

Burg, J.-P., Sokoutis, D., Bonini, M. (2002). Model-inspired interpretation of seismic stzructures in the Central Alps: Crustal wedging and buckling at mature stage of collision. Geology, 30, 643–646.

Burri, T., Berger, A., Engi, M. (2005). Tertiary migmatites in the Central Alps: regional distribution, field relations, conditions of formation, and tectonic implications. Schweizerische Mineralogische und Petrographische Mitteilungen, 85, 215–232.

Bussien, D., Bussy, F., Magna, T., Masson, H. (2011). Timing of Paleozoic magmatism in the Maggia and Sambuco nappes and paleogeographic implications (Central Lepontine Alps). Swiss Journal of Geosciences, 104, 1–29.

Dale, J., Holland, T. J. B. (2003). Geothermobarometry, P-T paths and metamorphic field gradients of high-pressure rocks from the Adula nappe, Central Alps. Journal of Metamorphic Geology, 21, 813–829.

Engi, M., Berger, A., Roselle, G. (2001). The role of the tectonic accretion channel in collisional orogeny. Geology, 29, 1143–1146.

Galli, A., Le Bayon, B., Schmidt, M.W., Burg, J.P., Reusser, E., Sergeev, S.A., & Larionov, A. (2012). U-Pb zircon dating of the Gruf Complex: disclosing the late Variscan granulitic lower crust of Europe stranded in the Central Alps. Contributions to Mineralogy and Petrology, 163(2), 353–378.

Galli, A., Le Bayon, B., Schmidt, M.W., Burg, J.P., Reusser, E. (2013). Tectonometamorphic history of the Gruf complex (Central Alps): exhumation of a granulite–migmatite complex with the Bergell pluton. Swiss Journal of Geosciences, 106, 33–62.

Gebauer, D. (1996). A P-T-t path for an (ultra?-) high-pressure ultramafic/mafic rock-association and its felsic country-rocks based on SHRIMP-dating of magmatic and metamorphic zircon domains. Example: Alpe Arami (Central Swiss Alps). In: Basu, A., Hart, S. (eds): Earth processes: Reading the isotopic code, Geophysical Monograph, 95, American Geophysical Union, Washington, 307–330.

Handy, M. R., Herwegh, M., Regli, C. (1993). Tektonische Entwicklung der westlichen Zone von Samedan (Oberhalbstein, Graubünden, Schweiz). Eclogae Geologicae Helvetiae, 86, 785–817.

Heinrich, C. A. (1986). Eclogite facies regional metamorphism of hydrous mafic rocks in the Central Aline Adula nappe. Journal of Petrology, 27, 123–154.

Kempf, O., Pross, J. (2005). The Lower Marine to Lower Freshwater Molasse transition in the northern Alpine foreland basin (Oligocene; central Switzerland-south Germany): age and geodynamic implications. International Journal of Earth Sciences, 94, 160–171.

Lanza, R. (1982). Models for interpretation of the magnetic anomaly of the Ivrea body. Géologie Alpine, 58, 85–94.

Liati, A., Gebauer, D., Fanning, C.M. (2003). The youngest basic oceanic magmatism in the Alps (Late Cretaceous; Chiavenna unit, Central Alps): geochronological constraints and geodynamic significance. Contributions to Mineralogy and Petrology, 146, 144–158.

Lippitsch, R., Kissling, E. Ansorge, J. (2003). Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. Journal of Geophysical research, 108, ESE 5 1–15.

Merle, O., Cobbold, P.R., Schmid, S.M. (1989). Tertiary kinematics in the Lepontine dome. In: Alpine Tectonics (eds. Coward, M.P., Dietrich, D. and Park, R.G.). Geol. Soc. Spec. Publ. Nr. 45, 113–134.

Meyre, C., De Capitani, C., Zack, T., Frey, M. (1999). Petrology of high-pressure metapelites from the Adula nappe (Central Alps, Switzerland). Journal of Petrology, 40, 199–213.

Milnes, A.G., Pfiffner, A.O. (1980). Tectonic evolution of the Central Alps in the cross section St. Gallen-Como. Eclogae Geologicae Helvetiae, 73, 619–633.

Nicolas, A., Hirn, A., Nicolich, R., Polino, R., ECORS-CROP Working Group (1990). Lithospheric wedging in the Western Alps inferred from the ECORS-CROP traverse. Geology, 18, 587–590.

Niggli, E., Niggli, C. (1965). Karten der Verbreitung einiger Mineralien der alpidischen Metamorphose in den Schweizer Alpen (Stilpnomelan, Alkali-Amphibol, Chloritoid, Staurolith, Disthen, Sillimanit). Eclogae Geologicae Helvetiae, 58, 335–368.

Nimis, P., Trommsdorff, V. (2001). Revised Thermobarometry of Alpe Arami and other Garnet Peridotites from the Central Alps. Journal of Petrology, 42, 103–115.

Oberhänsli, R., Bousquet, R., Engi, M. et al. (2004). Metamorphic structure of the Alps. In: Explanatory note to the map “Metamorphic structure of the Alps”. Commission for the Geological Map of the World, Paris.

Paul, A., Cattaneo, M., Thouvenot, F., Spallarossa, D., Béthoux, N., Fréchet, J. (2001). A three-dimensional crustal velocity model of the southwestern Alps from local earthquake tomography. Journal of geophysical Research, 106, 19367–19389.

Pfiffner, A.O. (2009). Geologie der Alpen. Haupt UTB editions.

Ring, U. (1992). The Alpine geodynamic evolution of Penninic nappes in the eastern Central Alps: geothermobarometric and kinematic data. Journal of Metamorphic Geology, 10, 33–53.

Romer, R.L., Schärer, U., Steck, A. (1996): Alpine and pre-Alpine magmatism in the root-zone of the western Central Alps. Contributions to Mineralogy and Petrology, 123, 138–158.

Rubatto D, Gebauer D, Compagnoni R (1999). Dating of eclogite facies zircons: the age of Alpine metamorphism in the Sesia-Lanzo Zone (Western Alps). Earth Planet Sciences Letters, 167, 141–158.

Rubatto, D., Hermann, J., Berger, A., Engi, M. (2009). Protracted fluid-present melting during Barrovian metamorphism in the Central Alps. Contributions to Mineralogy and Petrology, 158(6), 703–722.

Savostin, L.A., Sibuet, J.C., Zonenshain, L.P., Le Pichon, X., Roulet, M.J. (1986). Kinematic evolution of Tethys belt from the Adriatic Ocean to the Pamirs since the Triassic. Tctonophysics, 123, 1–35.

Schmid, S.M., Aebli, H.R., Heller, F., Zingg, A. (1989). The role of the Periadriatic line in the tectonic evolution of the Alps. In: D. Dietrich and M.D. Coward (Eds.), Alpine Tectonics, vol. 45 (pp. 153–171). London: Geological Society of London Special Publications.

Schmid, S. M., Rück, P., and Schreurs, G. (1990). The significance of the Schams nappe for the reconstruction of the paleotectonic and orogenic evolution of the Penninic zone along the NFP 20 East Traverse. In A. Pfiffner and P. Heitzmann (Eds.), Deep structure of the Alps—results from NFP/PNR 20 (pp. 263–287). Basel: Birkhäuder.

Schmid, S. M., Berger, A., Davidson, C., Gieré, R., Hermann, J., Nievergelt, P., et al. (1996). The Bergell pluton (Southern Switzerland, Northern Italy): overview accompanying a geological-tectonic map of the intrusion and surrounding country rocks. Schweizerische Mineralogische und Petrographische Mitteilungen, 76, 329–355.

Schmid, S.M., Kissling, E. (2000). The arc of the Western Alps in the light of geophysical data on deep crustal structure. Tectonics, 19, 62–85.

Schmid, S.M., Fugenschuh, B., Kissling, E., Schuster, R. (2004). Tectonic map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae. 97, 93–117.

Staub, R. (1946). Geologische Karte der Berninagruppe und ihrer Umgebung im Oberengadin, Bergell, Val Malenco, Puschlav und Livigno, 1:500000. Geologische Spezialkarte 118, Schweizerische Geologische Kommission.

Steinmann, M., and Stille, P. (1999). Geochemical evidence for the nature of the crust beneath the eastern north Penninic basin of the Mesozoic Tethys Ocean. Geologische Rundschau, 87, 633–643.

Todd, C. S., Engi, M. (1997). Metamorphic field gradients in the Central Alps. Journal of Metamorphic Geology, 15, 513–530.

Trommsdorff, V. (1966). Progressive Metamorphose kieseliger Karbonatgesteine in den Zentralalpen zwischen Bernina und Simplon. Schweizerische Mineralogische und Petrographische Mitteilungen, 46, 431–460.

Trommsdorff, V. (1990). Metamorphism and tectonics in the Central Alps: the Alpine lithospheric mélange of Cima Lunga and Adula. Memorie della Società Geologica Italiana, 45, 39–49.

Trümpy, R. (1960). Paleotectonic evolution of the central and western Alps. Bulletin of the Geological Society of America, 71, 1–104.

Vavra, G., Gebauer, D., Schmid, R., Compston, W. (1996). Multiple zircon growth and recrystallization during polyphase Late Carboniferous to Triassic metamorphism in granulites of the Ivrea Zone (Southern Alps): an ion microprobe (SHRIMP) study. Contributions to Mineralogy and Petrology, 122, 337–358.

Von Blanckenburg, F., J. H. Davies (1995). Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps, Tectonics, 14, 120–131.

Walter, P. (1950). Das Ostende des basischen Gesteinszuges Ivrea-Verbano und die angrenzenden Teile der Tessiner Wurzelzone. Schweizerische Mineralogische und Petrographische Mitteilungen, 30, 1–144.

Wenk, E. (1955). Eine Strukturkarte der Tessiner Alpen. Schweizerische Mineralogische und Petrographische Mitteilungen, 35, 311–319.

Wenk, H.-R. (1970). Zur Regionalmetamorphose und Ultrametamorphose der Zentralalpen. Fortschritte der Mineralogie, 47, 34–51.