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Autor: Schmid, Stefan M.

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On the Insubric line and the Southern Steep Belt of the Penninic nappes in the Ticino area (including 2 excursion guides)

Stefan M. Schmid[1]

Abstract
The Insubric line is part of the Periadriatic line, representing the most prominent lineament of the Alpine chain, formed during the latest stages of orogeny in Oligocene to Miocene times. It divides the Southern Alp from the main body of the Alps and accommodates dextral strike slip movements, as well as major backthrusting along its western segment, the Insubric line. Displacements across the Insubric «line», in fact a 1 km thick mylonite belt, occurred after nappe stacking. The vertical component of offset of the Central Alps in respect to the Southern Alps in Oligocene times caused by backthrusting amounts to some 20 km displacement and is intimately linked to backfolding of the previously formed Penninic nappe stack in the adjacent Lepontine dome. Backfolding led to the steepening of the rearward parts of the Penninic nappe pile that became intensely attenuated, folded and tilted into an overturned orientation under amphibolite facies conditions in Oligocene times. This led to the formation of the Southern Steep Belt.

1 Institut für Geophysik Sonneggstrasse 5 8092 Zürich

1 Preface

This paper summarizes a talk by the author presented at the 2017 Annual Convention of the Swiss Association of Energy Geoscientists held at the Monte Verità in Ascona. It also offers a guide for two excursions actually held at this convention. A first one focuses on the Insubric line and adjacent units in the Arcegno area (chapter 6); a second one visits the Southern Steep Belt in the Penninic nappes in Valle Verzasca (chapter 8). The remainder of the text puts the areas visited by the excursions into a large-scale context, starting at the very large scale and progressively focusing on the areas actually visited.

2 The Insubric line at the scale of the Alpine orogeny

The Insubric line is a segment of the much longer Periadriatic line (Angenheister et al. 1972) that extends over at least 700 km all the way to Hungary (Fig. 1). The Periadriatic line (or lineament) divides the west to north verging nappe pile of the main body of the Alps to the north from the south verging Southern Alps over most of its distance; in Slovenia it roughly follows the limit between Alps and Dinarides. Over its entire distance it accommodates very substantial amounts of dextral strike slip movements: more than 100 km in the west, some 500 km in the east. The Periadriatic line is associated with other Cenozoic faults, some of them (e.g. Simplon line and the Brenner line) representing orogen-perpendicular normal faults.
The curved Canavese line follows the inner

arc of the Western Alps, reaching the east-west-running Tonale line at around Locarno. Together the two segments are referred to as Insubric line (Gansser 1968). At Locarno the Centovalli line with its minor dextral offset, but with a strong cataclastic overprint, joins the Tonale line. As is evident from Fig. 1, the Giudicarie line sinistrally offsets the Insubric line by some 80 km in respect to its eastern counterpart, the Pustertal line. This offset was caused by the north-directed indentation of the eastern part of the Southern Alps (Dolomites Indenter; Fig. 1) after some 22 Ma ago (Scharf et al. 2013), associated with very significant E-W extension in the Eastern Alps north of the Periadriatic line («lateral extrusion» of Ratschbacher et al. 1991) and in the Pannonian basin in Hungary. Miocene extension of the northerly adjacent Eastern Alps in respect to the southerly adjacent non-extending Southern Alps is responsible for the eastward increasing amount of dextral strike slip displacement along the Periadriatic Line. The offset caused by the Giudicarie line also shows that the displacements along the Insubric line must be older and pre-date indentation starting at 22 Ma ago; displacements along the Insubric line are essentially (apart the brittle overprint along the Centovalli and Tonale lines) of Oligocene age.

3 Insubric line, Southern Steep Belt and arc of the Western Alps

The Canavese line forms the boundary between the NNE-SSW striking Ivrea Zone

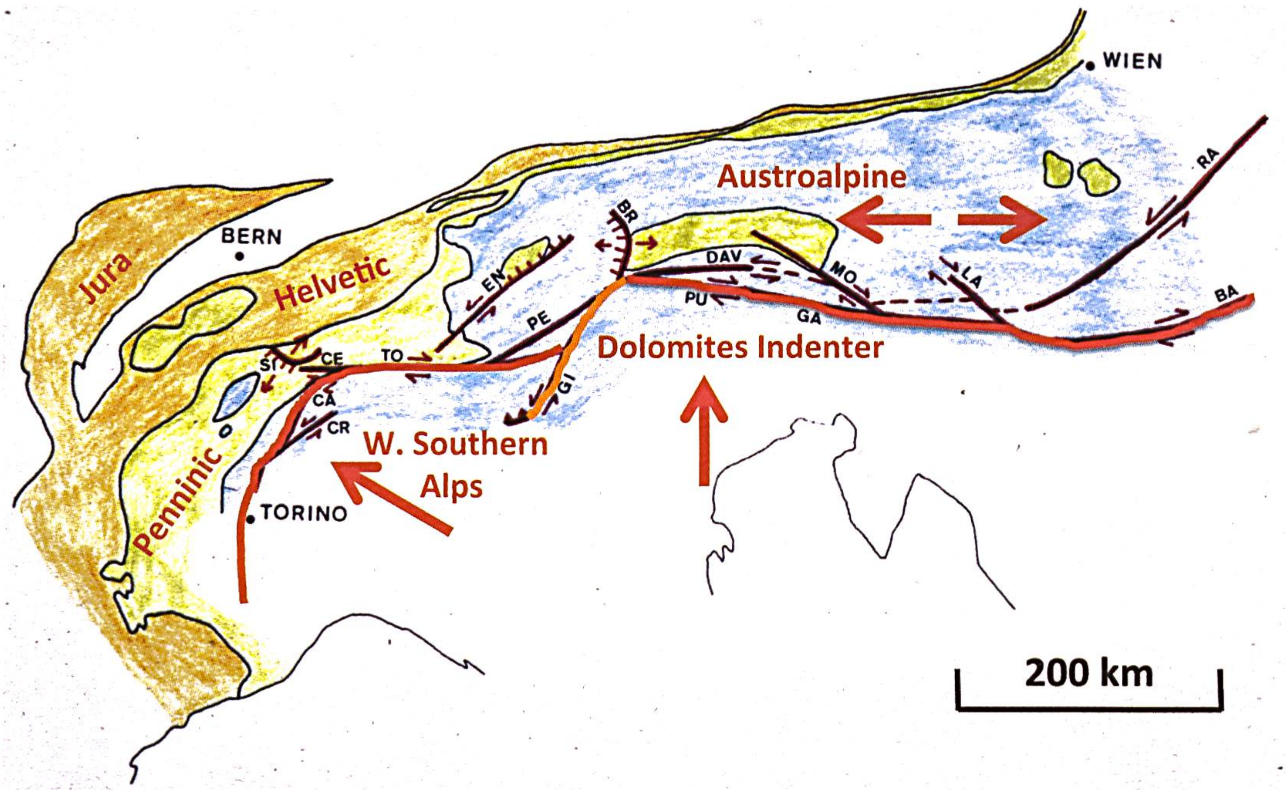


Fig. 1: The Canavese (CA) and Tonale lines (TO) constitute the Insubric line and formed at around 32-20 Ma during the WNW indentation of the western Southern Alps, including the Ivrea Zone (red arrow). They are part of the Periadriatic line that extends further to the east. At around 22 Ma the Periadriatic line became offset by the Giudicarie line (GI, marked in orange) as the dolomites indenter moved northward. At this time its former eastern segments, the Pustertal (PU), Gailtal (GA) and Balaton (BA) lines represented the southern boundary along which the Eastern Alps extended (opposite facing red arrows) and laterally extruded towards the east. Interfering lines of similar age are the Simplon (SI), Centovalli (CE), Cremosina (CR), (Engadine (EN), Pejo (PE), Brenner (BR), Defereggen-Anterselva-Vals (DAV), Mölltal (MO), Lavanttal (LA) and Raba (RA) lines. Figure modified after Schmid et al. (1989).

that is part of the Southern Alps and the Sesia Zone that is part of the Central Alpine nappe stack (Fig. 2a). As the Ivrea Zone wedges out near Locarno, the Insubric line swings into the E-W-strike characteristic for the Tonale line. Geometrically, Canavese line and Ivrea Zone form the backbone of the arc of the Western Alps (Schmid et al. 2017).

Apart from defining the boundary between Southern and Central Alps, the Insubric line also forms a marked limit concerning grade of metamorphism; metamorphic overprint is essentially restricted to the areas north and west of the Insubric line (Fig. 3). In the Western Alps the metamorphic overprint is pressure dominated and of Paleocene to Eocene age (blueschists and eclogites). The Lepontine dome located in the Central Alps north of Locarno, however, is affected by temperature-dominated metamorphism of amphibolite grade, initiating at around 30 Ma ago and seen to overprint an older pressure-dominated metamorphic event (Berger et al. 2011). The abrupt juxtaposition of amphibolite grade rocks, locally undergoing anatectic melting (temperatures > 650 °C), with the non-metamorphic Southern Alps (temperatures < 250 °C) in the area around Locarno demonstrates that the displacements that took place across the Insubric line also involve a substantial vertical component, vertical N-side up displacements being responsible for the exhumation of the Lepontine dome.

The Ivrea Zone that is adjacent to the Canavese line is famous for exposing a section across the lower crust of the Southern Alps (e.g. Handy et al. 1999). In places the Ivrea zone is rimmed by mantle rocks at its NW margin. As seen from the profile of Fig. 2b Ivrea mantle rocks (peridotites) form huge volumes of dense material in the subsurface known for causing a strong positive gravity anomaly and also known for high p-wave velocities (volumes often referred to as «Ivrea body»).

Paleogeographically the Ivrea Zone was located at the distal passive continental margin of the Apulian microplate, near the transition into the Piemont-Liguria Ocean (now incorporated in the Central Alpine nappe system). Substantial exhumation of the lower crust of the Ivrea zone, inducing cooling below 300°C, was caused by crustal thinning during the Early Mesozoic giving birth to the Alpine Tethys. Hence, Late Oligocene to Miocene Alpine deformations («Insubric phase», contemporaneous with faulting across the Insubric mylonite belt) affected these lower crustal rocks at moderate temperatures (i.e. below 300°C). Given the fact that a large portion of the Ivrea Zone is made up of flow-resistant quartz-free lithologies, deformed at temperatures below 300°C during Alpine orogeny (mafics, ultramafics), it is not surprising that the Ivrea zone (1) acts as an essentially rigid indenter (see profile Fig. 2b), controlling the shape of the internal part of the arc of the Western Alps (Fig. 2a), and, (2) that there is a very abrupt transition from pre-Alpine fabrics preserved in the Ivrea rocks into Alpine-age quartz-bearing and extremely ductile greenschist facies mylonites of the Insubric mylonite belt described later in more detail.

The Central Alpine nappe pile north of the Insubric Line around Locarno is characterized by a belt of steeply north-dipping and overturned gneisses that define the Southern Steep Belt of the Alps classically referred to as the «root zone» of the Penninic and Austroalpine nappes (Fig. 2b). As first pointed out by Milnes (1974) the development of this «root zone» is not genetically related to the development of the nappe structures but rather the result of backfolding that post-dates nappe formation. The schematic profile of Fig. 2b shows a major almost isoclinal backfold located immediately north of the Insubric line that brings the southwards progressively thinned nappe stack into a steeply overturned orientation. Such backfolds are typical for the entire area north of the Insubric line, from the Monte Rosa nappe in the west all the way to the area of the Valposchiavo in the east. Based on geophysical evidence it is clear that the real «root» of these nappes is to be found below the mantle rocks that constitute the Ivrea geophysical anomaly (Fig. 2b). Some 10 km north of the Insubric line the nappe contacts swing into a flat lying orientation before a second backfold, associated with the formation of the Northern Steep Belt, affects the northern most parts of the Penninic nappe stack, including the Gotthard massif (Fig. 2b). The real root of the Helvetic nappe

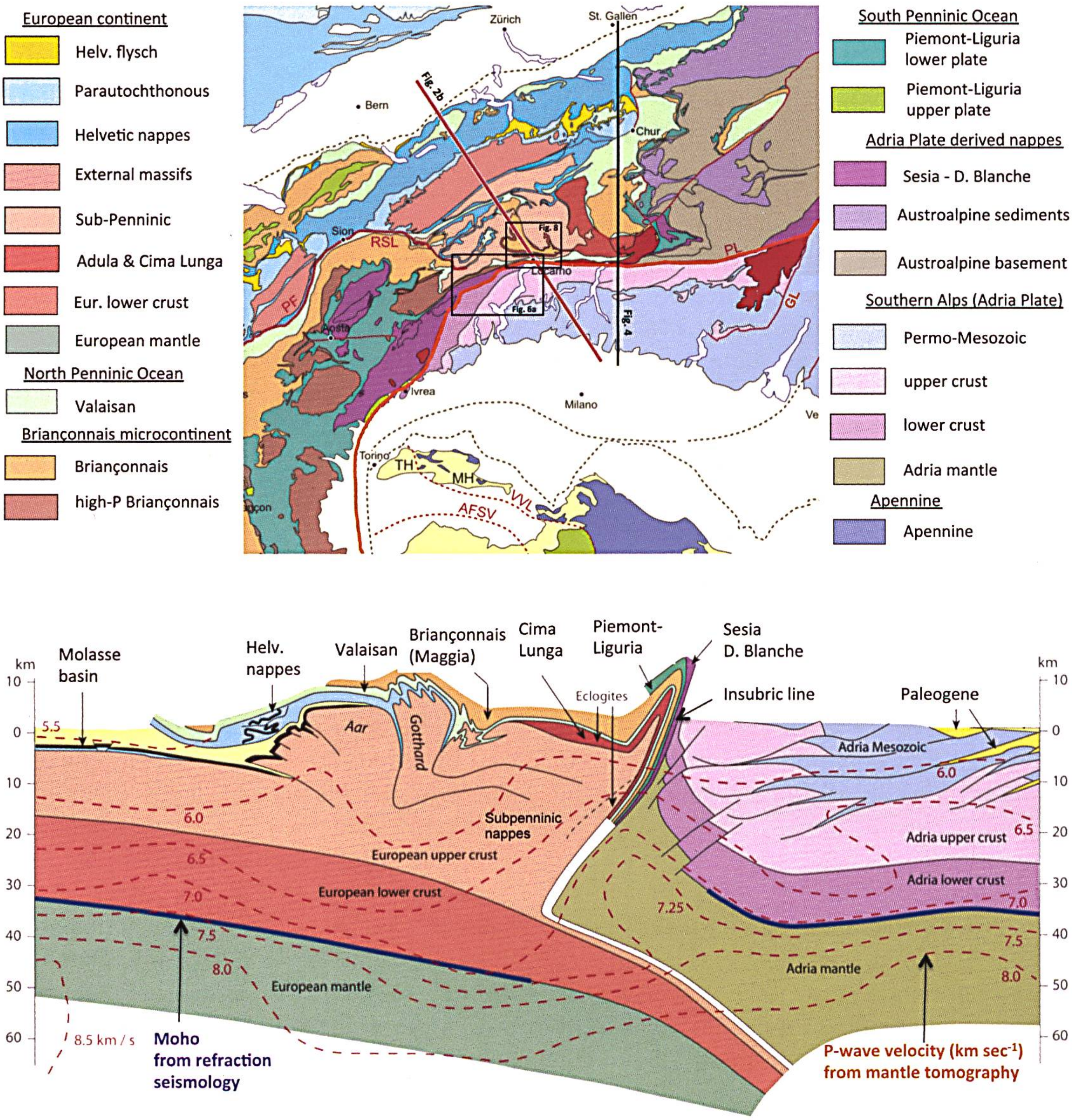


Fig. 2: Tectonic map of the western Alps and profile after Schmid et al. (2017). a: Map indicating the profile traces of Figs. 2b and 4, as well as the locations of Figs. 6a and 8. PF: Penninic Front; RSL: Rhone-Simplon line; PL: Periadriatic line; VVL: Villalvernia-Varzi line; GL: Giudicarie line; AFSV: northern front of the metamorphic core of the Ligurian Alps; TH: Torino hills; MH: Monferrato hills. b: Large-scale geological profile across the Lepontine Alps including geophysical data.

is to be found within the Penninic gneiss nappes, which raises questions about the existence of a discrete boundary between «Helvetic» and «Penninic» nappes. Both the lowermost Penninic (Subpenninic) as well as the Helvetic nappes are part of the European distal margin, being located north of the Alpine Tethys (Schmid et al. 2004).

4 Kinematics and timing of movements along the Insubric line derived from large-scale constraints

Backfolding in the southern Steep Belt that post-dates nappe emplacement as discussed above is intimately related to backthrusting along the Insubric line, or more precisely, along an approximately 1 km thick belt of mylonites. The time sequence of profiles presented in Fig. 4 presents a qualitative estimate of the total vertical component of displacement of the Central Alps in respect to the Southern Alps across the steeply dipping Insubric line and its timing along a profile that crosses the Bergell intrusion located east of Locarno (see trace of the profile in Fig. 1a). The depth of the final emplacement of the Bergell batholith that intruded some 32-30 Ma ago (von Blanckenburg 1992) can be inferred from the pressures obtained from hornblende barometry (Berger et al. 1996 and references therein). At the base of the pluton they reach 6-7 kbar, corresponding to a depth of 22-26 km. Based on a profile construction of the present-day geometry of the Bergell batholith (Schmid et al. 1996a) this locates the top of the intrusion presently cropping our at the eastern margin of the pluton at a depth of some 13 km at the time of emplacement of the plu-

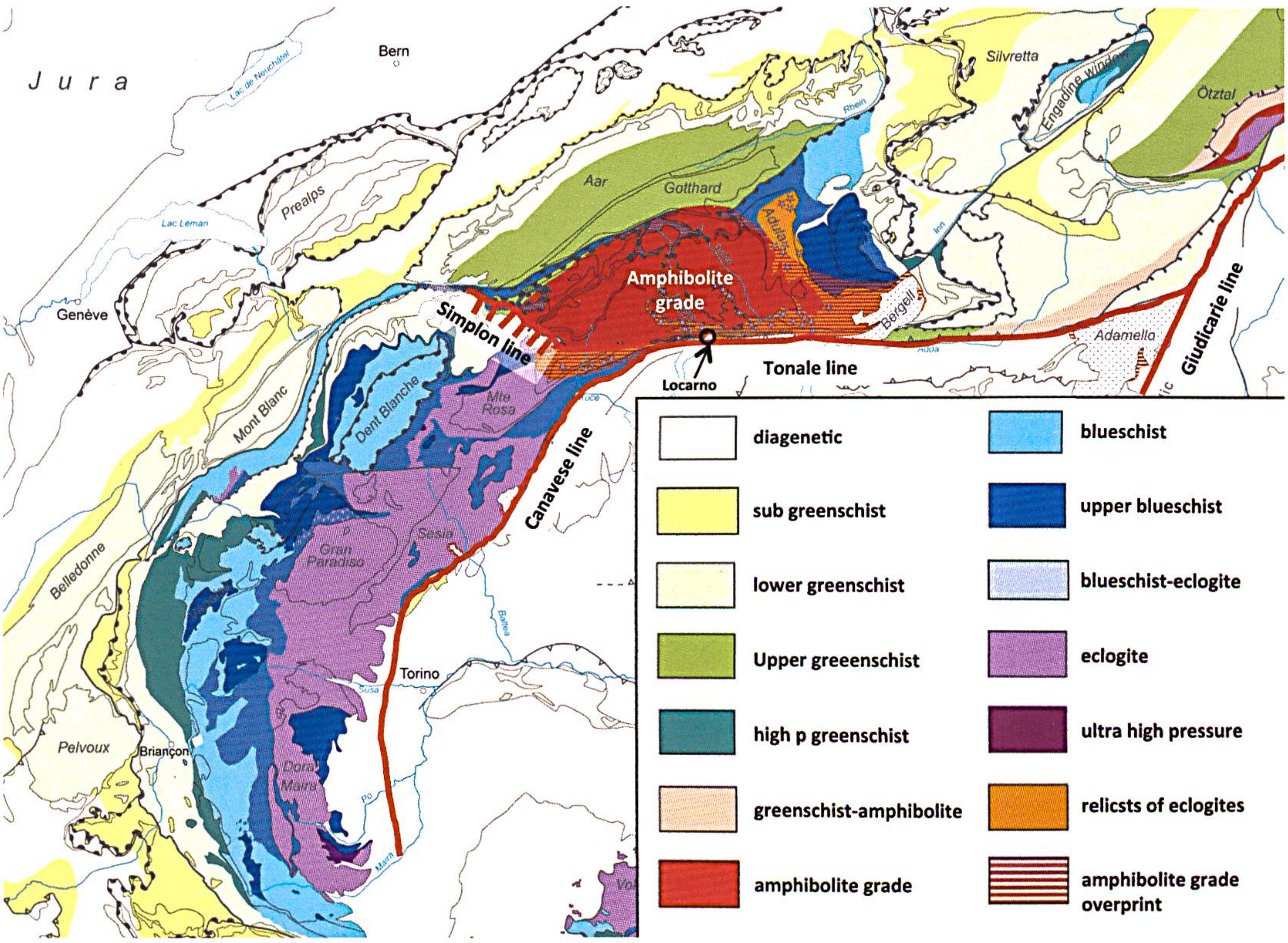


Fig. 3: Metamorphic structure of the Alps after Oberhänsli et al. (2004).

ton (Fig. 4a). It follows from this that backthrusting along the Insubric line initiated after the intrusion, i.e. after 30 Ma. Pebbles derived from the Bergell intrusion began to be deposited in the Como formation (Gunzenhauser 1985) since some 25 Ma ago, pro-

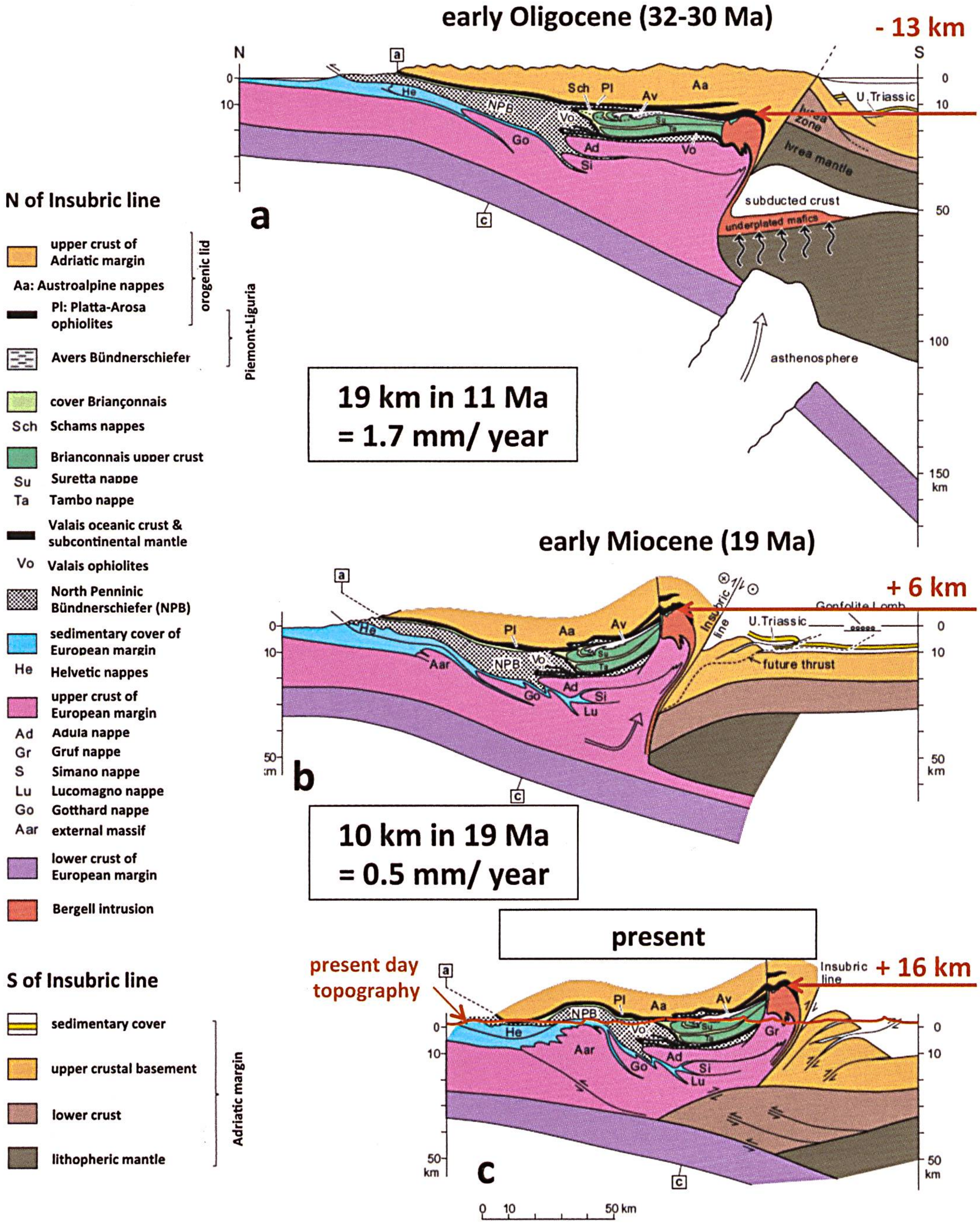


Fig. 4: Late-stage tectonic evolution of the Alps; scaled and area balanced sketches of the kinematic evolution of the eastern Central Alps after nappe stacking for the stages before (a) and after (b) backthrusting and present-day profile (c) along a transect across the Bergell intrusion (see Fig. 2a for profile trace) after Schmid et al. (1996).

viding evidence that parts of the Bergell intrusion must have reached the earth's surface by this time (Gianola et al. 2014). The end of backthrusting pre-dates 19 Ma by an unknown amount of time. In any case, according to the reconstruction in Fig. 4b, the top of the intrusion at 19 Mio years was at 6 km above sea level. This constrains the vertical component of the N-side-up displacement along the Insubric line to some 19 km; the rate of vertical rock uplift was at least 1.7 mm/year. This high value suggests that the Bergell area immediately north of the Insubric line must have represented a very high mountain range at the end of the Oligocene. After 19 Ma, when shortening migrated into the Southern Alps and the Insubric line became underthrusted by a lower crustal wedge, the rate of rock uplift decelerated to some 0.5 mm/year (Fig. 4c).

The amount of dextral strike slip displacement along the eastern segment of the Insubric line (the Tonale line) is more difficult to assess in the absence of a displaced marker horizon. Existing estimates therefore rely on large-scale considerations in the context of the formation of the arc of the Western Alps. According to the interpretation of Schmid & Kissling (2000) thrusting at the Penninic Front (PF in Fig. 2a), also initiating during the Early Oligocene, was kinematically connected to dextral strike slip along the Rhone-Simplon Line (RSL in Fig. 2a) and along the Tonale line. Holding the Central Alps fixed, such dextral shearing along the Tonale and Rhone-Simplon lines allows for the relative movement of the Ivrea Zone, together with the Penninic units of the French-Italian Alps, towards NNW. A detailed reconstruction of the evolution of the arc of the Western Alps available yields some 90 to 150 km displacement of the Ivrea Zone to the WNW relative to fixed Europe (Schmid et al. 2017).

Backthrusting, allowing for the N-side up displacement and exhumation of the Central Alps and dextral strike slip motion were at least partially coeval. Below we will provide evidence, however, that the strike-slip component outlasted the vertical component of displacement along the Insubric line during the last stages of deformation. The offset of the Tonale line by the Giudicarie line at 22 Ma ago provides a solid time marker for the end of the dextral displacement along the Insubric line.

5 Detailed observations in the vicinity the Insubric line

5.1 Ivrea Zone south of the Insubric line

In spite of the fact that the Ivrea Zone was already at a relatively low temperature (<300°C) at the time the Insubric line formed, and hence very flow-resistant, it exhibits Alpine-age strain features in the area around Ascona. The pre-Alpine foliation of the Ivrea Zone, whose lithologies largely preserved the Variscan microstructure and mineral assemblages, was affected by an east-plunging antiform of Alpine age formed by foliation-parallel flexural slip while largely preserving the pre-Alpine fabric. Fig. 5 shows how the two predominant lithologies of the Ivrea Zone, Ivrea mafics and Ivrea paragneisses (so-called «kinzigites») bend around this antiform that plunges with 30°-40° to the east and whose hinge runs across the Monte Verità at Ascona (Pozzorini 1989). The mechanism of folding is flexural slip; numerous slickensides that formed under sub-greenschist facies conditions are testimony of slip along the pre-existing foliation planes. This mechanism of folding produces kink-type and box-fold type geometries reminiscent of folding in the Jura Mountains. According to Schmid et al. (1987) and Zingg et al. (1990) it is the rotation of the southern limb of a similar and even larger antiform adjacent to the Insubric line located further to the SE (the Proman antiform in Valle d'Ossola) that was responsible for the tilting of the famous Ivrea Zone lower crustal section into a subvertical orientation. As in the Valle d'Ossola the Insubric mylonites in the Ascona area (see Fig. 5) are located in the very attenuated northern limb of such a large-scale antiform. Along the northern limb upper crustal levels of the basement of the Southern Alps, including its Mesozoic cover (the so-called Canavese Mesozoic), became mylonitized and are now in direct contact with the southerly adjacent lower crustal Ivrea rocks.

5.2 Southern Steep Belt north of the Insubric line

Fig. 5 illustrates that the Insubric line is not a «line» in the strict sense but rather an approximately 1 km thick belt of greenschist facies mylonites. North of this belt, in the area around Arcegno a section across an extremely thinned pile of nappes in a steeply N-dipping overturned orientation is exposed. Within a short distance one passes across the entire Sesia Zone (granitic gneiss, phyllonite, fine-grained biotite gneiss and meta-diorite, Fig. 5), then across an extremely thinned Zermatt-Saas Unit representing a remnant of the South-Penninic Ocean (mafics, ultramafics and various gneisses in Fig. 5) and finally reaches the «root» of the Monte-Rosa nappe (granitic gneiss in Fig. 5), still in a N-dipping and overturned orientation. The boundary between mylonites and Sesia Zone mapped in Fig. 5 is not a sharp one and was tentatively mapped as the boundary north of which the amphibolite-grade mineral assemblages of the Lepontine dome are well preserved. South of this boundary all the amphibolite grade minerals were retrogressed into lower greenschist facies mineral assemblages rich in chlorite and epidote.

Note that the greenschist facies Insubric mylonites are rimmed by amphibolite-grade rocks of pre-Alpine (Variscan) age in the south while the Southern Steep belt is part

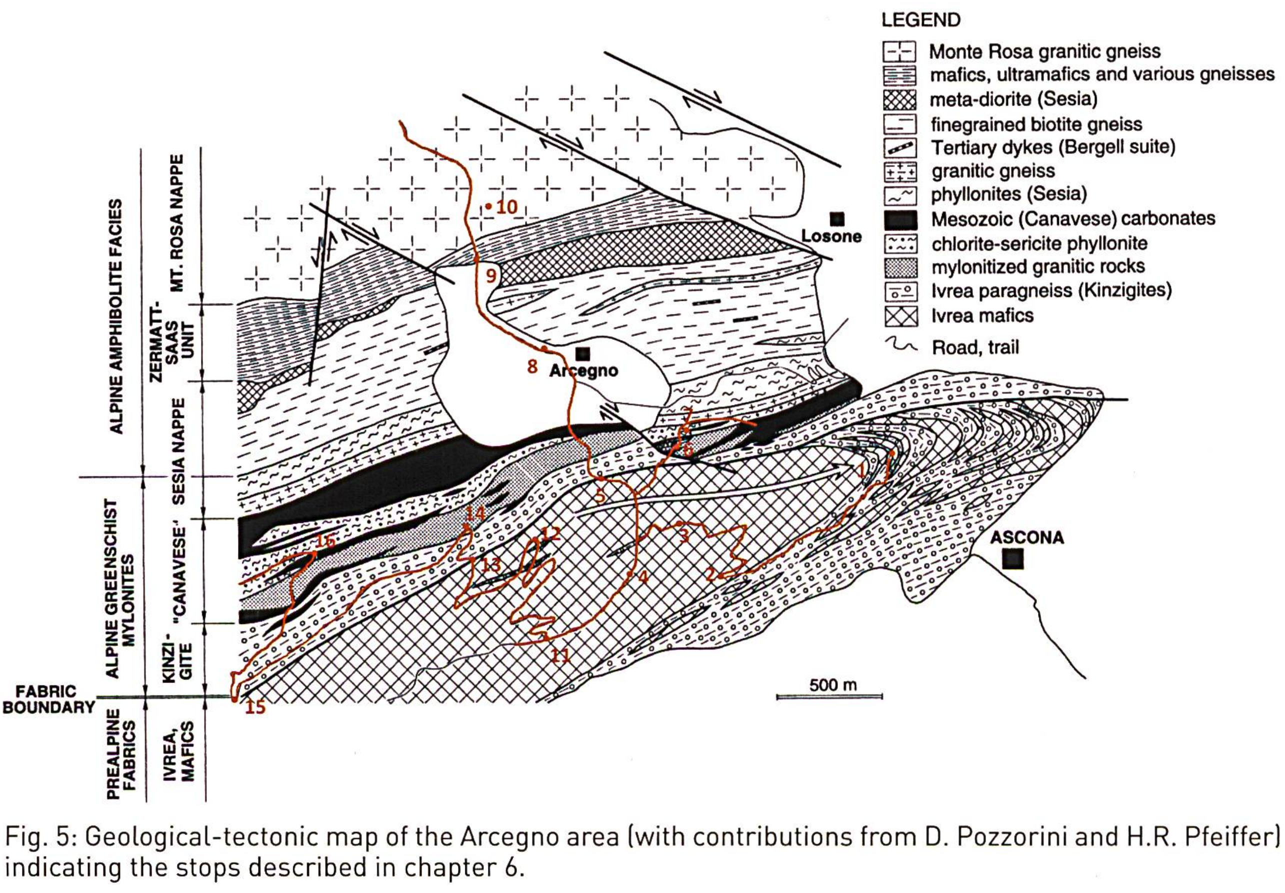


Fig. 5: Geological-tectonic map of the Arcegno area (with contributions from D. Pozzorini and H.R. Pfeiffer) indicating the stops described in chapter 6.

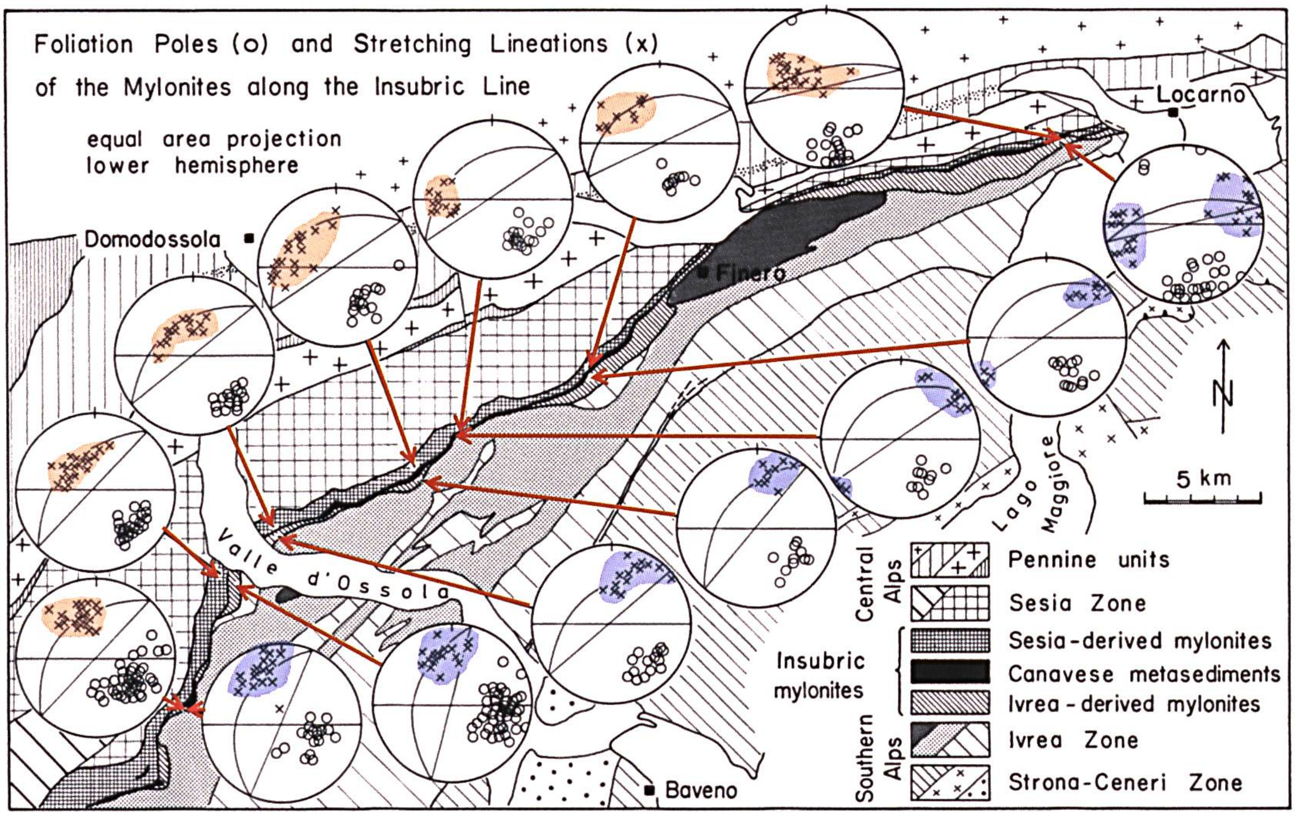
of an amphibolite grade area of Alpine age (see Fig. 3). At the time of backthrusting along the Insubric mylonite belt, the still hot units of the adjacent Lepontine dome (650°C or more) became cooled by the adjacent Ivrea block that was at less than 300°C at this time. This led to a retrograde overprint of the southern rim of the Lepontine dome near its contact with the Ivrea Zone.

5.3 The Insubric mylonite belt

Strictly speaking the term Insubric «line» is a misnomer since it is a ca. 1 km thick belt of mylonites (Fig. 6a) that took up the displacements across this important tectonic boundary. The term mylonite is used for ductilely deformed rocks formed by the accumulation of extreme shear strain in ductile fault zones. Mylonites typically are very fine-grained rocks characterized by a mm-thin lamination parallel to the foliation produced by domains of different mineralogical composition. The reduction in grain size is dominantly brought about by the mechanism of dynamic recrystallization, reducing the original grain size of viscously deforming minerals (typically quartz, see Fig. 7a) to a few tens of microns (Schmid & Handy 1991). Formerly it was wrongly believed that the process of grain size reduction is one of cataclastic grinding and crushing of minerals, which gave the rock its name «mylonite» (after the Greek word μυλών =«mulōn» for a mill). The foliation of mylonites typically carries a stretching lineation (see Fig. 7b) that can be measured in order to deduce the direction of shearing, i.e. the direction of tectonic transport once one has determined the sense of shear (in the case of Fig. 7a sinistral).

The directions and senses of shearing within the 1 km wide Insubric mylonite belt west of Locarno indicate a complex kinematic history (Fig. 6a). The southern part of the mylonite belt indicates dextral shear with horizontal stretching lineations in the Ascona-Locarno area, exhibiting a modest pitch to the NE further to the southwest (blue in Fig. 6a). In the northern part of this mylonite belt, however, the lineations plunge approximately down-dip, senses of shear indicating backthrusting (red in Fig. 6a). Hence, the Insubric line may be viewed as a dextral strike slip zone and a steeply N-dipping (45°-70°) backthrust (or retro-shear) at the same time, confirming what was inferred from large-scale considerations.

In the Ascona-Arcegno area occasionally observable overprinting relationships indicate that some of the mylonites formed during backthrusting have been re-mylonitized during strike slip shearing. However, these local overprinting relationships have to be viewed as part of a continuous deformation process related to dextral transpression (see arrows in Fig. 6b). During W- to NW-directed movement of the Adriatic block relative to fixed Europe, with the Ivrea geophysical body at its western edge (lower part of Fig. 6b), parts of the Central Alps (upper part of Fig. 6b) became first backthrusted in the area of the Canavese line and displaced to the east by later strike slip movements along the southern part of the mylonitic belt (blue lineations in Fig. 6a) and dextral shearing at the Tonale line (Fig. 6b). The cooling ages within the Lepontine metamorphic dome, related to exhumation by backthrusting, systematically decrease in age going from W to E (Schmid et al. 1989). Hence the eastern parts of this dome were uplifted first. The resulting complex strain pattern resulted in the formation of a complicated internal structure within the Lepontine dome, formed during this same Insubric phase, as discussed by Merle et al. (1989). Towards the end of these transpressive movements and after cooling below 300°C, the Tonale line (but not the Canavese line) was overprinted by cataclastic dextral movements under brittle conditions (Gansser 1968). Westwards, and N of the Canavese line, these brittle dextral movements contin-



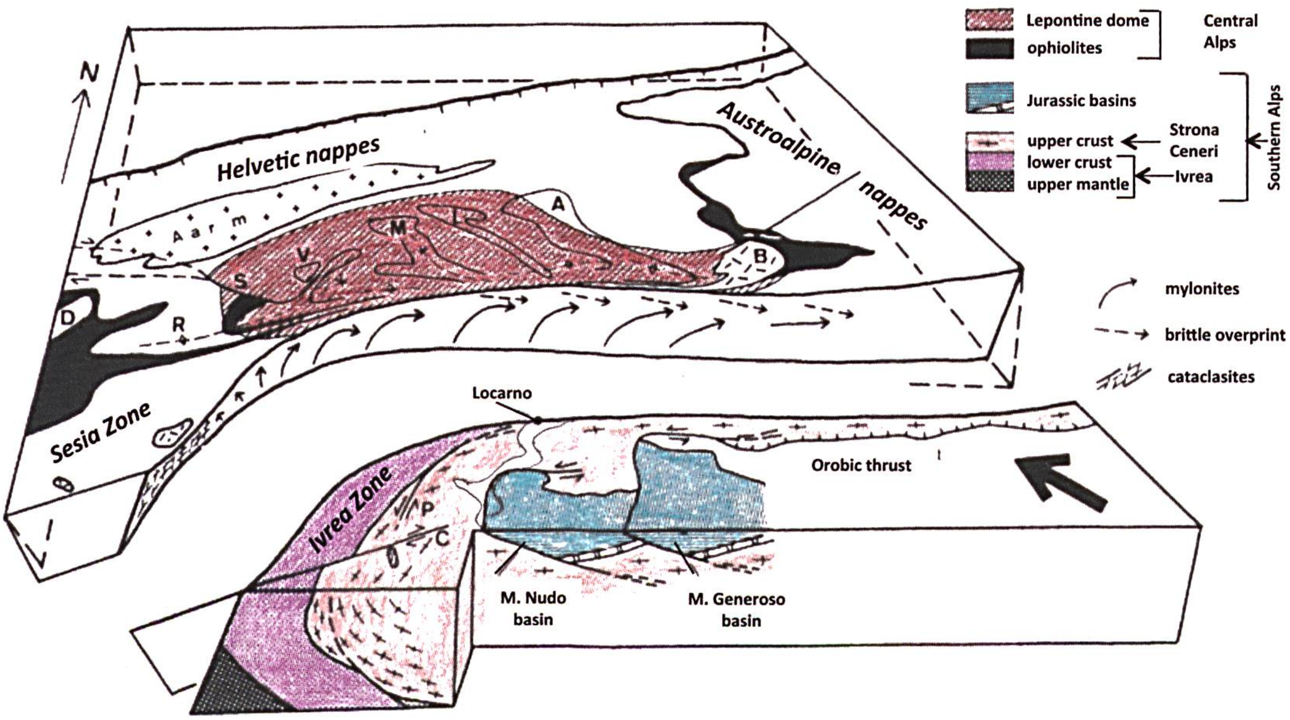


Fig. 6: a: Tectonic map (area outlined in Fig. 2a) indicating the orientations of foliation planes and stretching lineations measured in the Insubric mylonites between Locarno and Valle d'Ossola. Red: stretching lineations indicating backthrusting; blue: stretching lineations indicating dextral stike slip in lower hemisphere equal area projection (after Schmid et al. 1987). b: Block diagram illustrating the asymmetric eastward escape of the Lepontine nappes (top) as a result of the WNW-directed indentation of the Ivrea Zone of the Southern Alps. The arrows indicate the displacement path of the Central Alps in relation to the Southern Alps as inferred from the stretching lineations in the Insubric mylonites and striations of slickensides during late-stage brittle overprint (after Schmid et al. 1989).

ue into the Centovalli line, associated with cataclastic Riedel faults affecting the part of the area immediately north of Arcegno (Fig. 5; WNW-ESE-striking dextral faults W of Losone).

From S to N one can map the following groups of mylonites, based on the nature of the protoliths the mylonites were derived from (Fig. 6a):

The **Ivrea-derived mylonites** predominantly consist of former Ivrea paragneisses (the kinzigites), former amphibolite grade rocks, transformed into brownish mica- and chlorite-rich greenschist facies mylonites (Qtz-Ab-Czo-Wmica-Chl-Sphene). Complete retrogradation of the pre-Alpine Plag-Grt-Bi-Sill-Kf assemblage induces reaction-enhanced softening and an associated inversion of the relative strength of quartz in respect to the other mineral phases. Quartz, deforming by dislocation creep, initially represents the weakest mineral phase. With progressive deformation quartz is boudinaged within the fine-grained matrix of greenschist facies reaction products, which presumably deforms by some grain size sensitive mechanism. This phenomenon is widespread in mylonites and has been extensively discussed by Stünitz and Fitzgerald (1993). It indicates that the strength of quartz overestimates the strength of quartz-bearing rocks. Thin amphibolite and pegmatite layers, interbedded with former kinzigite, are relatively more flow resistant. The northern edge of a massive body of Ivrea mafics almost totally escaped mylonitization in our area (area mapped as Ivrea mafics south of the fabric boundary in Fig. 5). There, only modest amounts of Alpine strain are produced by brittle faulting with associated epidote-bearing slicko-fibres. Hence, the transition between pre-Alpine fabrics preserved in this large mafic body and the mylonites is extremely abrupt («fabric boundary» in Fig. 5). Only thin layers of amphibolite contained within the kinzigites north of the fabric boundary are mylonitized, presumably due to sufficient water access, allowing for the breakdown of the original mineral composition of the amphibolites into Ab-Act-Chl-Czo-Sphene. This again implies reaction-enhanced work softening. Along the fabric boundary pseudotachylites are occasionally found (Fig. 7d). Pseudotachylites are characterized by veins or layers of glassy material, often containing inclusions of wall-rock fragments or forming the matrix of tectonic breccias. Pseudotachylite material is typically dark in color. This glass formed by frictional heating during fracturing of these very strong and flow-resistant rocks. Melt generation is only possible if the mechanical energy is converted into heat very quickly; hence it is widely accepted that pseudotachylites represent fossil earthquakes.

The **Canavese mylonites** predominantly consist of Mesozoic cover of the Southern Alps (mostly siliceous limestone of Lower Jurassic age derived from the Moltrasio Formation of the Southern Alps, Figs. 7b and c). The Mesozoic Canavese sediments underwent prograde Alpine lower greenschist facies metamorphism; hence they contrast in this respect with the rest of the Insubric mylonites, which formed under retrograde conditions in respect to pre-Alpine (Ivrea zone) or Alpine (Sesia unit) metamorphism. Occasionally also mylonitized granitic rocks and former paragneisses are found; they represent upper crustal levels of the Southern Alps (equivalent to the Strona-Ceneri Zone).

The **Sesia-derived mylonites** formed by mylonitization of gneisses of the highest tectonic unit of the Central Alps, the Sesia unit. Only the southernmost rim of the Sesia nappe was affected by mylonitization under greenschist facies conditions. The lithologies found in these mylonites are mostly granitic (former muscovite-bearing orthogneisses). The gneissic units further to the N, which largely preserved their Alpine amphibolite facies assemblages, must also have suffered large strains during the displacements along the Insubric line. But in detail is not easy to distinguish fabrics formed during the Insubric phase from earlier fabrics found within the gneissic amphibolite grade region to the north.

6 Excursion guide to the area around Arcegno

The stops described below are located in Fig. 5. A first excursion (stops 1-10) takes some 5 hours for walking and inspecting outcrops and often follows a footpath, inviting for easy walking. A second excursion follows a paved road to Monti die Ronco (stops 11-16) and can also be made using a car. Taking the car it takes some 3 hours to inspect these outcrops.

In the following we only briefly describe the stops; the reader is referred to sub-chapters 5.1-5.4 for additional information.

Stop 1 (46.1590 / 8.7617): East of the asphalt road two antiformal hinges represent a pair of parasitic folds that form the core of the E-plunging large-scale antiform of the Ivrea zone running across the park around the Monte Verita hotel. Note the cataclastic overprint with slickensides visible on the foliation planes of Ivrea Zone amphibolites, which preserve their amphibolite-grade Variscan fabric.

Following the asphalt road from Stop 1 to *Stop 2 (46.1538 / 8.7509)* one follows an alternation of metabasic rocks (amphibo-

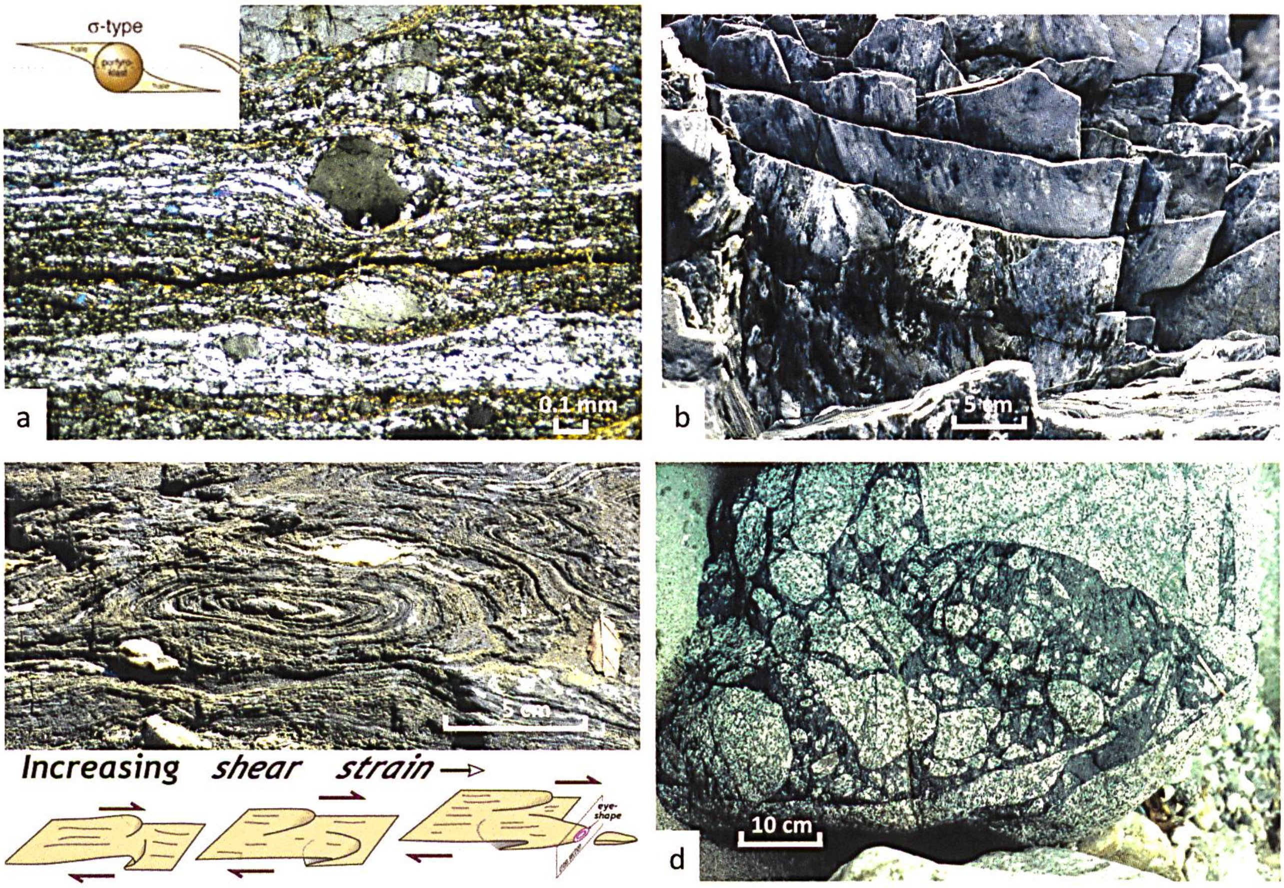


Fig. 7: Photographs illustrating some fault rocks found along the Insubric line. a: granitic mylonite from Valle Loana; note asymmetric sigma-clast of feldspar indicating sinistral sense of shear and dynamic recrystallization in quartz-rich ribbon (bottom) and in the pressure shadows of the sigma-clast. b: a look at steeply dipping mylonitic foliation planes featuring approximately down-dip plunging stretching lineations; mylonitized Lower Jurassic cherty limestones (Canavese; Moltrasio formation) from Val Grande. c: subhorizontal cut across sheath folds («Zungenfalten») in mylonitized Moltrasio formation from Val Loana. D: Pseudotachylite breccia in mafic rocks of the Ivrea zone from Val Sesia.

lites), paragneisses (kinzigites) and rare pegmatites almost along strike the southern and steeply overturned limb of the antiform. Several stops allow for observing the well-preserved Variscan fabric with a foliation carrying a pre-Alpine stretching lineation and occasionally isoclinal folds of pre-Alpine age. The effect of Alpine deformation is essentially one of tilting due to folding, and signs of Alpine cataclastic overprint are rare. Turn off the paved road at the coordinates of stop 2 into a trail, first heading ENE, and then follow the signs leading you to the top of the Balladrüm hill towards stop 3.

Stop 3 (46.1563 / 8.7494): On the way to the top there are some good outcrops of mafic rocks free of kinzigite intercalations (so-called "basischer Hauptzug" of the Ivrea Zone). The top of the hill not only offers a splendid panorama but also glacially polished outcrops of very fresh mafic rocks that are folded, whereby the majority of the folds are of pre-Alpine age at this place. Note the Brissago Island located near the southern rim of the Ivrea Zone and exposing sillimanite-bearing paragneisses. The mountains on the opposite SE shore of Lago Maggiore (Gamborogno and M. Tamaro) expose high-grade gneisses of the Strona Ceneri Zone that represent the upper crustal basement of the Southern Alps.

Stop 4 (46.1540 / 8.7456): To reach this point turn left after you join the asphalt road in order to reach a bench on the SE side of the asphalt road. This again offers a splendid panorama. The bench is installed on steeply overturned mafic rocks of the Ivrea zone. Opposite the bench, right at the sharp bend of the road a type of amphibolite carrying centimeter-scale white aureoles is exposed («Fleck-Amphibolit»), also containing clinopyroxene apart from dominating amphibole. Occasionally garnet can be seen in the center of these aureoles, which formed by retrograde reactions around a now mostly replaced formerly larger garnet.

Stop 5 (46.1580 / 8.7456): Walking back north along the asphalt road one reaches a sharp left turn of the road. Close to stop 5 one notices a moderately inclined foliation of the metabasic rocks on the western side of the road; then the outcrops abruptly terminate along an E-W running vertical cliff hidden in the forest. Follow the foot of this cliff into the forest in order to search for pseudotachylites. This outcrop illustrates the sharp contact between the rocks of the Ivrea Zone that preserve their pre-Alpine fabric and the adjacent Alpine mylonites (here not exposed in the forest). The map of Fig. 5 refers to this contact as «fabric boundary» because it represents the generally sharp boundary between intact Ivrea rocks with a pre-Alpine fabric (except for the pseudotachylites and a narrow cataclastic zone) and the Alpine fabric of the mylonites.

Stop 6 (46.1593 / 8.7484): To reach this point follow the asphalt road backwards and turn off to the NE along a trail until you reach a wooden bridge crossing a creek in a small swamp. Ascending the trail towards the Gratena hill one can study two types of mylonites in a small cliff and in loose boulders falling off the cliff. A whitish variety of mylonites were derived from quartz-rich granitoid rocks (Sesia-derived mylonites, see thin section in Fig. 7a). The other type is brown weathering and more mica-rich (Ivrea-derived mylonite derived from former kinzigites and now petrographically representing chlorite-sericite schist). Both types of mylonites beautifully expose lineations that can be used to deduce the sense of shear in suitably cut thin sections.

Stop 7 (46.1603 / 8.7490): The trail towards NNE and the Gratena hill crosses more granitic mylonites until it bends to the right and towards the east. After a few meters the trail crosses Canavese-derived mylonites cropping out at the trail and also forming a small cliff a few meters away from the trail in the hillside to the right. These light grey siliceous limestone mylonites are very hard to hammer and do not look like limestones at first sight. One may follow the trail further to the east and all around Gratena hill in order to observe more varieties of mylonites along the trail. Go back back the same way via stop 5 to reach the village of Arcegno and stop 8.

Stop 8 (46.1637 / 8.7414): at a left turn of the village road, 50 meters before reaching Grotto Zelindo, the roadside exposes thinly banded and fine-grained biotite gneisses of the Sesia Zone. Opposite the Grotto, a few meters before the entrance, an about 1 m thick porphyrite dyke of granodioritic composition is exposed at the roadside. The porphyrite can easily be recognized by the porphyritic structure with large feldspar phenocrysts. These dykes have been found along the entire Sesia Zone all the way to Valle d'Ossola (Reinhardt 1966). They have recently been dated by U-Pb zircon dating to have intruded at around 33.7 Ma ago (Pleuger et al. 2014), and hence they represent magmatic rocks that belong to the Bergell magmatic suite. This proofs that the Bergell magmatic suite formerly extended west of the Bergell for a long distance. Some of them remained undeformed by the Insubric deformations while others, located nearer to the Insubric mylonites, are strongly deformed.

Stop 9 (46.1676 / 8.7368): at this point, the road crosses a small creek near some houses. Following the creek to the west for some 50 meters and walking north towards a cliff one crosses amphibolites and meta-gabbros representing the ophiolites of the Zermatt-Saas Zone. Walking further north across paragneisses one approaches this cliff located behind the footpath leading to Monti di Losone. The cliff forms the southern limit of the two mica augengneisses of the M. Rosa nappe.

Stop 10 (46.1695 / 8.7370): climb up to a surface of glacially polished augengneisses of the M. Rosa nappe east of the road and discover a fist class outcrop exposing a series of folded leucocratic dykes that intruded the granitoids in pre-Mesozoic times. You may follow a small track leading to the highest point of these polished cliffs named Barbescio. Note that the augengneisses are still steeply north dipping, i.e. the root of the Monte Rosa nappe is in an overturned position and subparallel to rest of the Sothern Steep Belt all the way to the Insubric line further south. The stretching lineation in the augengneisses, as well as the fold axes, plunge down-dip the foliation and perpendicular to the polished surface of the cliffs.

Stop 11 (46.1516 / 8.7410): Turn off to the road leading to the Monti di Ronco. Note polished outcrop exposing the well-preserved pre-Alpine fabric of the meta-diorites and meta-gabbros belonging to the Ivrea Zone at the roadside near the turnoff.

Stop 12 (46.1555 / 8.7394): Near and in the forest behind the villa located at a left turn of the road sillimanite-bearing paragneisses of the Ivrea Zone («kinzigites») can be studied. Walking up-section and uphill towards stop 13 across the forest allows for studying progressive mylonitization of these kinzigites. Here, unlike at most other localities, the northern rim of the Ivrea Zone is formed by paragneisses rather than by the more flow resistant mafic lithologies.

Stop 13 (46.1555 / 8.7361): Non-mylonitic mafic rocks form the northern boundary of the Ivrea Zone. These are in direct contact with mylonitized kinzigites (fine-grained brown-colored mica and chlorite-rich lithologies) along the sharp fabric boundary running across the left-turn of the road. Post-mylonitic crenulation, with fold axes sub-parallel to the horizontal stretching lineation of the mylonites, is intense.

Stop 14 (46.1563 / 8.7358): Above the road, immediately after a left turn, another prominent lithology of the Insubric mylonites can be studied: light-grey colored mylonitized granitic rocks, either derived from upper crustal portions of the Southern Alps, or from the granitic lithologies of the Sesia Zone. Dislocation creep and dynamic recrystallization take up most of the deformation in quartz-rich layers (see Fig. 7a).

Stop 15: (46.1517 / 8.7261): A small forest road leaves this sharp right turn in a southwesterly direction. This road exposes abundant conjugate fracture planes in mafics of the Ivrea Zone coated by epidote-bearing slicko-fibres indicating direction and sense of slip along the fracture planes. Between the discrete fractures the pre-Alpine fabric is preserved. Hence, here the mafics exclusively deform by brittle fracturing. By following the main road further up towards stop 16 one can study mylonitized paragneisses and rarely also thin mafic layers, as well as less deformed pegmatites, lithologies derived from the former Ivrea Zone.

Stop 16: (46.1553 / 8.7262): At the parking place adjacent to the sharp left turn mylonitized siliceous limestones derived from the Moltrasio Formation of the Southern Alps can be studied (similar to those depicted in Fig.7 b & c). Relicts of Triassic carbonates can also be inspected along the roadside a few meters below the left turn. It is recommended to walk further to the NE along a small footpath leading to the ridge (46.1569 / 8.7287). Here one can study overprinting relationships between older mylonites carrying steeply plunging lineations indicating backthrusting by younger mylonites formed during dextral strike slip carrying subhorizontal lineations. Going further into Val Brima, a deep valley incised into a 100 m thick band of mylonitized siliceous limestones, one reaches granitic mylonites after crossing the creek. These mylonites are derived from the Sesia Zone and carry steeply plunging lineations that formed during backthrusting.

7 The Southern Steep Belt north of Locarno

The Southern Steep Belt consists of steeply north dipping packets of gneisses that can be followed further north and around a backfold into the flat-lying nappe stack of the Lepontine dome (Figs. 2b, 8 & 9), consisting of a stack of nappes. However, the Mesozoic rocks defining nappe boundaries in the northern part of the Lepontine dome eventually wedge out southwards, most of them before reaching the Southern Steep Belt. Therefore one lacks unequivocal lithological criteria for assigning the gneisses of the Southern Steep Belt to particular nappes, and the extremely intense strain including post-nappe emplacement isoclinal folding does not make the task easier. To some extent it is a matter of interpretation as to which part of this steep belt represents the "root" of which nappe. Hence, to a large extent the attributions presented in Figs. 2b, 8 & 9 reflect the interpretation of the author. Additional complications arise from the complicated 3-dimensional structure of the Maggia transverse structure (Fig. 8) and from the often isoclinal folding within the Southern Steep Belt, both post-dating nappe emplacement. The Maggia nappe forms an almost orogen-perpendicular synclinorium, bending into a strike that is sub-parallel to the Insubric Line in the lower Verzasca valley around the area of the Verzasca dam, pointing to non-cylindrical geometries formed during late-stage post-nappe folding. From south to north we distinguish the following tectonic units (see Fig. 8):

Sesia Zone: the correlation of the Sesia Zone in the Arcegno area with the Sesia Zone further west in the Valle d'Ossola area (Reinhardt 1966) is undisputed.

Monte Rosa Nappe: The root of the Monte Rosa nappe (interpreted to represent the basement of the Briançonnais microcontinent by many authors; e.g. Schmid et al.

2004) is divided from the Sesia Zone by a thin band of lithologies that can be attributed to the Zermatt-Saas Fee ophiolites issued from the Piemont-Liguria Ocean. These mafic and ultramafic rocks rimming the southern boundary of the root of the Monte Rosa nappe can be followed almost continuously into the area of Arcegno (Knup 1958; Reinhardt 1966; Colombi 1989; Pfeifer et al. 1989; Swisstopo 2005). Sesia Zone, Piemont-Liguria ophiolites and Monte Rosa Nappe laterally wedge out east of Locarno.

Bellinzona-Dascio Zone: Strictly speaking this name was coined for a lithologically very similar part of the Southern Steep Belt located further east between Bellinzona and Dascio located north of Lake Como. The major characteristic of this zone is the small-scale (meter to decameter) diversity of rocks of clearly different origin, including continental upper- and middle crustal metasediments and igneous rocks as well as ophiolitic mafic and ultramafics rocks. Intense deformation led to its characteristically

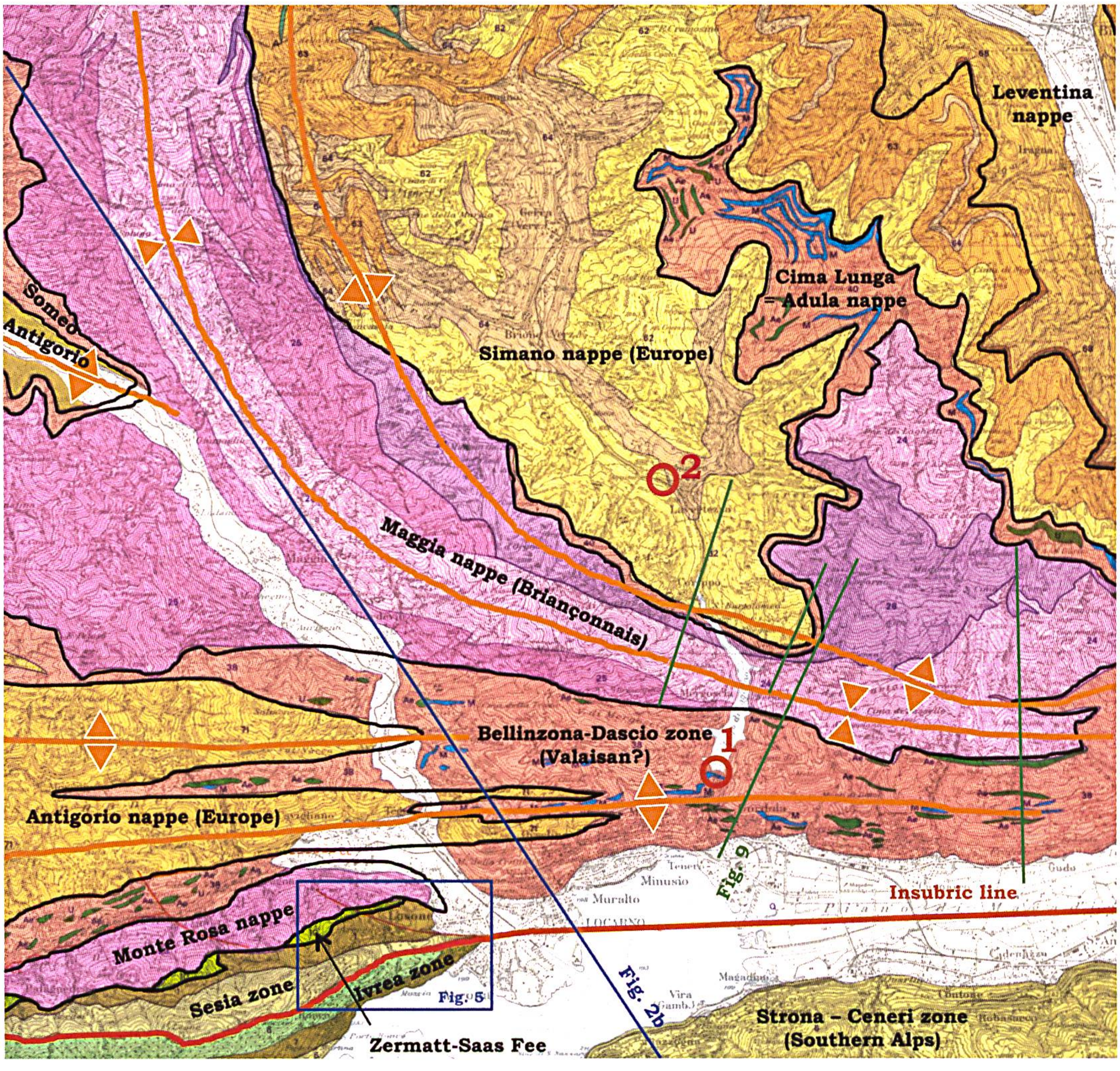


Fig. 8: Tectonic map of the Southern Steep Belt north of Locarno; extract of the tectonic and petrographic map of the Central Lepontine Alps by Berger and Mercolli, 2005a, reproduced with the approval by swisstopo (BA17086). Traces of the axial planes of post-nappe emplacement folds and tectonic attribution of nappes are those of the author. The map also indicates the excursion stops described in chapter 8, the locations of the map of Fig. 5 and those of the profiles found in Figs. 2b and 9.

lenticular and banded aspect. In Fig. 8 we follow Berger & Mercolli (2005 a & b) and also include very similar associations further west into this same unit, associations that were given a multitude of different names in the past (e.g. Zone of Arbedo-Mergoscia, Zone of Orselina and Zone of Onsernone). Ophiolitic fragments within this zone (green in Fig. 8) have been followed further to the west towards Valle d'Ossola where they rim the northern contact of the Monte Rosa nappe and connect with the Antrona ophiolites (Knup 1956, Reinhardt 1966, Colombi 1989). Similar lithologically heterogeneous series, interpreted to represent an accretionary complex (tectonic mélange) that formed at the interface between the subducting and the hanging plate (Berger & Mercolli 2005b), rim the southern margin of the Maggia nappe. The attribution of the ophiolitic fragments of the Bellinzona-Dascio Zone and the Antrona ophiolites to the Valais Ocean (Fig. 8; following structural arguments presented in Schmid et al. 1996b and in Keller & Schmid 2001) is not undisputed (e.g. Escher et al. 1997, who attribute the Antrona ophiolites, together with the Zermatt-Saas ophiolites, to the Piemont-Liguria ocean). However, the interpretation that Antrona and Zermatt-Saas ophiolites belong to different oceanic domains on structural grounds is also supported by geochemical data (Pfeiffer et al. 1989).

Antigorio nappe: This nappe, dominated by fine-grained quartzo-feldspatic gneisses, mostly lies outside the area of Fig. 8 (part of the Subpenninic units in Fig. 2) and represents the second-deepest exposed nappe in the western Lepontine dome (Simplon subdome) that we laterally correlate with the Simano nappe (see below) of the eastern Lepontine dome (Ticino subdome; Merle et al. 1989). The areas mapped as Antigorio nappe in Fig. 8 are only found east of the Verzasca valley and were attributed to the so-called Pioda di Crana Zone and the Salmone Zone by Knup (1956; his table IV). The Antigorio nappe is interpreted to have been issued from the distal European margin and is therefore referred to as Subpenninic (Schmid et al. 2004).

Maggia nappe: The tectonic position of this basement nappe is the subject of longstanding controversies that persist up to the present day (see Steck et al. 2013 and references therein). In the N-S section of Fig. 9 the Maggia nappe is depicted in a synformal position, tectonically overlying the Bellinzona-Dascio Zone in the south and the Cima Lunga and Simano nappes (see below) in the north (see Fig. 8). This synform with the Maggia nappe in its core is seen to be gradually deflected into a N-S-strike in Fig. 8, defining a remarkably non-cylindrical synclinal structure often referred to as "Maggia Querzone", dividing Simplon and Ticino subdomes from each other (Merle et al. 1989). North of the area of Fig. 8 the western margin of the Maggia nappe also overlies the Antigorio nappe, proving that Antigorio and Simano nappes occupied the same tectonic position before being affected by the late-stage post-nappe emplacement folding (Steck et al. 2013). Paleogeographically, the Maggia nappe is here considered to represent a slice of the Briançonnais micro-continent (following Schmid et al. 2004). This brings Maggia and Monte Rosa nappes into a similar tectonic position. As can be seen from Figs. 8 & 9 the Maggia nappe would remain a rootless klippe unless one postulates the existence of an antiform, bringing the Maggia nappe back into the ground below the gravels of the Magadino plain, south of the outcropping Bellinzona-Dascio Zone and immediately north of the Insubric line (see N-S section of Fig. 9, as well as the larger-scale NW-SE section of Fig. 2b that follows a different trace).

Cima-Lunga slice: The Cima Lunga slice represents the western equivalent of the much larger Adula nappe. Both these nappes were derived from the distal-most European margin and became deeply subducted as the Valais Ocean closed when Briançonnais micro-continent and Europe collided in Late Eocene times (42-40 Ma; Wiederkehr et al. 2009). As a consequence the Adula-Cima Lunga nappe suffered eclogite facies metamorphic overprint at around 38 Ma (Herwartz et al. 2011) that later, from around 32 Ma onward (Wiederkehr et al. 2009) was overprinted by the temperature-dominated Lepontine metamorphic event (Fig. 3). Westwards the Cima Lunga slice wedges out. The Someo Zone above the Antigorio nappe in Valle Maggia is in a similar tectonic position. Accepting the Maggia nappe to occupy a synformal position (see Fig. 9), also the Bellinzona-Dascio Zone is in a similar position and part of the same accretionary complex (tectonic mélange, also referred to as tectonic accretion channel by Engi et al. (2001), probably formed at the interface between the distal European and Valaisan units subducting below the Briançonnais micro-continent representing the hanging plate.

Simano nappe: Only the southernmost parts of this nappe, parallelized with the Antigorio nappe and hence part of the Subpenninic nappe system, is affected by late-stage steepening and hence part of the Southern Steep Belt (Fig. 9). In the Ticino subdome it is underlain by the still deeper Leventina nappe (NE edge of Fig. 8).

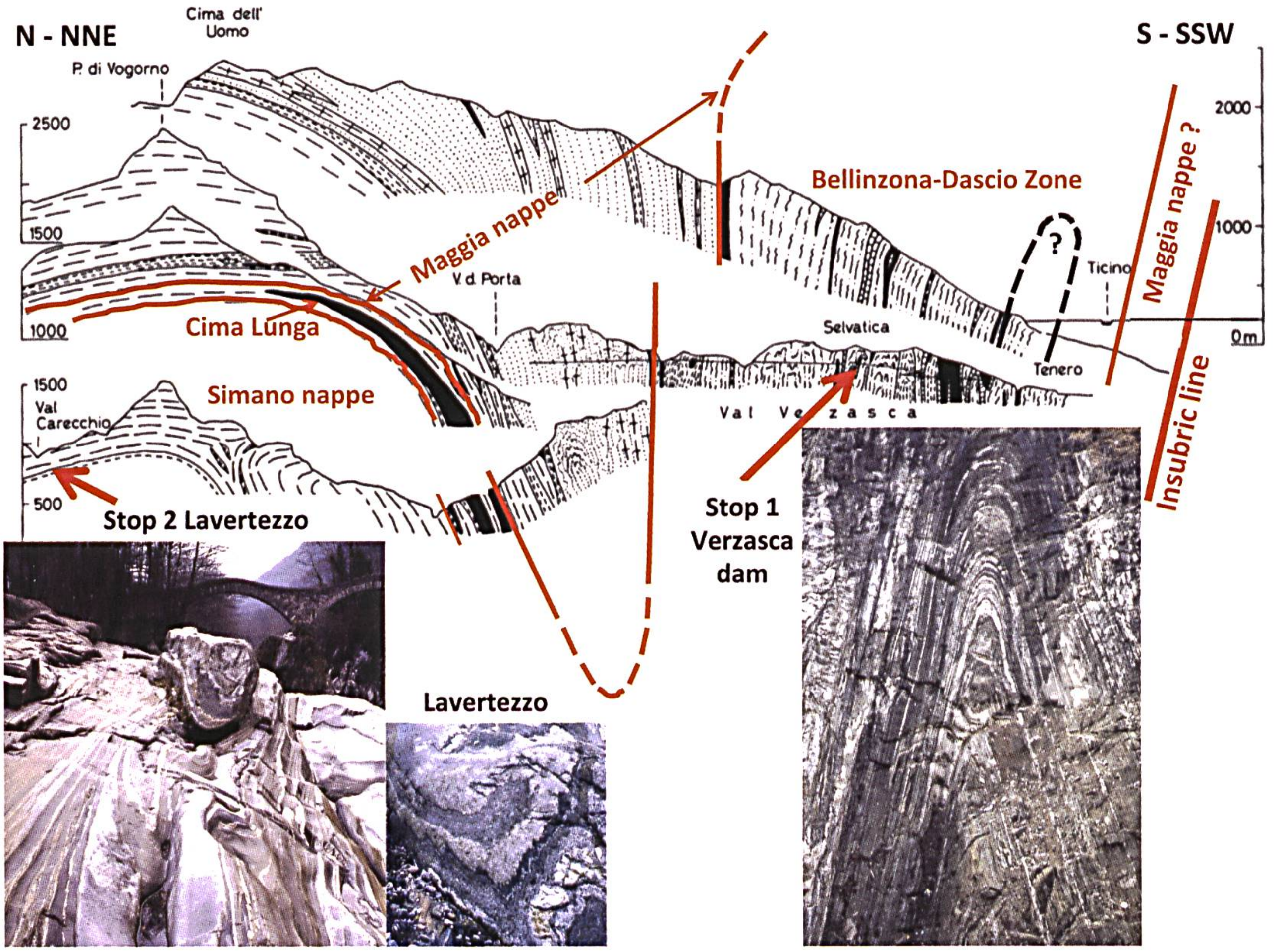


Fig. 9: Interpretation of 4 cross sections across the lower Verzasca valley published by Frey et al. (1980, their figure 7). The synform folding the base of the Maggia nappe is supported by the map pattern depicted in Fig. 8 that also indicates the location of the 4 profiles. The antiform indicated at the southern end near Tenero is only conceptual; its non-existence would make the Maggia nappe rootless. See text of chapter 8 for further details.

8 Excursion guide to Valle Verzasca

This excursion is best done by car and takes 3 to 4 hours. It offers 2 spectacular outcrops and fascinating panoramas between the 2 stops indicated in Figs. 7 and 8.

Stop 1 (46.1950 / 8.8509): Take the road into Valle Verzasca starting from Gordola. First take the small road opposite the parking space for visitors of the Verzasca dam, on the eastern side of the road, and inspect the hinge of a tight chevron fold that is exposed within the first meters from the bifurcation of a small road leading to Selvatica. This fold results from flexural slip along pre-existing foliation planes. The axial planar cleavage is only weakly developed; the main foliation is folded and hence pre-dates the formation of the chevron fold. Then walk over the dam to the western side, where more outcrops exposing such chevron folds can be inspected from near. The panorama from the dam offers a spectacular sight onto several of those chevron folds to both sides of the dam (see photo of folded marbles mounted into Fig. 9). These chevron folds affect banded quartzo-feldspatic gneisses, interlayered with marbles that belong to the Bellinzona-Dascio zone. The chevron folds have been tightened up during the latest stages of folding, leading to considerable thickening of the gneissic layering in the fold hinges. Although their amplitudes may reach up to 100m or more they only represent parasitic folds whose asymmetry indicates the existence of much larger synform north of the dam, or an antiform south of the dam, respectively. The major synform expected to the north is the one that in-folds the base of the Maggia nappe (see serial profiles of Fig. 9).
On the way to Lavertezzo (stop 2) the roadside repeatedly offers splendid views onto Pizzo di Vogorno (eastern side of Val Verzasca) exposing the gradual bending of the flat lying foliation of the gneisses of the central Lepontine dome into steep orientation characterizing the Southern Steep Belt.

Stop 2 (46.2601 / 8.8360): Below and downstream from Ponte dei Salti, located NW of the center of Lavertezzo village, the riverbed of the Verzasca creek is rimmed by beautiful glacially polished outcrops exposing folded gneisses of the Simano nappe. A series of NW-SE striking younger folds with subhorizontal fold axes, presumably formed after nappe emplacement, are seen to fold the older main foliation of the banded gneisses of the Simano nappe, including Latest Carboniferous felsic intrusions and a few Alpine dykes related to migmatization. These late-stage folds affect the pre-existing foliation including multiple generations of small-scale folds of probably Alpine age. These folds were mapped in great detail by Sharma (1969; his table III).

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