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A crustal-scale magmatic system from the Earth's mantle to the Permian surface – Field trip to the area of lower Valsesia and Val d'Ossola (Massiccio dei Laghi, Southern Alps, Northern Italy)

Peter Brack¹, Peter Ulmer¹, with a contribution by Stefan M. Schmid

This field guide was born out of an excursion of the Swiss Association of Petroleum Geologists and Engineers on the occasion of its Annual Convention at Stresa (June 2010). The visited area includes the lower parts of Valsesia and Val d'Ossola and the itinerary includes geological stops that are easily accessible and at low altitudes (and thus ideal for excursions in spring and in autumn). Additional points of interest in the same area are located in Val Mastallone and in Val Strona. With fair weather, especially with northerly winds, a trip to Mottarone between Lago Maggiore and Lago d'Orta is highly recommended. Mottarone offers spectacular views to the high peaks of the Valais Alps and across the Po Plain towards the Ligurian Alps and the Apennines. On the ridges and slopes immediately southwest of the Mottarone summit road good outcrops of the composite Baveno granite body and its contact aureole occur. Besides the points of geological interest the area hosts numerous exceptional cultural sites such as the remarkable Sacro Monte di Varallo (geological stop 3) and the village of Orta.

1. The Southern Alps: a short introduction

Geologically, the «Southern Alps» comprise a more than 400 km long portion of the Alpine chain extending from the town of Ivrea (Piemont) to the mountains of Carnia in Friuli (Northeast Italy). The Periadriatic or Insubric Line marks the border between the Southern Alps and the nappe piles of the Western, Central and Eastern Alps (Fig. 1). The Alpine orogeny imposed a metamorphic overprint reaching upper amphibolite-facies grade, especially on the rocks of the Central

Alps. Lithologies of the adjacent Southern Alps were not affected by this metamorphism, but do record substantial Alpine tectonic deformation. In different phases the South Alpine realm, or portions of it, were compressed to form a south- to southeast-vergent fold- and thrustbelt. East of Lago Maggiore the average width of the deformed area is around 60 km with the most external structures known from the subsurface of the Po Plain east of Milano. Thrusting involved both metamorphic basement and cover rocks. Estimates of the total shortening range between 60–120 km. In the western part of the Southern Alps this deformation was achieved in at least two prominent phases, before emplacement of the 42–33 Ma-Adamello intrusions, and after this event during the Miocene. In the subsurface of the western Po Plain the external thrusts and folds are truncated by the Messinian unconformity, whereas in the eastern part of the Southern Alps (Veneto, Friuli) tectonic deformation remained active until present. The Southern Alps originally belonged to the northern border area of the Adriatic (Apulian) plate, and their alpine compression is ultimately a result of the north- and west-directed movement and rotation of this plate.

In transects across the Southern Alps west of the Adamello intrusion the following domains are encountered from north to south:

- The innermost portion immediately south of the Insubric Line consists of (Variscan) greenschist to amphibolite facies metamorphic ortho- and paragneisses, with

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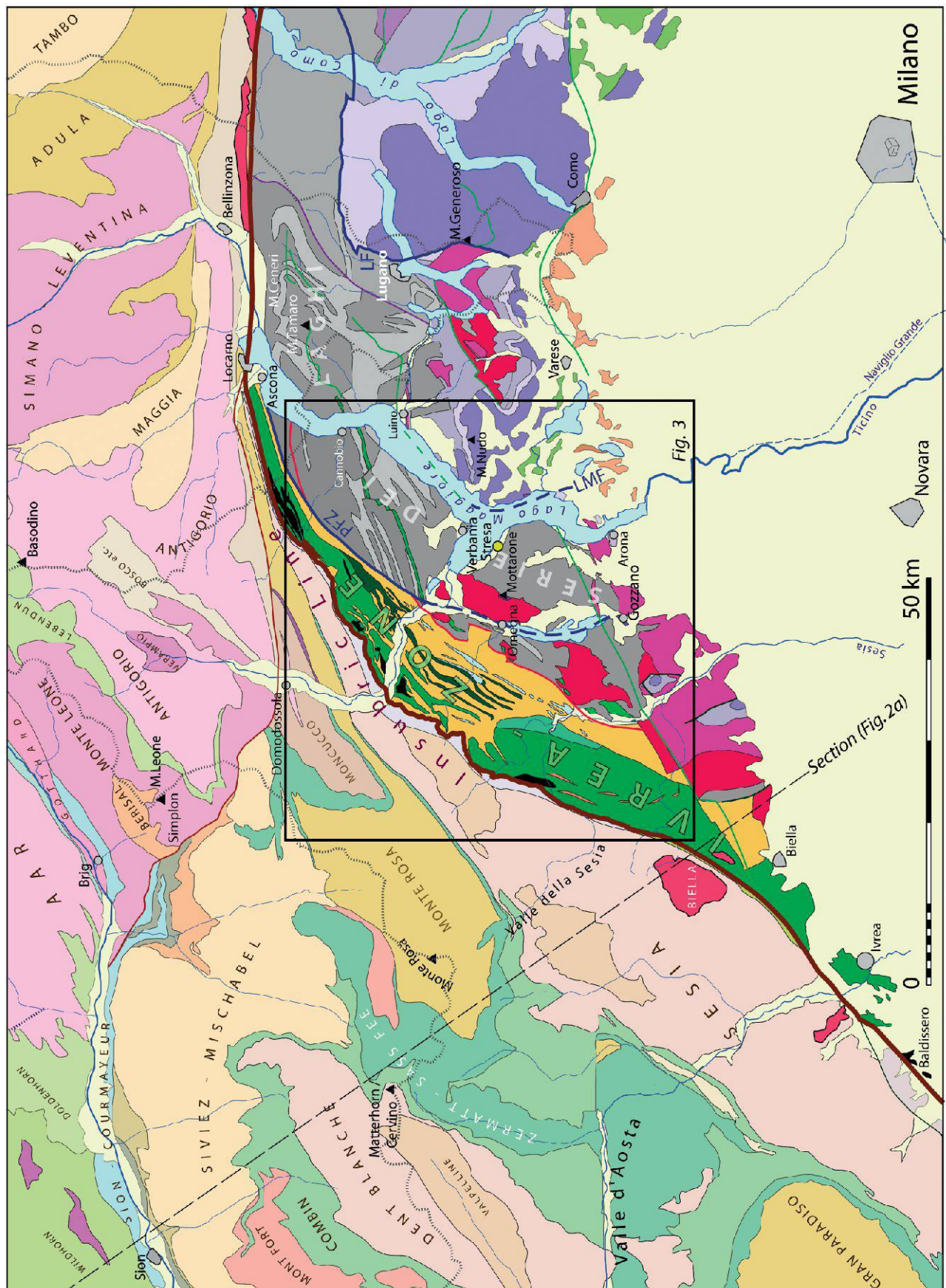


Fig. 1: Geological sketch of the westernmost Southern Alps and of the tectonic units of the Central and Western Alps. The black frame outlines the geological map of the Massiccio dei Laghi as in Fig. 3 (see this figure for a legend of the South Alpine units).

presumably early Paleozoic protoliths, which in places are cut by Permian intrusions. Permo-Mesozoic cover-rocks locally occur as thin slivers between different tectonic slices of basement units. In a corresponding portion of the easternmost Southern Alps (Carnia), Ordovician to Carboniferous sediment successions are preserved without significant metamorphic overprint, but are affected by Variscan and Alpine deformation.

- A belt of detached sedimentary units consisting of Permian clastic and volcanic rocks and Mesozoic sediments forms a wide area between the basement units to the north and the recent clastic rocks of the Po Plain. The youngest exposed folded sediments are Cretaceous Flysch deposits in the Bergamask sector.
- Molasse-type sediments (Gonfolite Group) are occasionally visible in several places along the southern border of the Alps, forming south-dipping slices that may have been lifted due to «hinterland»-directed local thrusts.
- In the subsurface of the northern Po Plain the deformed part of the Tertiary clastic fill increases in thickness with increasing distance from the Alps. This also holds true for the undeformed Plio-Pleistocene deposits above the Messinian unconformity. Around Milano the base of the Pliocene is currently at a depth of 2.5 km. Subsidence evidently decreased towards the rising Alps, and close to the present border of the mountain chain the unconformable cover of marine Pliocene sediments is preserved up to an altitude of 500 m (e. g., at Monte S. Bartolomeo, west of Lake Garda).

The Massiccio dei Laghi: a window to depth

The Massiccio dei Laghi (Serie dei Laghi and Ivrea-Verbano Zone) between Biella and Lago di Como belongs to the internal part of the westernmost Southern Alps and contains rocks of the South Alpine upper and

lower crust. To the southeast the upper crustal basement is bordered by an irregular array of Permian volcanic rocks and Mesozoic sediments. The latter disappear under the young clastic deposits of the Po Plain.

The detailed architecture of the Massiccio dei Laghi and, in particular the Alpine geometries, are still a matter of debate. Away from the Insubric Line prominent large and small-scale structures within crustal rocks predate the Permian intrusions, thus showing that this area remained intact during Tertiary uplift. Results of gravimetric and seismic tomography studies suggest that the dense rocks of the deep portion of the visible South Alpine crust (i.e. the Ivrea-Verbano Zone) are close to the tip of a body of dense rock that rises steeply from the northwestern portion of the Adriatic mantle at normal depths west of Milano (Fig. 2). Hence, the overall geometry of the Massiccio dei Laghi is indeed that of a southeastward tilted segment of the South Alpine crust.

In map views (Figs. 1, 3) the assembly of lower and upper crustal rocks can be observed over 50 km in a SW-NE direction, with an average width of approx. 25 km. This provides a unique situation of an extended 2D-cross-sectional view of continental crust. The upper crust portion comprises the barely visible cover rocks along the border hills and different gneiss units and schists of the Serie dei Laghi, which are cut by plutons of Early Permian age. In its outermost and shallowest part, this sector dips gently towards the Po Plain. Towards the deeper portion its inclination likely increases. The contact between the upper crust and the lower crust (Ivrea-Verbano Zone) is tectonic and marked by segments of the Cossato-Mergozzo-Brisago (CMB) Line and of the Pogallo Fault Zone (PFZ). The CMB-Line is a high-temperature shear zone that was active until the period of Permian magmatism. The PFZ is most likely a mid-crustal extensional fault related to Jurassic extension as it dissects the CMB-Line, and because it was active at lower temperatures.

The lower crust portion of the Ivrea-Verbano Zone consists of a heterogeneous assembly of high-grade metamorphic rocks, predominantly mafic intrusives and mantle slices. Minerals and their compositions from both metapelitic lithologies («Kinzigites», «Stronalites») and the metabasic rocks are indicative of high-temperature metamorphic re-equilibration at amphibolite to granulite-facies conditions. Metamorphic pressures increase towards the northwest, with inferred pressure-gradients indicating that this part of the crustal section is both tilted upright and shortened. This is in agreement with the orientation of steeply dipping (originally horizontal) magmatic layers in the mafic intrusive rocks. Prominent slices of mantle peridotites (e. g., Finero, Premosello, Balmuccia) are found in the northwestern border area of the Ivrea-Verbano Zone, cor-

responding to the deepest exposed crust portion. As indicated above, the shape of the gravimetric Ivrea-body at depth suggests that coherent mantle material reaches near-surface levels beneath the Ivrea-Verbano Zone.

Two main factors may have contributed to this peculiar crustal section being visible at the Earth's surface:

- During the Jurassic-Cretaceous, i.e. prior to the Alpine collision and compression, the sector of the Massiccio dei Laghi was situated on the distal portion of a passive continental margin, close to the continent-ocean-transition between the Adriatic plate and the Piemonte-Liguria ocean to the NW (in present orientation). The continental crust of the Southern Alps and, in particular of its westernmost portion, had been stretched prior to the continental

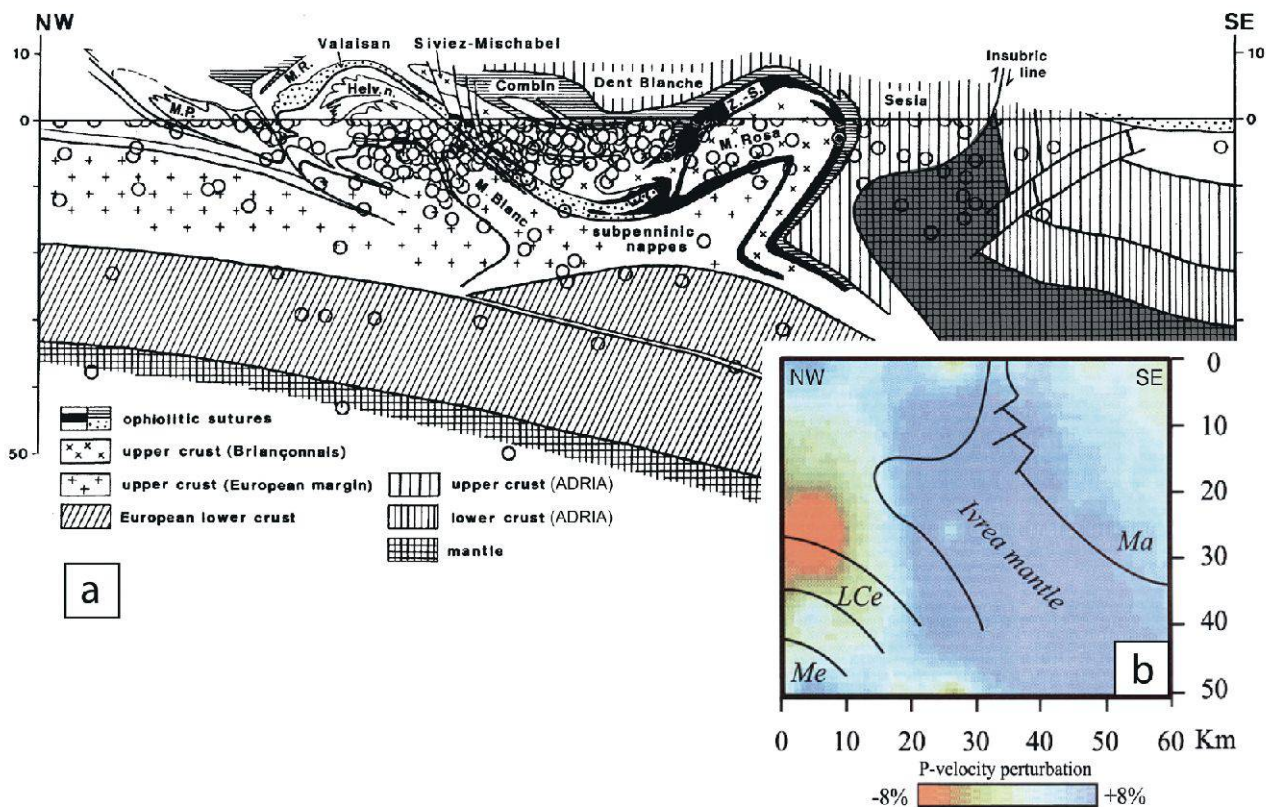
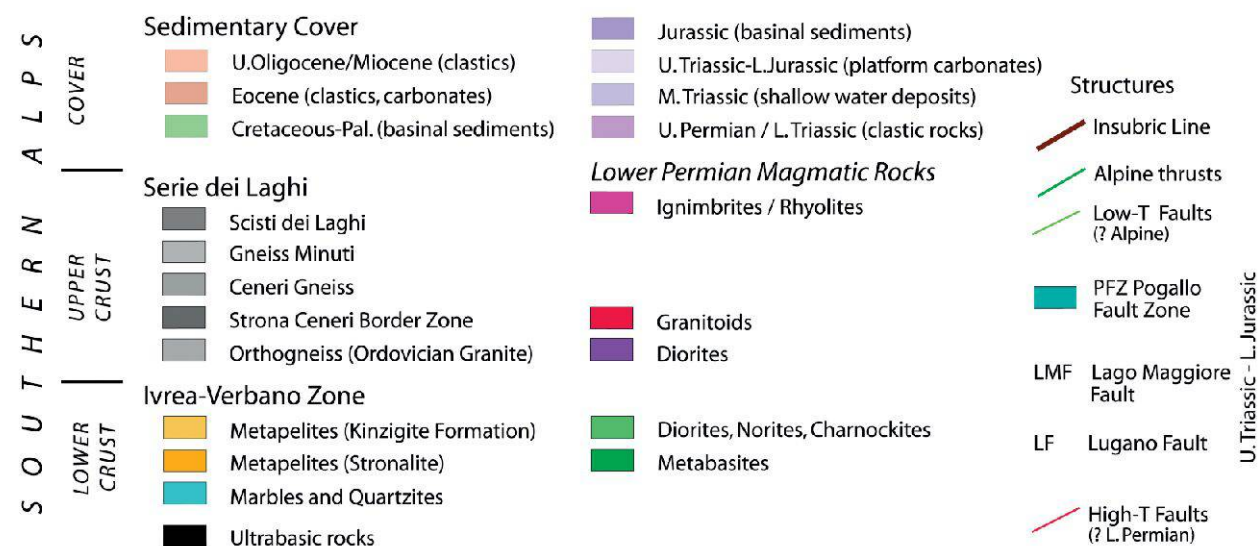


Fig. 2: a) Schematic geophysical-geological cross section through the western part of the Central Alps and the adjacent Southern Alps. Circles mark well-locatable earthquake foci for the 1980-95 time period from within a 30 km wide corridor projected onto the transect. See Fig. 1 for the trace of the section. b) Vertical cross section based on results of seismic tomography along the SE part of the CROP-transsect (parallel but southwest of section Fig. 2a). The maximum resolution capabilities of the seismic tomography model is about 10 km. Blue and red colours: high and low velocity perturbations respectively. Ma – Adriatic Moho; Me – European Moho; LCe – European lower crust. Figures modified after Schmid & Kissling 2000.



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break-up separating Adria from Europe. Due to extension, the crust-mantle boundary at the base of the Ivrea-Verbano Zone likely rose from an original depth of > 30 km in Permian times to around 25–30 km after the Early Jurassic.

- During Alpine collision the underthrusting of less dense material at depth beneath the present Ivrea-body and the back-thrusting of shallow portions induced the formerly extended South Alpine crust and upper mantle portion to rise further, eventually reaching the surface.

Reconstruction of the Lower Permian crust

Prior to the opening of the Piemont-Ligurian ocean, the South Alpine realm, including the Massiccio dei Laghi, had been stretched at different stages (during the Late Triassic – Early Jurassic). The roughly E-W directed extension (present orientation) produced topographic lows and highs separated by discrete fault zones. Variable thickness and contrasting sedimentary environments (shallow vs. deep basinal lithologies) of corresponding stratigraphic intervals allowed the reconstruction of the 2d-geometry of numerous platforms and basins along the strike of the Southern Alps (Fig. 4). Moreover, some of the bounding faults such as the Lugano-Val

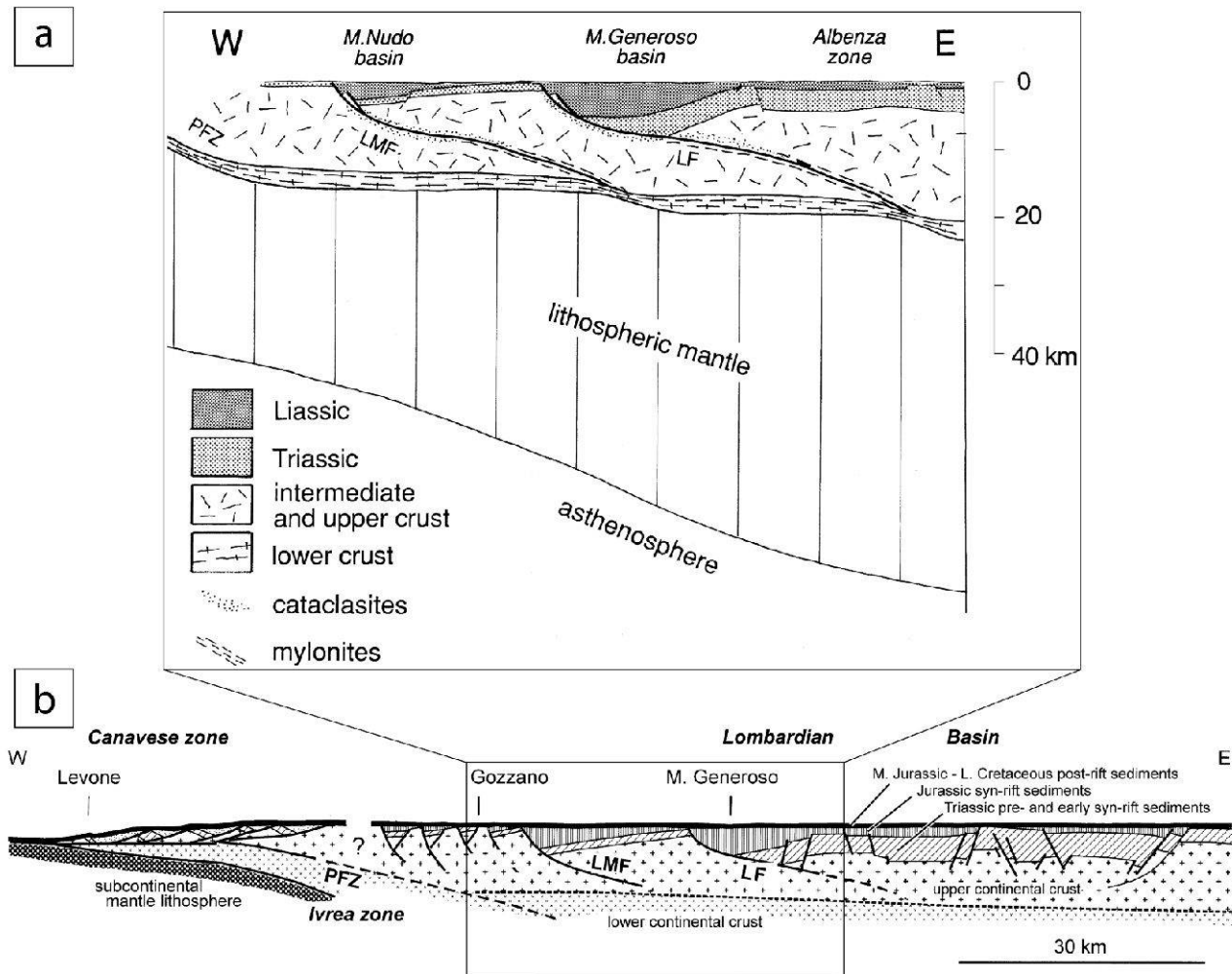


Fig. 4: a) Lithospheric profile across the western part of the South-Alpine segment of the Adriatic passive continental margin. PFZ: Pogallo Fault Zone; LMF: Lago Maggiore Fault; LF: Lugano-Val Grande Fault. Figure from Bertotti 1991. b) architecture of the South-Alpine continental margin during the Jurassic. Abbreviations as in Fig. 4a. Figure modified after Ferrando et al. 2004.

Geological map



Restored cross sections

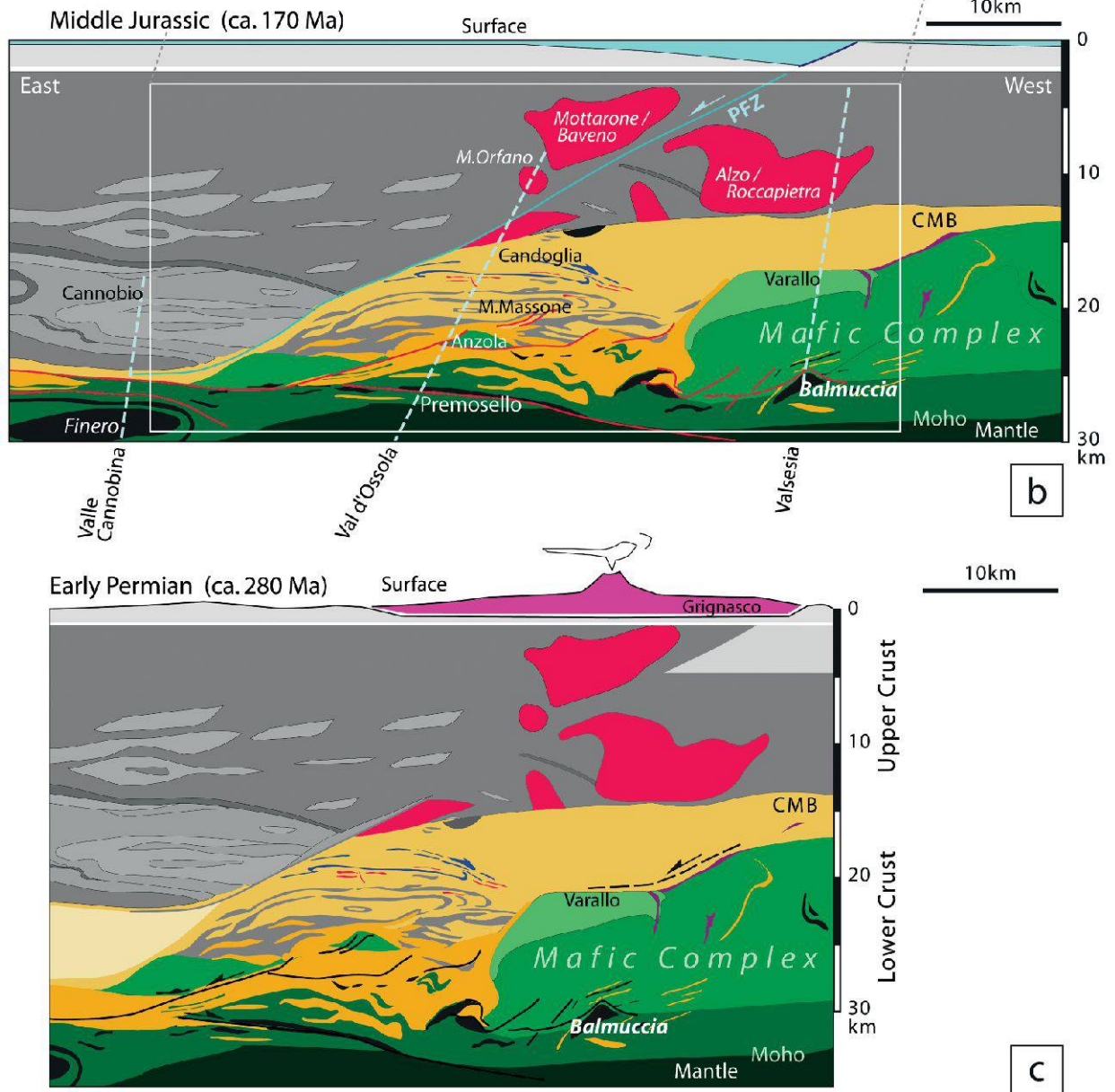


Fig. 5: a) Geological map of the Ivrea-Verbano Zone – Laghi area [see also Fig. 3] and b) corresponding crustal-scale section depicting the situation after the Late Triassic – Early Jurassic extension [simplified version of the restored cross section in Rutter et al. 1999]. c) Schematic reconstruction of the crust for the time of Early Permian magmatism. Figures b) and c) are modified after Schaltegger & Brack 2007.

Grande Fault (LF) can be traced into the basement rocks and hence into deeper levels of the upper crust. The PFZ in the Massiccio dei Laghi is likely a similar fault that continues into the middle crust. Based on correlated lithologic markers the offset along this fault is on the order of 10 km, with the hangingwall (i. e. eastern) part displaced towards the (north-)east (Fig. 3).

The crustal section derived from the actual distribution of rocks on the geological map thus represents crustal geometry following the Mesozoic extension, i.e. with a crust-mantle boundary at shallower levels than «normal» (Fig. 5a, b). Removal of the Mesozoic extension (such as the offset along the PFZ) provides a first-order approximation of the crust during the Permian magmatism (Fig. 5c). In this reconstruction the crust-mantle boundary lies at «normal» levels, in agreement with metamorphic pressure indications from lower crustal rocks. This is

comparable with the distant but similar crust-mantle assembly in Valmalenco, where a fossil Adriatic Moho between lower continental crust and mantle rocks is crosscut and tied together by Lower Permian gabbros.

The Lower Permian crust along the Southern Alps

Lower Permian magmatic products in the lower and upper crust of the Southern Alps, and continental and marine deposits in near surface settings, allow the reconstruction of a several hundred kilometres long transect from a near-mantle level (basal portion of Ivrea-Verbano Zone) to a coeval sea-level in Carnia (Figs. 6, 7). The reconstruction is constrained to a narrow time interval between 285–275 Ma, corresponding to the occurrence of coeval rocks across the entire area. In Carnia the stratigraphic successions of

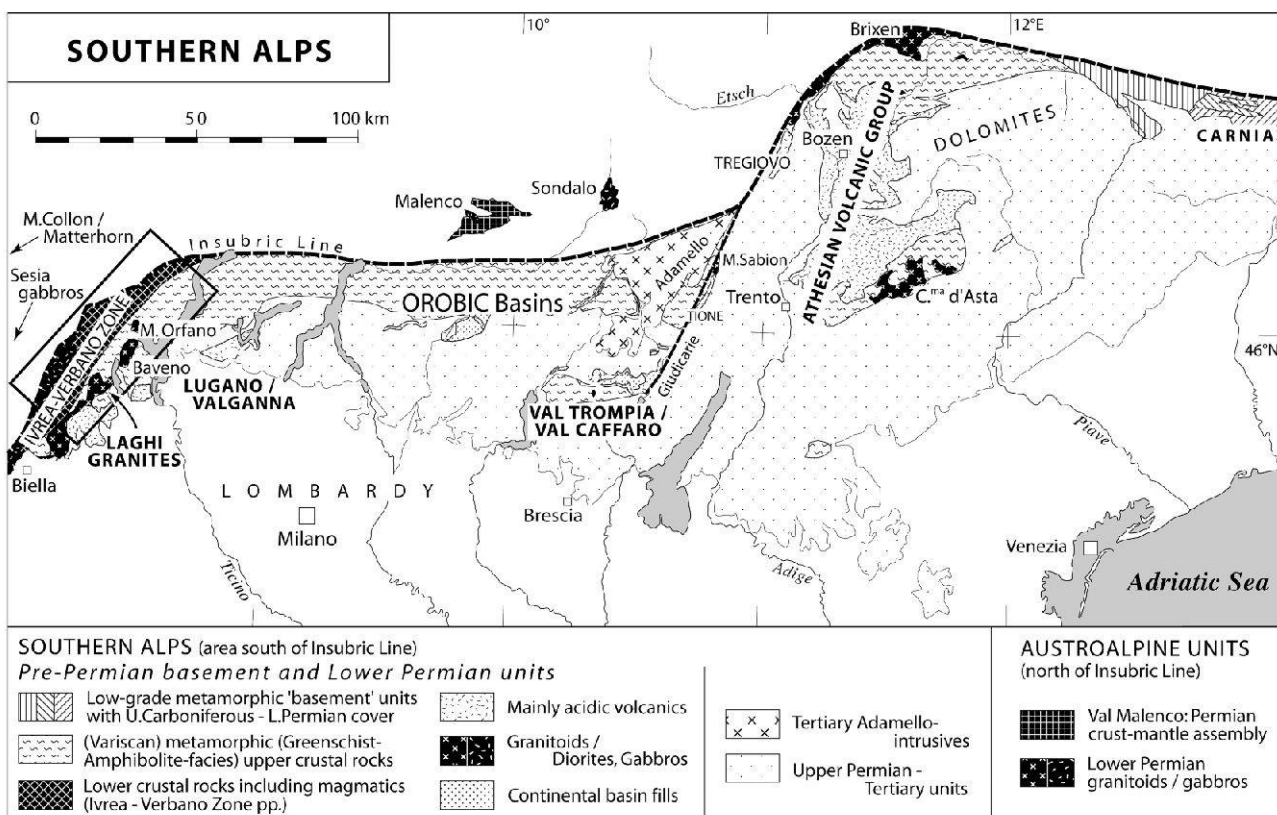
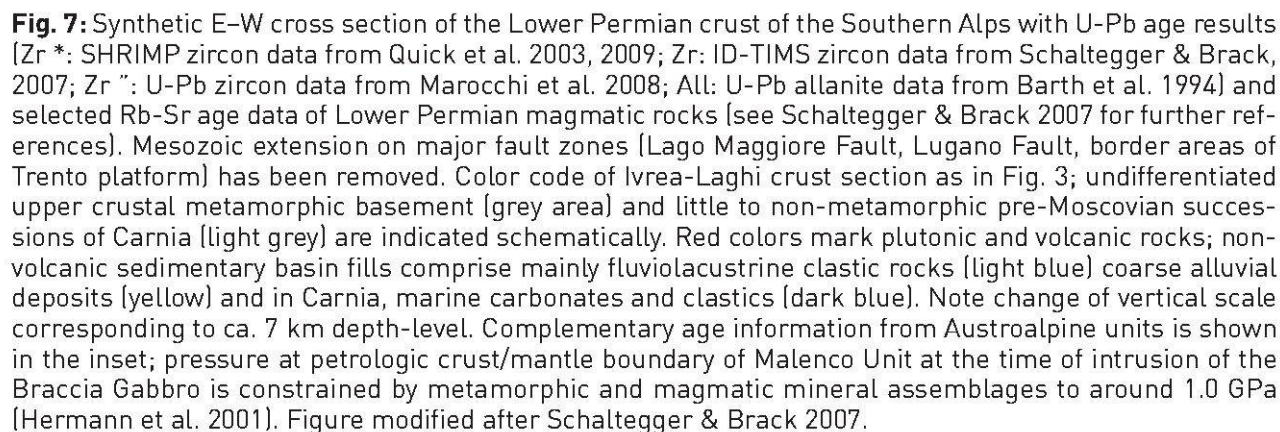


Fig. 6: Distribution of pre-Lower Permian basement and cover rocks of the Southern Alps. The black frame approximately marks the crustal section displayed in Fig. 5. Also indicated are Austroalpine areas with dated Lower Permian magmatic rocks (north of Insubric Line). Figure modified after Schaltegger & Brack 2007.

ern Alps Lower Permian rocks occur as volcano-sedimentary fills of asymmetric continental basins (Orobic and Collio Basins) and volcano-tectonic depressions (290–275 Ma). Only during the Late Permian was a smooth topography east of Lake Como covered by widespread alluvial plain deposits (red conglomerates and sandstones of the Verrucano Lombardo – Gröden Sandstone). In the latest Permian to Early Triassic a shallow sea invaded the area from east to west.



Magmatic products and geodynamic scenarios for the Early Permian

Near-surface and upper crustal intrusions of Early Permian age are concentrated in two realms along the Southern Alps (Fig. 6): the Athesian (Etsch) district to the east (Cima d'Asta, Brixen) and in the Verbano province to the west, i. e. between Biella and the surroundings of Lake Lugano (e. g., Alzo-Roccapietra, Baveno, Cuasso al Monte). Both areas also correspond to prominent centres of Permian volcanic activity, but only the crustal section across the Massiccio dei Laghi and its cover rocks (in Valsesia) exposes the complete magmatic system which ranges from voluminous mantle-derived basic intrusions into the lower crust, to coeval volcanic products (lavas, ignimbrites, volcanoclastic rocks) at the Earth's surface (Figs. 3, 5). However, the Lower Permian crust reconstructed for the Massiccio dei Laghi is likely representative also for other areas with similar near-surface magmatic products.

The formation of basic mantle-derived melts such as those which led to the formation of gabbros and diorites in the lower crust of the Ivrea-Verbano Zone (and in the Malenco unit of the Eastern Alps) is usually related to decompression of mantle material above a rising asthenosphere. A popular theory states that such upward movement of mantle material could result from the post-orogenic gravitational collapse of an overthickened crust, such as the Variscan orogen. Alternatively a rising asthenosphere could generate an active rift, but a passive rift with transtension in connection with crust-scale strike-slip might also induce upward motions of portions of the deep mantle.

Recent paleomagnetic results from Permian rocks in the Southern Alps and other Adria-Gondwana portions indeed suggest a profound reorganization of Pangea during the Permian: from an Early Permian «Pangea-B» to a Late Permian/Triassic (Wegnerian) «Pangea-A». In this model the short (10–15

Ma) phase of extension and formation of Lower Permian basins and associated magmatic products could correspond to the initial stage of rifting just prior to the onset of a large-scale strike-slip translation. In this reconstruction for the Early Permian, the realm of the Southern Alps belongs to Gondwana and would have been situated several thousand kilometres east of the present position relative to Central Europe and Russia, i. e. somewhere southeast of the present Caspian Sea (for details see Muttoni et al. 2003).

2. Field trips

Between Valsesia and Val d'Ossola the Massiccio dei Laghi exhibits two significantly different crustal sections (for itineraries and proposed stops see Fig. 3):

- The Valsesia section provides insight into the shallowest (volcanic) and the deepest portions of the crustal-scale Lower Permian magmatic system. The excursion follows the Sesia River between Romagnano and Balmuccia.
- The Val d'Ossola section allows the study of upper crustal intrusions and a variety of lithologies and structures in the lower crust, with only scarce Permian magmatic rocks.

2.1 The Valsesia transect

Valsesia in its lower part between Romagnano southeast of Grignasco and Balmuccia crosses a complete section of crustal rocks ranging from Lower Permian volcanic rocks that erupted at the Earth's surface (stops 1, 2) through coeval upper crustal granite plutons to an enormous volume of mafic intrusive rocks in the lower crust (stops 3, 4) and in direct contact with deep seated mantle lithologies (stop 5). The following paragraphs provide a short outline of the petrologic and geochemical characteristics of the main units.

Permian granitoids and associated volcanic rocks

In the excursion area, several Lower Permian granitoid plutons with ages coeval with the «Mafic Complex» of Valsesia-Val Sessera crop out; the most voluminous complexes are (from southwest to northeast): Valle Mosso Granites, Alzo-Roccapietra Granite and Baveno/Mottarone Granite/Granodiorite. These mid to upper crustal granites are biotite – two feldspar granites and granophyres, geochemically identified as metaluminous granites with isotopic characteristics indistinguishable from the «main gabbros» of the «Mafic Complex». The plutonic granitoids are accompanied by volcanic products, dominantly re-sedimented explosive tephra deposits, with minor lava flows and plugs of predominantly rhyolitic to rhyo-

dacitic composition. The majority of outcropping volcanic deposits are non to poorly welded chaotic, unsorted «tuffs» representing volcanoclastic mass flow deposits that can either be interpreted as poorly welded ignimbrites (ash-flow tuffs), lahars (volcanic mud-flow deposits) or breccias formed by land-slides from the collapse of instable caldera walls (**stop 1** [N 45°41'18", E 08°19'27.9"]): roadcut northwest of Grignasco; Lower Permian volcanoclastic rocks with clasts of folded basement schists of the Scisti dei Laghi, Fig. 8a). Common feature of these deposits are the lack of sorting, grading or stratification, the presence of angular fragments of both volcanic (e. g., lapilli and lava, juvenile and lithic) and country rock (basement and granites) origin, dispersed in a fine-grained (muddy, ash-rich) matrix inferring the presence of water during depo-

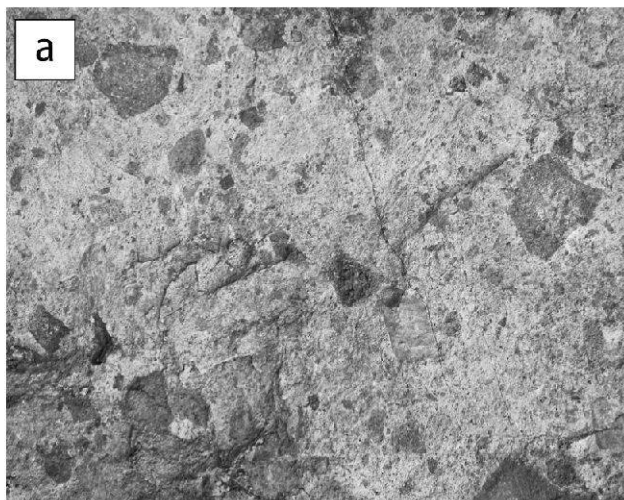
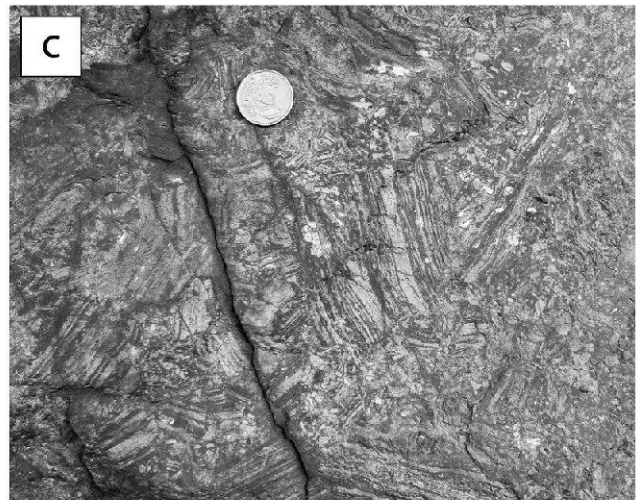
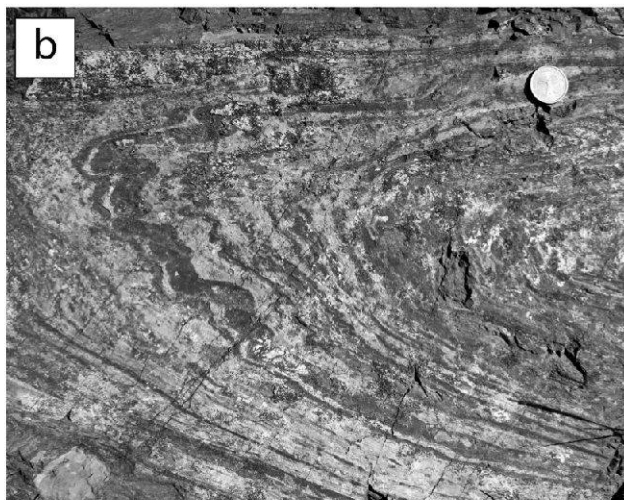


Fig. 8: a) Lower Permian volcanoclastic «tuff» at Grignasco (stop 1) composed of unsorted angular fragments of country rocks (basement schists, granites) and volcanic clasts (lava and lapilli) in a fine grained «muddy» matrix consisting of altered volcanic ash. b) Folded banded obsidian at Crevacuore (stop 2) forming a lava flow; banding represents alternating degassed (obsidian) and foamed (pumice) layers of rhyolitic glass; folding is igneous and produced during deformation of slowly advancing lava flows (or plugs). c) Banded obsidian at Crevacuore (stop 2); brecciation of banded lava at the tip of highly viscous lava flow caused by cooling at the surface and internal shearing during movement.



sition. These «tuff» deposits are typical for high silica, explosive Plinian eruptions potentially associated with the formation of large caldera structures and subsequent remobilization of primary tephra (fallout and ignimbrite). Minor lava flows forming short flows and plugs of (banded) obsidian locally accompany the volcanoclastic sediments (**stop 2** [N 45°41'23.2", E 08°15'26.4"]): Crevacuore [turnoff to Guardabosone]; Lower Permian banded rhyolites, Figs. 8b, 8c). Geochemical and isotope geochemical characteristics of the Permian igneous products are typical for extensional magmatic systems comparable to present-day igneous systems in the Western US, e. g., the Basin and Range province. Such magmatic systems are characterized by bi-modal magmatism dominated by tholeiitic basaltic (gabbroic) and rhyodacitic-rhyolitic (granodioritic-granitic) compositions and extensive interaction with crustal lithologies by assimilation–fractional crystallization processes producing isotopic signatures intermediate between purely mantle and crustal derived source compositions respectively. High resolution U-Pb age dating of igneous zircons (Fig. 7) reveals that the lower crustal gabbroic rocks, the mid to shallow crustal plutonic granitoids and the acidic volcanics are coeval around 280–285 Ma with some granites extending to slightly lower ages of about 275–280 Ma testifying to the existence of a large scale, complex igneous system encompassing the entire crustal column.

The Kinzigite Formation and the «Mafic Complex»

The Kinzigite Formation represents a pre-Variscan volcano-sedimentary succession with predominantly metapelitic sedimentary protoliths metamorphosed under amphibolite- to granulite-facies conditions. Rarely also arenaceous metasediments and marbles occur. The igneous component is basaltic, actually transformed into amphibolite and pyribole (a granulite-facies meta-

morphic rock containing pyroxene, amphibole and plagioclase). Amphibolite- and granulite-facies metamorphic mineral assemblages record temperatures lower than 600°C and higher than 800°C and pressures between 0.4 – 0.7 and 0.6 – 1.1 GPa respectively. The transition between the two metamorphic zones is rapid and often tectonic, marked by high-temperature shear zones.

The «Mafic Complex» intrudes the Kinzigite Formation (Figs. 3, 5) and primary contacts are preserved locally. It reaches its maximum thickness of around 11 km in the southern part of the Ivrea-Verbano Zone, along Valsesia. Primary igneous features (layering, intrusive contacts, magma mingling, more rarely textures) are generally preserved. All igneous rocks of the «Mafic Complex» underwent slow isobaric cooling which induced re-equilibration of the primary igneous phases, resulting in the common occurrence of granoblastic and coronitic textures and unmixing in coexisting low- and high-Ca pyroxenes. Re-equilibration pressures have been estimated to vary between 0.5 and 0.8 – 0.9 GPa from the roof to the bottom of the «Mafic Complex». The complex represents an enormous magma system in the lower crust that grew during continuous input of mantle-derived magma during extensional tectonics (mantle uplift with partial melting) in a relatively small stationary magma chamber of estimated 4 × 1 km in size. Concomitant large-scale ductile deformation of the complex and transport of cumulates downward and outward from the magma chamber occurred as a consequence of extensional tectonics. The Valsesia section exhibits the most complete «stratigraphy» and major thickness of the various lithological units consisting, from top to bottom, of an upper dioritic zone (diorite units) in contact with the metasedimentary rocks, a virtually homogenous gabbro (main gabbro) and a layered series of cumulus rocks in contact with the mantle rocks of the Balmuccia body.

At Sacro Monte di Varallo (**stop 3a** [N 45°49'12.5", E 08°15'32.2"]) folded Kinzigitegneisses with marble streaks are exposed along the access road immediately north-east of Sacro Monte. They represent the roof-levels of the «Mafic Complex» whose garnet-bearing diorites form the hill of Sacro Monte s. s. (**stop 3b** [N 45°49'5.8", E 08°15'20.6"]) in front of the basilica).

A much deeper level inside the «Mafic Complex» is well exposed on the south bank of the Sesia River, ca. 400 m west of the small village of Isola di Vocca (**stop 4** [N 45°49'31.9", E 08°09'55.5"]) exhibiting stratified gabbroic and pyroxenitic rocks of the intermediate zone of a layered series with conspicuous compositional layering and syn-magmatic deformation structures (shearing, faulting and folding; Fig. 9a). The main lithologies are gabbro-norites and websteritic pyroxenites.

Mantle Peridotites: The ultramafic body of Balmuccia

The largest and best known peridotite units in the Ivrea-Verbano Zone are from south to north the Baldissero, Balmuccia and Finero

bodies (Fig. 3; labeled as ultrabasic rocks). These bodies are aligned close to the north-western margin, i. e. in the «stratigraphically» deepest part of the Ivrea-Verbano Zone. Minor bodies of peridotite, recognized as lithospheric upper mantle material, also occur at other stratigraphic levels. The peridotite bodies display different petrologic characteristics (composition, degree of depletion, metasomatic overprint) documenting a heterogeneous South Alpine (Adriatic) lithospheric mantle. The Baldissero and Balmuccia massifs are the least depleted (most fertile, lherzolitic) and least metasomatized lithologies, whereas the Finero peridotite is highly depleted (harzburgitic) and has been pervasively metasomatized by late K-rich fluids, possibly during extension in the Late Triassic.

The Balmuccia ultramafic body between Valsesia and Val Mastallone has the shape of an elongated, NNE-trending lens, 5 km long and with a maximum width of 0.8 km. To the west the body is sheared by the Insubric fault system and in tectonic contact with mylonitized members of the «Mafic Complex» or with metasediments of the Kinzigite

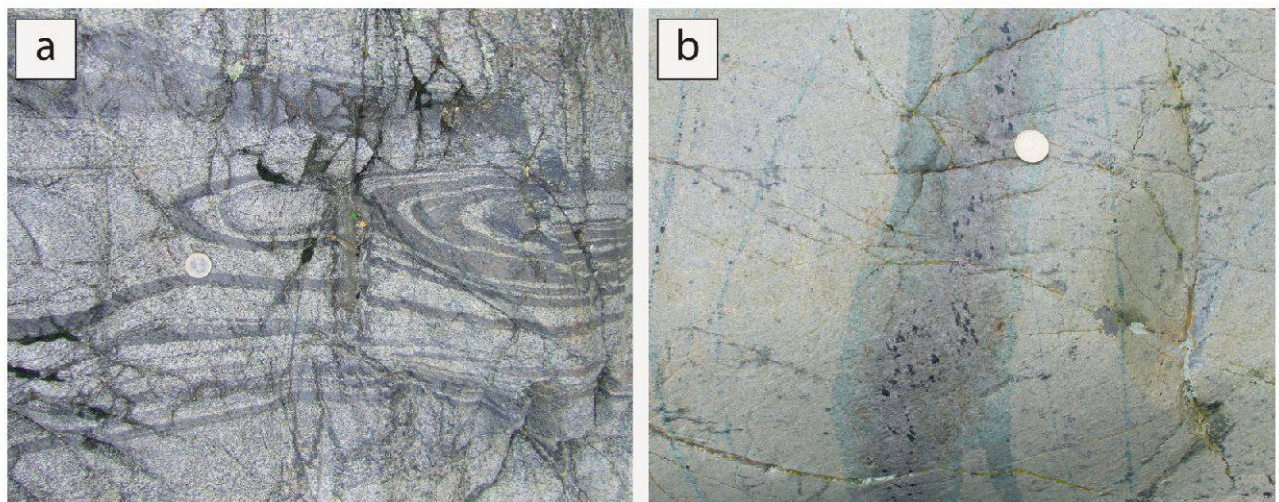


Fig. 9: a) Layered gabbro-norites (two pyroxenes, plagioclase) at Isola [stop 4; layered series of the «Mafic Complex»]: The layering consists of plagioclase-rich and dark pyroxene-rich strata. Folding is syn-magmatic, most probably representing «slump-folds» in partly solidified cumulate layers at the floor or along the wall of a magma chamber. b) Balmuccia peridotite [stop 5]: Crosscutting relationship between a first generation of Cr-diopside vein (green) cut and offset by a later dyke of Al-augite websterite (2-pyroxene + spinel, grey) in lherzolite. Second generation dykes can possibly be attributed to magmas feeding the overlying «Mafic Complex».

Formation. To the east, the peridotite is in igneous contact with the basal zone of the «Mafic Complex». Balmuccia is a very fresh peridotite. The dominant rock-type is a clinopyroxene-poor spinel-facies lherzolite (Fig. 10). Harzburgitic or dunitic compositions are rare and mostly occur at the contacts of pyroxenite dykes or in layers along with spinel streaks. Amphibole is present in trace amounts, phlogopite is basically absent, except in a few places along the eastern contact.

Pyroxenite dykes form approximately 5 % of the Balmuccia outcrops. The dykes can be distinguished into a Cr-diopside and an Al-augite suite (Fig. 9b). The Cr-diopside suite is composed of at least three generations of dykes and their thickness varies from less than 1 cm to about 1 m. They consist of websterites bearing clinopyroxene, orthopyroxene, spinel and minor olivine. In the field Cr-diopside dykes are recognized by the intense green color of the Cr-bearing clinopyroxenes. The Al-augite dykes are up to 1.5 m thick, have a gray color and abundant spinel reaching up to 20 %. Apart from

spinel, they consist of Cr-poor clinopyroxene, orthopyroxene and sometimes amphibole. Several dyke generations can be distinguished on the basis of crosscutting relationships and all of them are younger than the Cr-diopside suite.

In general, the Cr-diopside dykes record all the deformation episodes of the host peridotite. They show the same foliation and, when discordant, they are folded with axial planes parallel to the peridotite foliation. Al-augite dykes are syn- to post-kinematic with respect to the older foliation. Only the latest, black Al-augite dykes and associated gabbro pods do not show signs of deformation. These relationships suggest that the different generations of dykes record distinct episodes ranging from the accretion of asthenospheric mantle material to the lithosphere to the emplacement of such mantle lithosphere at the base of the crust. The age of these processes is unknown but assumed to be much older than the Lower Permian magmatism.

The cliffs of both riverbanks south of Balmuccia (**stop 5** [N 45°49'11.3", E 08°09'10.0"])

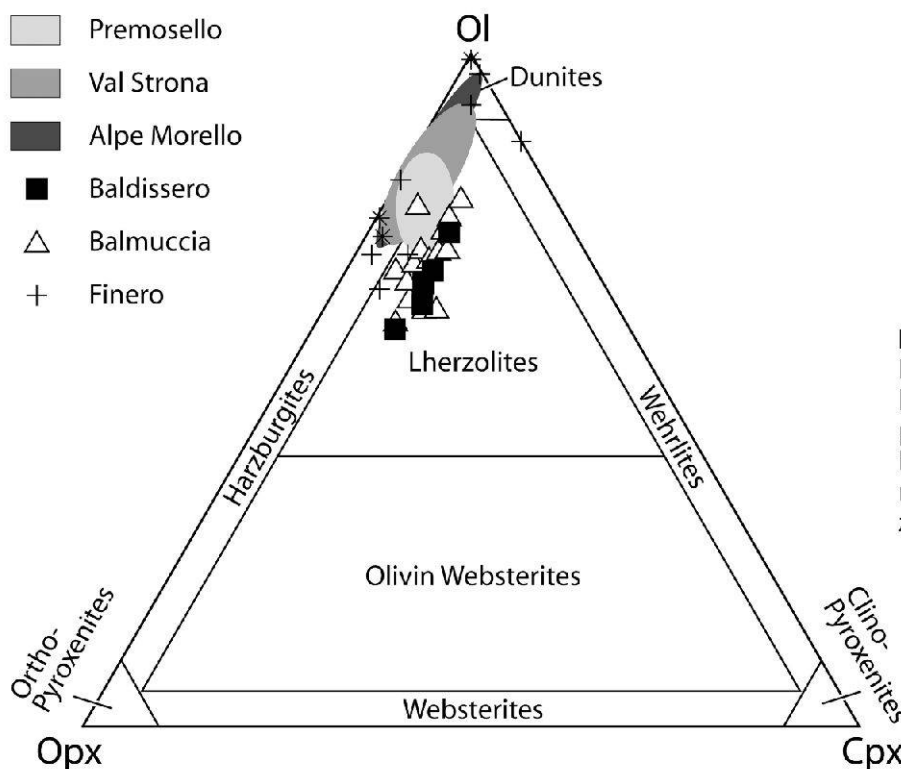


Fig. 10: Modal composition of Ivrea-Verbano Zone peridotites [Val Strona rocks include samples from Alpe Piumero, Alpe Francesca, Alpe Crotta]. Figure modified after Rivalenti & Mazzucchelli 2000.

exhibit variable textures of the peridotite, the relationships between the Cr-diopside and Al-augite dykes and between dykes and peridotite. The dominant peridotite lithology is lherzolite, except in the contact regions of the dykes as well as in dunitic or harzburgitic layers containing spinel trails. These latter are interpreted as the refractory remnants of Cr-diopside dyke melting. Texture is foliated, locally porphyroclastic to proto-granular. Various generations of Cr-diopside and Al-augite dykes are easily distinguished on the basis of intersections. Cr-diopside dykes vary from concordant to discordant with respect to the peridotite fabric and dykes are sometimes ptigmatically folded. Al-augite dykes cut all the Cr-diopside dykes and are less or not deformed. Black veins of pseudotachylites occasionally cross all lithologies.

2.2 The Val d'Ossola transect

The rocks exposed between Lago Maggiore and the Insubric Line in the lower part of Val d'Ossola comprise the deeper part of the upper crustal Serie dei Laghi and the Ivrea-Verbano Zone (Fig. 3). Prominent Lower Permian granite plutons (Baveno, Mont'Orfano) occur in the upper crust (i. e. east of the CMB-Line and Pogallo Fault Zone) whereas coeval magmatic rocks are subordinate in the lower crust of this transect. There, the largely pre-Permian metamorphic lithologies and the structure of the lower crust are preserved and provide insight into the architecture of a «magma-poor» deep portion of the South Alpine crust.

The Serie dei Laghi and Permian granite plutons

The Serie dei Laghi comprises a series of metasedimentary schists and gneisses with occasional amphibolite sheets that are cut by orthogneisses of Ordovician age. The outcrops of the rocks of the Strona-Ceneri unit form a distinct tract comprising Ceneri-Gneiss, Gneiss Minuti and other gneisses

with amphibolites and ultramafic rocks of the Strona-Ceneri border zone. Along the Pogallo Fault Zone northeast of Omegna the outcrops of this tract are displaced by about 14 km (Fig. 3). The rocks of the Serie dei Laghi were folded at least twice on a range of scales but only the last (local) folding event (open folds) may be geometrically correlated with late folding in the Ivrea-Verbano Zone. Apparently undeformed gabbrodioritic rocks of Permian age seem to cut the Cosato-Mergozzo-Brissago (CMB) Line. Therefore the Permian stretching and magmatism probably postdates all folding events. All structures and also Permian magmatic rocks are cut by the Pogallo Fault Zone (PFZ).

The Serie dei Laghi hosts undeformed granitic intrusions of Permian (275 – 285 Ma) age, which range in diameter from 1 km to more than 10 km (Figs. 3, 5, 7). In the region east of the main granitic bodies the dominant schistosity of the metasediments of the Serie dei Laghi dips gently (ca. 25°) towards the southeast. The Baveno body itself shows evidence for moderate post-Permian tilting. Immediately to the west of the granite intrusions but also towards the PFZ the host rock schistosity becomes vertical.

At **stop 6** ([N 45°56'19.3", E 08°26'29.8"] small quarry on the western slope of Mont'Orfano) the Lower Permian white granite of Mont'Orfano (U/Pb-zircon age: 281.8 ± 1.5 Ma; Schaltegger & Brack 2007) can be studied in outcrop. Mont'Orfano and the pink and white granites between Baveno and Omegna (Mottarone) most probably belong to the same intrusive suite. Typical mica-schists of the surrounding Serie dei Laghi are exposed between the railway line and the main road at Mergozzo; **stop 7** [N 45°57'39.8", E 08°26'39.6"].

The Ivrea-Verbano Zone

The Ivrea-Verbano Zone (Figs. 1, 3) is dominated in its lower metamorphic grade (i. e. south-eastern) portion by a thick unit of variably migmatized metasedimentary

schists (garnet, biotite, plagioclase, quartz, sillimanite and muscovite), known as the Kinzigite Formation. This unit forms a strikingly continuous and uniform interval about 2 – 4 km wide along the entire length of the visible part of the Ivrea-Verbano Zone. In a northwestern direction the metamorphic grade increases and the metasedimentary rock texture changes due to progressive replacement of muscovite and biotite by sillimanite, K-feldspar and garnet. The schistose lithologies grade into more massive banded migmatitic gneiss, known locally as «Stronalite». In the middle portion of the Kinzigite Formation a heterogeneous group of variable metasediments occurs. An apparent «stratigraphic» succession comprises the quartz-feldspatic gneisses at the top, followed by a quartzite layer, then marbles, metapelites and marls. Below is a thick quartz-feldspatic and metapelitic layer followed by interlayered bands of amphibolite, between 1 – 10 m thick. These latter have been interpreted as mafic lavas or intrusions within an early (Palaeozoic) pelitic accretionary complex. Finally, there are up to 1 km thick streaks of banded and massive amphibolite (e. g., big blocks in the gorge behind the small village of Nibbio [N 45°59'52.2", E 08°23'41.8"]).

Rocks exposed along the road from Candoglia to Cava Madre (Fig. 11a, b) comprise several layers of marble and quartzite, Kinzigite-gneiss and pegmatites. The exploited marble layer forms a narrow band of relatively coarse-grained white to pink calcite-marble with dm-thick layers of calc-silicate and amphibolite. The latter show spectacular boudinage structures. Streaks of sulfides (pyrite, chalcopyrite) are unwelcomed impurities. The Candoglia marble layer is possibly a folded isoclinal fold with its uphill termination at approx. 900 m altitude. Close to the office of the quarry workings at Candoglia [N 45°58'33.9", E 08°25'20.9"] a marble model shows the concession owned by the «Veneranda Fabbrica del Duomo di Milano». Since the 14th century this marble has been exploited and used as the main building stone of the dome of Milano. Taking advantage of a wide network of canals (Naviglio Grande; Fig. 1) river boats managed to transport the rock material from the quarries to the immediate neighbourhood of the majestic dome in the historical centre of Milano. Currently the main excavation activities are at Cava Madre (Fig. 12) where workings started around 1800.

The quarries at Candoglia are not open for the public. However, along strike, on the

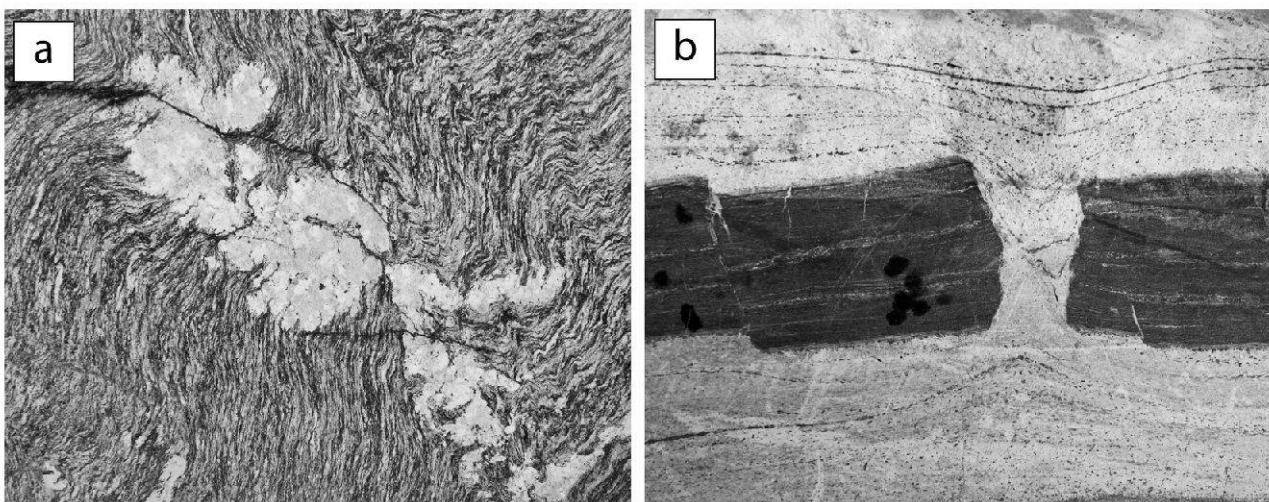


Fig. 11: a) Migmatitic biotite-rich Kinzigite gneiss on a cut surface along the road close to Cava Madre at Candoglia. Undeformed white leucosomes cut the folded schistosity of the gneiss and consist of coarse feldspar, quartz and tourmaline. b) Boudinaged amphibolite layer in a matrix of calcite-marble on the floor surface at Cava Madre as in 2010.

opposite flank of Val d'Ossola the corresponding layer is found to continue above the village of Ornavasso. Similar marbles also occur in the Kinzigit-gneisses in Val Strona southwest of Val d'Ossola. At **stop 8** [N 45°58'08.5", E 08°24'10.4"] in a hair-pin bend along the road from Ornavasso to the Sanctuary of the Madonna del Boden the entrance of an old abandoned underground excavation of «Candoglia marble» is visible. The San Nicolao church along the same road [N 45°58'05.8", E 08°24'27.3"] is a prominent edifice made of this local marble.

The traverse along Val d'Ossola displays the curious arrangement of large antiformal structures in succession, each several kilometres in amplitude but without any obvious synformal structures in between (e. g., Massone antiform in Fig. 12). On the SE limb of the major Massone fold structure, peg-

matitic granitoid sheets occur in concordant and discordant lenses up to a few tens of metres thick and a few hundred metres long. The coarse-grained pegmatitic pockets and sheets are supposed to be of Permian age. The Massone folding predates the intrusion of the «Mafic Complex» of Valsesia, which at least locally produced sufficient heat to cause migmatization (Fig. 11a) and granulite facies metamorphism in the surrounding metasediments. However, the episode of melting that is strictly related to the «Mafic Complex», is superimposed on an earlier episode of regional metamorphism and it is as yet unclear whether all the migmatization and degranitization of metapelitic rocks observed in this region is due to the thermal effects of the hot basic magmas of the «Mafic Complex» and its possible northeastern extensions.

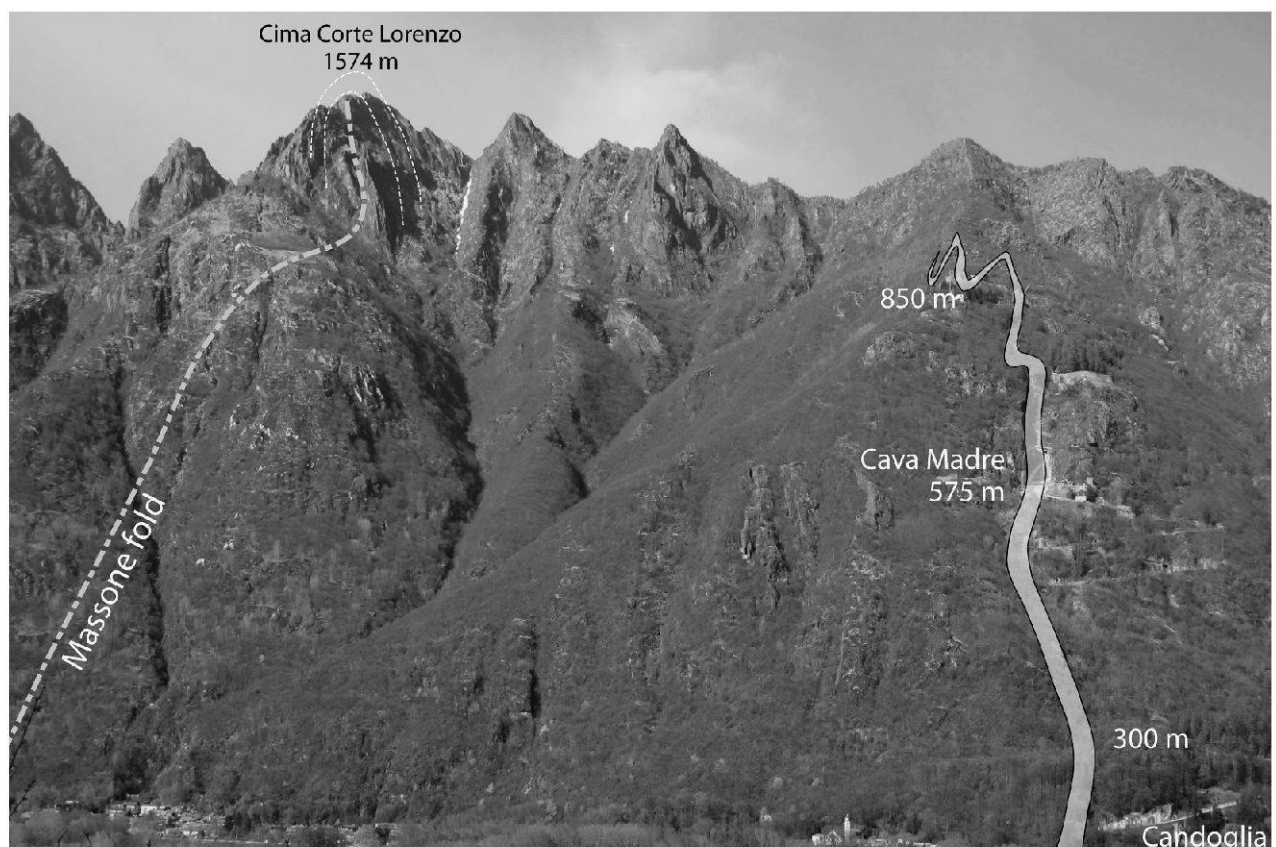


Fig. 12: View of the eastern flank of Val d'Ossola looking from the San Nicolao church above Ornavasso. The traces of the Massone fold and of the main marble layer at Candoglia are indicated. The marble band is folded, terminates uphill and possibly represents a refolded isoclinal fold illustrating the multi-phase nature of the structures in the Ivrea-Verbano Zone. All these structures are cut by predominantly NW-SE oriented white pegmatites of supposed Early Permian age.

Towards the northwestern border of the Ivrea-Verbano Zone, sheet-form or lensoid ultramafic bodies include lherzolites, dunites and pyroxenites (Fig. 10). Although prominent lenses such as the one at Premosello [N 46°00'19.9", E 08°19'09.6"] are undoubtedly of upper mantle origin, the ultramafic sheets may have been detached from the mantle and are tectonically incorporated into the lowermost part of crustal rocks.

Lithologies typical for the deeper part of the lower crust (Ivrea-Verbano Zone) in the Ossola transect comprise granulite-facies metapelites («Stronalites», with garnet and sillimanite), garnet-bearing metabasic rocks and peridotites. Spectacular blocks of these rocks can be studied in a river bed at Ruminca (**stop 9** [N 45°59'35.4", E 08°17'31.5"]).

The Insubric «Line» [by S. M. Schmid]

Insubric «Line» is a misnomer in that there is no sharp line between the Southern Alps (in our area represented by the Ivrea-Verbano Zone) and the southern steep belt (or «root zone») of the nappe pile of the Central Alps. In fact it is a some 1000 m thick belt of mylonites that accompanies complex differential movements between the Southern Alps and the Central Alps. The latter are back-thrusted to the SE to S, with a vertical component of displacement that reaches 20 km in the Ticino area. At the same time some of the mylonites, namely those immediately adjacent to the Ivrea-Verbano Zone, also accommodated significant dextral strike-slip. Combined back-thrusting and strike-slip movements occurred between about 35 – 20 Ma ago. After 20 Ma ago pure dextral strike-slip was still ongoing, but manifested itself by exclusively brittle faulting that is confined to the Jorio-Tonale Line east of Locarno and the Centovalli Line north of the SW part of the Insubric Line in Val d'Ossola. The chapel of Loro (**stop 10** [N 45°59'54.8", E 08°16'49.5"]) is right at the contact between massive mafic rocks, marbles and

ultramafic rocks of the Ivrea-Verbano Zone (only with signs of alteration in the immediate surroundings; exposures along trail south of chapel) and an approx. 1000 m wide belt of Insubric mylonites north of the chapel. This sharp contact, referred to as «fabric boundary», separates the well preserved pre-Mesozoic fabrics found south of the chapel from the alpine-age fabrics within the Ivrea-derived mylonites north of the building. The mylonites were syn-tectonically retromorphosed under greenschist facies conditions, the complete break-down of the granulite to amphibolite facies parageneses being a pre-requisite for penetrative alpine overprint («reaction-induced strain softening»). The «fabric boundary» represents the southern edge of the area that had sufficient supply of water – a prerequisite for retro-morphosis and mylonitization. Note that there are no brittle features visible at all. North of the Ivrea-derived mylonites follows a thin band of dark calc-mylonites and quartzitic mylonites ascribed to Mesozoic rocks that once covered the northwesternmost part of the Southern Alps (Canavese sediments). This is then followed by granitic mylonites derived from the Sesia Zone. From the chapel there is also a splendid view to the eastern flank of Val d'Ossola. South of the Insubric Line, the Ivrea-Verbano Zone is characterized by the huge Alpine-age Proman antiform. North of the Insubric Line, the NW-dipping Insubric mylonites and northerly adjacent banded gneisses of the Sesia Zone contrast with the massive rocks of the Ivrea-Verbano Zone.

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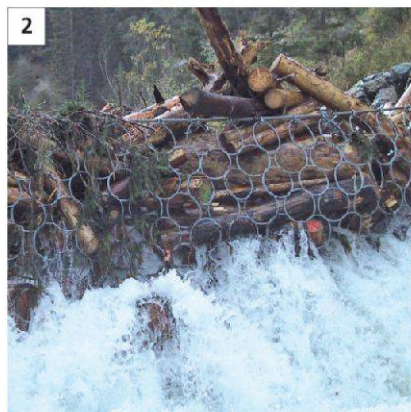
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