Advanced Field Geology 2024: Central Alps

Fred Gaidies
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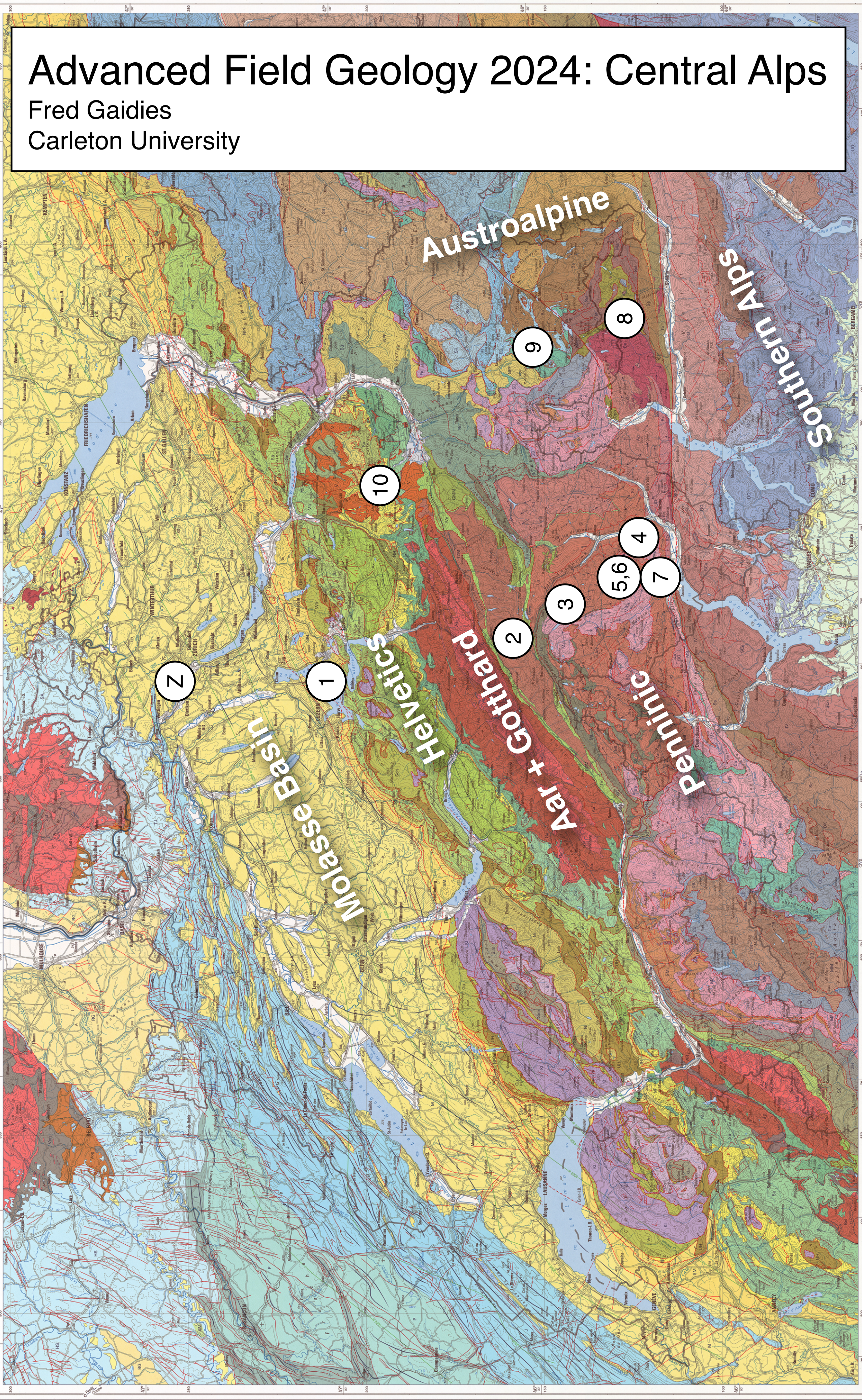


Date	Activities	Accommodation
Saturday, August 24	Arrival at Zurich airport.	Zurich Youth Hostel Mutschellenstrasse 114 CH-8038 Zürich Tel: +41 43 399 78 00 zuerich@youthhostel.ch www.youthhostel.ch/zuerich
Sunday, August 25	Rigi (Molasse Basin), Helvetic nappes	Hospental Youth Hostel Gotthardstrasse 31 CH-6493 Hospental Tel: +41418870401 info@jugendherberge-hospental.ch
Monday - Wednesday, August 26 - 28	Gotthard massif (pre-Triassic basement of Helvetic nappe system); Campolungo mapping exercise (Lower Penninic)	Capanna Leit 46°28′01.02″N 8°43′07.64″E +41 91 868 19 20 capannaleit@gmail.com www.capanna-leit.ch
Thursday, August 29	Alpe Arami (UHP metamorphism - depending on time); Lavertezzo: Ponte dei Salti (polydeformed para- and orthogneisses, pegmatites), Verzasca Dam, Ponte Brolla (migmatites)	Ostello per la gioventù "Palagiovani" Via B. Varenna 18 CH-6600 Locarno Tel: +41 (0)91 7561500 locarno@youthhostel.ch www.youthhostel.ch/locarno
Friday and Saturday, August 30 and 31	Field trip Valmalenco (Permian crust-mantle transition)	Rifugio Gerli Porro 23023 Chiesa In Valmalenco SO, Italy Tel: +39 0342 451404 info@rifugiogerliporro.it www.rifugiogerliporro.it
Sunday and Monday, September 1 and 2	Contact between Lower Austroalpine (Err nappe complex) and Upper Penninic (ophiolite-bearing Platta nappe) at Julier Pass; Glarus Thrust (Vorab)	Ferienlager "alte Säge" Via davos Sulten 13 CH-7017 Flims-Dorf Tel.: +41 (0)81 911 28 07 edwina.candrian@gmail.com http://www.altesaege.ch/
Tuesday, September 3	Glarus Thrust (Lochsite)	Zurich Youth Hostel Mutschellenstrasse 114 CH-8038 Zürich Tel: +41 43 399 78 00 zuerich@youthhostel.ch www.youthhostel.ch/zuerich
Wednesday, September 4	Departure to Ottawa	

A brief geological introduction

The European Alps form a ca. 1000-km-long fold and thrust belt which has been the focus of geological research for more than 200 years. However, unlike some other orogens, the European Alps record a complex history of collisional and extensional events, making discerning its tectonic evolution an ongoing task.

Western Europe experienced four orogenic cycles in the Phanerozoic: (1) Cadomian (Cambrian), (2) Caledonian (Ordovician - early Devonian), (3) Hercynian or Variscan (late Devonian - Carboniferous), and (4) Alpine (Mesozoic to present), as well as two important periods of failed rifting in the Permian ("Verrucano") and late Paleogene (Rhine-Bresse graben system in the foreland of the Alps). The Alpine basement rocks were involved both in the Variscan orogeny and the Permian rifting. During our field trip across the Central European Alps, we will mainly be investigating the results of Alpine metamorphism and deformation but will also be studying structures and mineral assemblages that formed during the Variscan orogeny.

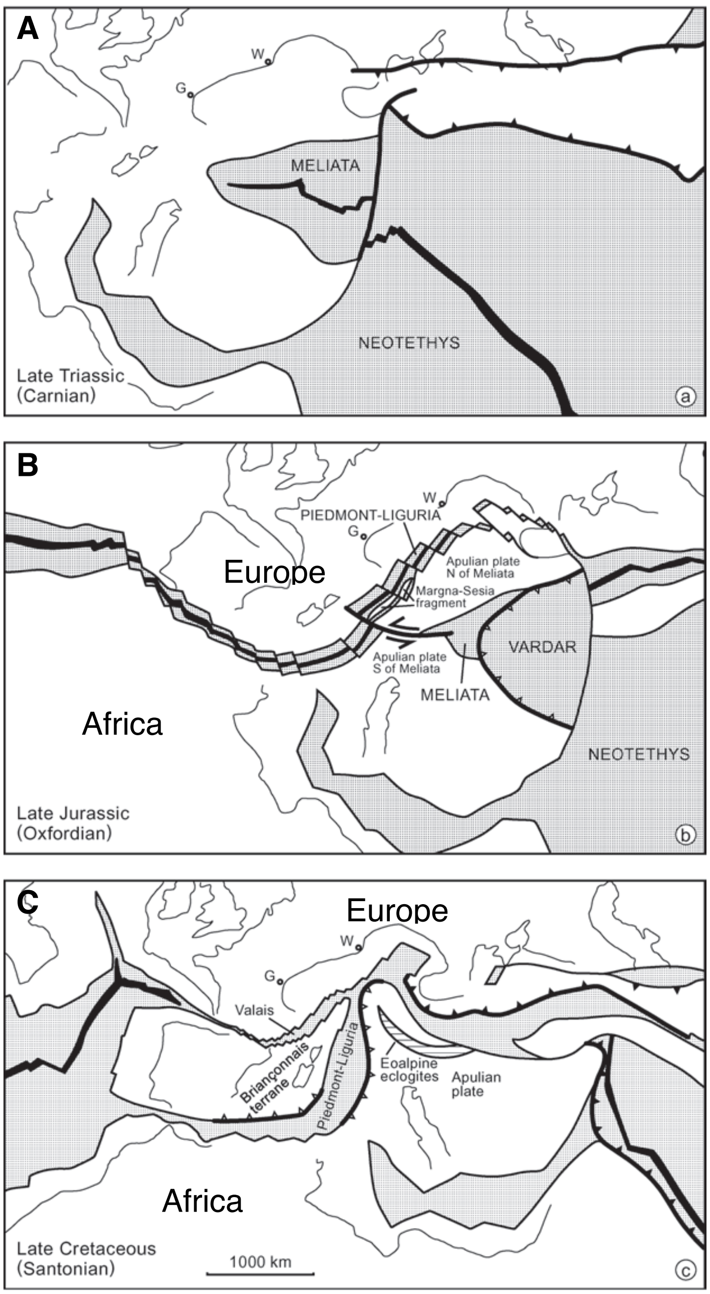


Fig. 1: Paleogeographic reconstruction (Schmid et al., 2004).

The Alpine orogeny involved a typical Wilson cycle, starting in the latest Permian to Triassic with a continental to shallow marine platform that covered a large part of western Europe. These platform sediments are characterized by (locally) basal quartzites overlain by limestones, shales and dolomites (with particularly thick dolomite horizons in the Southern and Eastern Alps). Evaporitic horizons deposited in the middle and late Triassic acted as important detachment horizons during Alpine deformation and to a large extent facilitated the thin-skinned tectonics typical of the more external parts of the Alpine chain. Although minor rifting already started in the Triassic (Fig. 1A), the main rifting occurred in the early Jurassic (Liassic).

Initially there was little volcanic activity during rifting and the lithospheric mantle was in places exposed to the ocean floor before development of a true mid-ocean ridge with mid-ocean ridge basalt (MORB) injection. The first

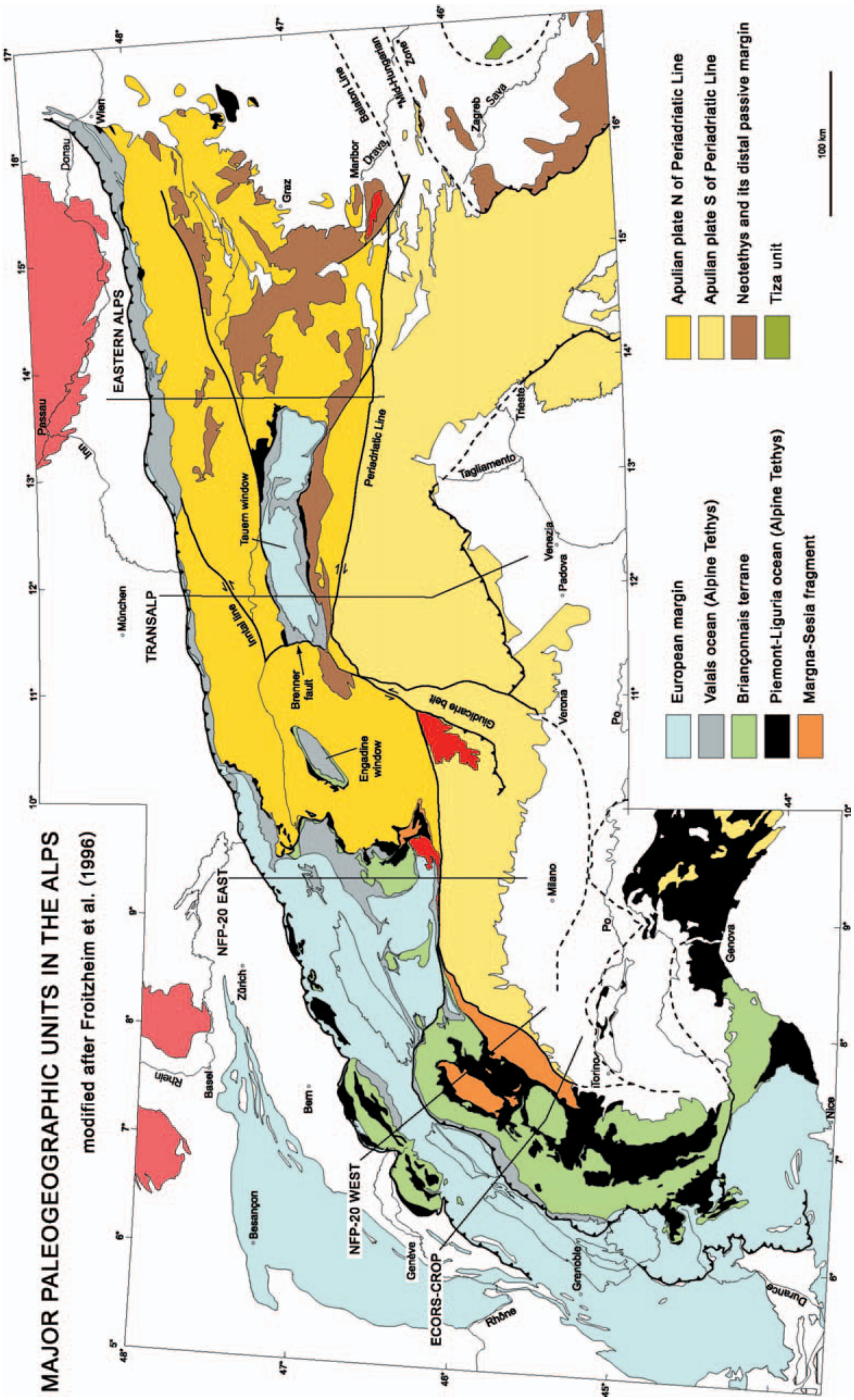


Fig. 2: Major paleogeographic units of the Alps (Schmid et al., 2004).

documented oceanic basalts and gabbros associated with this development have mid-Jurassic ages around 160-165 Ma (Rubatto et al., 1998; Schaltegger et al., 2002). Rifting occurred in a sinistral transtensional regime, and associated normal faults generally had a ca. NS strike, although the average margin orientation was more EW and parallel to the current Alpine trend (e.g. Bernoulli and Weissert, 1985). In a continuation of this rifting stage, **Europe** and the southern **Apulian** (**Adriatic) continent** drifted apart in an oblique sinistral manner. It is during this drifting stage, from the mid-Jurassic to late Cretaceous, that the classic paleogeographic domains of the Alps were developed on the northern and southern passive margins (e.g. Trümpy, 1980). Fig. 1B illustrates the paleogeographic situation during the late Jurassic when the Apulian plate is separated from Europe by the **Piedmont-Ligurian ocean**.

Sediments were continuously deposited on the European platform and the **Helvetic** (proximal carbonate platform) located further to the south. The Ultrahelvetic domains (characterized by marly distal and deeper water sedimentation) developed on thinned continental crust south of the Helvetic, and were separated by the Piemont-Ligurian ocean from the opposite passive margin carbonate platform of the **Southern Alps** on the Adriatic (Apulian) continent. This simple pattern is complicated in the Central and Western Alps (i.e. in Switzerland and France) by the presence of a northerly oceanic domain, the **Valais ocean**, immediately south of the Ultrahelvetic domain and separated from the Piemont-Ligurian ocean to the south by the elongate ridge of the **Briançonnais micro-terrane**. Although paleontological or geochronological control is rather limited, current models suggest that the Valais ocean only developed in the Cretaceous and that previously the Briançonnais domain was still part of the European passive margin. This section of the margin then split off during the Cretaceous, again in a sinistral transtensional manner, and indented into what had previously been the Piemont-Ligurian ocean domain (Fig. 1C).

The earliest **flysch** sediments in the southern Piemont-Ligurian oceanic domain also appear at this time. The term “flysch” was originally used by farmers of the Simmental (canton Bern) for fields with slaty, “bad” rocks. According to the modern definition of this rock type, flysch is a thick, bedded sedimentary sequence composed of marine sandstones, calcareous arenites or conglomerates, intercalated with marine claystones or shales, deposited by turbiditic currents or mass flows into a foreland basin to an active orogen. The earliest flysch in the southern Piemont-Ligurian domain have been interpreted as representing the accretionary prism developed with the initiation of subduction on the southern margin of the Piemont-Ligurian ocean. In this model, the initiation and subsequent opening of the Valais ocean was coeval with the closing of the Piemont-Ligurian ocean to the south. The earliest continental material to be subducted is a fragment from the Southern Alps and preserves high pressure metamorphism of an age close to the Cretaceous-Tertiary boundary (ca. 65 Ma, Rubatto et al., 1999). Remnants of the Piemont-Ligurian ocean also locally preserve ultra-high pressure metamorphism developed in the Eocene (ca. 44 Ma, Rubatto et al., 1998), whereas ultra-high pressures preserved in lenses from the Valais oceanic domain give Oligocene ages (ca. 35-38 Ma, Becker, 1993; Gebauer, 1996; Gebauer et al., 1997).

The age of the youngest sediments involved in the Alpine orogenic cycle also decreases progressively from upper Cretaceous in the south to early to mid-Eocene in the Briançonnais, to mid-Oligocene in the Helvetics and locally down to Pliocene in the most NW part of the Jura mountains toward the European platform. This progression in age of metamorphism and deformation generally decreasing to the N or NW is one of the arguments for a south-directed subduction of the European plate under the Adriatic plate (Fig. 3). Reflection and refraction seismic, as well as the

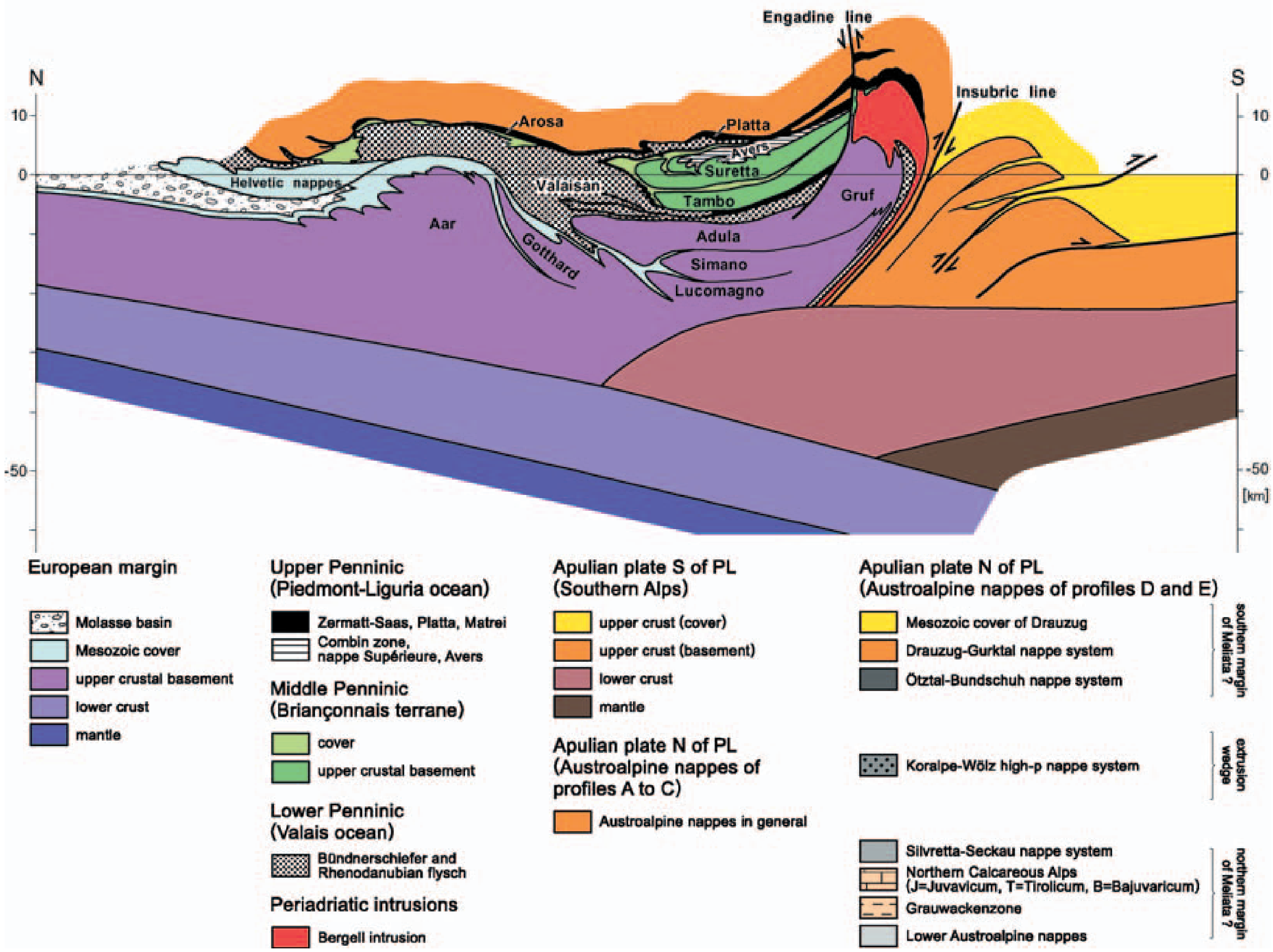


Fig. 3: Schematic N-S transect (NFP-20 East) showing the major paleogeographic and tectonic units to be observed during the field trip (Schmid et al., 2004).

seismic tomography, confirms that the European Moho in the Central and Western Alps dips southward under the Adriatic plate.

As a generalized simplification, deformation involved **in-sequence piggy-back development of thrust units**, so that going from bottom to top of the current tectono-stratigraphy is equivalent to going from north to south and from youngest to oldest thrusting. Loading from the prograding orogenic wedge led to the development of a foreland basin in the north (the Molasse Basin) from the mid-Oligocene onwards. These sediments were progressively overridden (up to ca. 50 km) by the advancing thrust packet, which also provided the source for the clastic molasse sediments. Local **out-of-sequence thrusting** is important, the most spectacular example being the **Glarus thrust** with a thrust displacement of at least 40-50 km.

In the more internal regions, discrete thrusts were replaced by recumbent fold "**nappes**", with strongly sheared overturned limbs. The stacked nappe sequence was subsequently overprinted by both recumbent and upright folds to produce a complex fold interference pattern (e.g. Milnes, 1974a). Barrovian-type metamorphism produced a distribution of mineral zones that crosscut both the initial nappe stack and the main (D2) recumbent refolds. Upright, generally open D3 are broadly oblique to the orogen (“cross-folds”) and in the Lepontine region form two regional antiforms (Simplon or Toce to the west and Ticino or Leventina to the east) separated by a synform (Campo Tencia synform or “Maggia cross-fold”) in EW profile (Merle et al., 1989). In NS profile (Fig. 3), subsequent broad folds with an orogen-parallel axial trend produce a pattern that can be simplified into (1) a broad synform in the north (the Helvetic nappes and klippe of Briançonnais sediments – the “Prealps”), followed by (2) an antiform (the “**External Crystalline Massifs**” – Mt Blanc/Aiguilles Rouges in the west and Gastern/**Aar/Gotthard** in the east), whose southern limb is commonly steep to overturned, and has been called the “Northern Steep Zone” (Milnes, 1974b), followed by (3) a rather tight synform (Berisal Synform in west, Chiera synform in east, Milnes, 1976), followed by (4) a rather flat zone in the **central Lepontine Alps**, and finally followed by (5) an antiformal bend into the steep to overturned “**Southern Steep Zone**” immediately north of the **Periadriatic fault-system** which can be followed from the Western Alps, through the Central Alps and to the estern end of the Eastern Alps (Gansser, 1968; Milnes, 1974b).

The Periadriatic fault system developed since the mid-Oligocene (ca. 32 Ma), with a dextral plus north side up relative displacement. In the region of the Central Alps, the Periadriatic fault system separates the Southern Alps from the Penninic and Austroalpine nappe systems that lie to the north. This segment of the Periadriatic fault system is referred to as the **Insubric line**. Whereas the Southern Alps were hardly metamorphosed during the Alpine orogeny (Schmid et al., 1987; Schmid et al., 1989), the highest grade Alpine metamorphism, resulting in the development of migmatites, occurred immediately north of the Insubric line, and the jump in metamorphic conditions across the fault line in the Bellinzona area implies a relative vertical displacement on the order of 15 to 20 km depending on the geothermal gradient assumed.

Exhumation of the Central Alps began in the mid-Oligocene, at upper levels due to top to SE normal shearing related to D2 (e.g., Grujic and Mancktelow, 1996; Nagel et al., 2002) and continuing with the activity of the Periadriatic fault system (e.g., Schmid et al., 1989). Exhumation in the western part of the Lepontine metamorphic dome is directly related to activity of the Simplon Fault Zone (e.g., Mancktelow, 1985), a low-angle normal fault active from at least ca. 18-5 Ma (Grasemann and Mancktelow, 1993). The current overall domal shape of the metamorphic isograds (e.g. Trommsdorff, 1980) reflects the combined effect of the top-to-SE normal shearing of D2 on the eastern border (Nievergelt et al., 1996), the north-side-up component of the Periadriatic fault in the south (e.g. Hurford, 1986) and exhumation in the footwall of the Simplon fault to the west (Grasemann and Mancktelow, 1993).

The Southern Alps developed on the opposing margin of the Piemont-Ligurian ocean as part of the Adriatic plate. They were subsequently in the hanging wall of the subduction zone and therefore have a distinctly different history. Alpine thrusts and folds in the Southern Alps are largely south-vergent, generally thick-skinned, and much more localized (Schmid et al., 1996). Alpine metamorphism is weak to non-existent (Frey et al., 1974; Frey et al., 1999) and the pre-Alpine history can still be studied in detail.

Field trip stops

1. **Rigi (Molasse Basin), Helvetic realm, and tectonic klippen**
   A spectacular overview of Lake Lucerne (Vierwaldstaetter See) and its geology may be obtained from the top of the Rigi (ca. 1798 m). The Rigi is one of the best-known mountains of Switzerland even though it is not part of the Alps (but the "pre-Alps"). Geologically, the Rigi is situated in the **Subalpine Molasse Basin**. The Subalpine Molasse Basin is distinguished from the distal plateau molasse to the north based on its Alpine structures. The northern plateau molasse was not affected by Alpine tectonics.

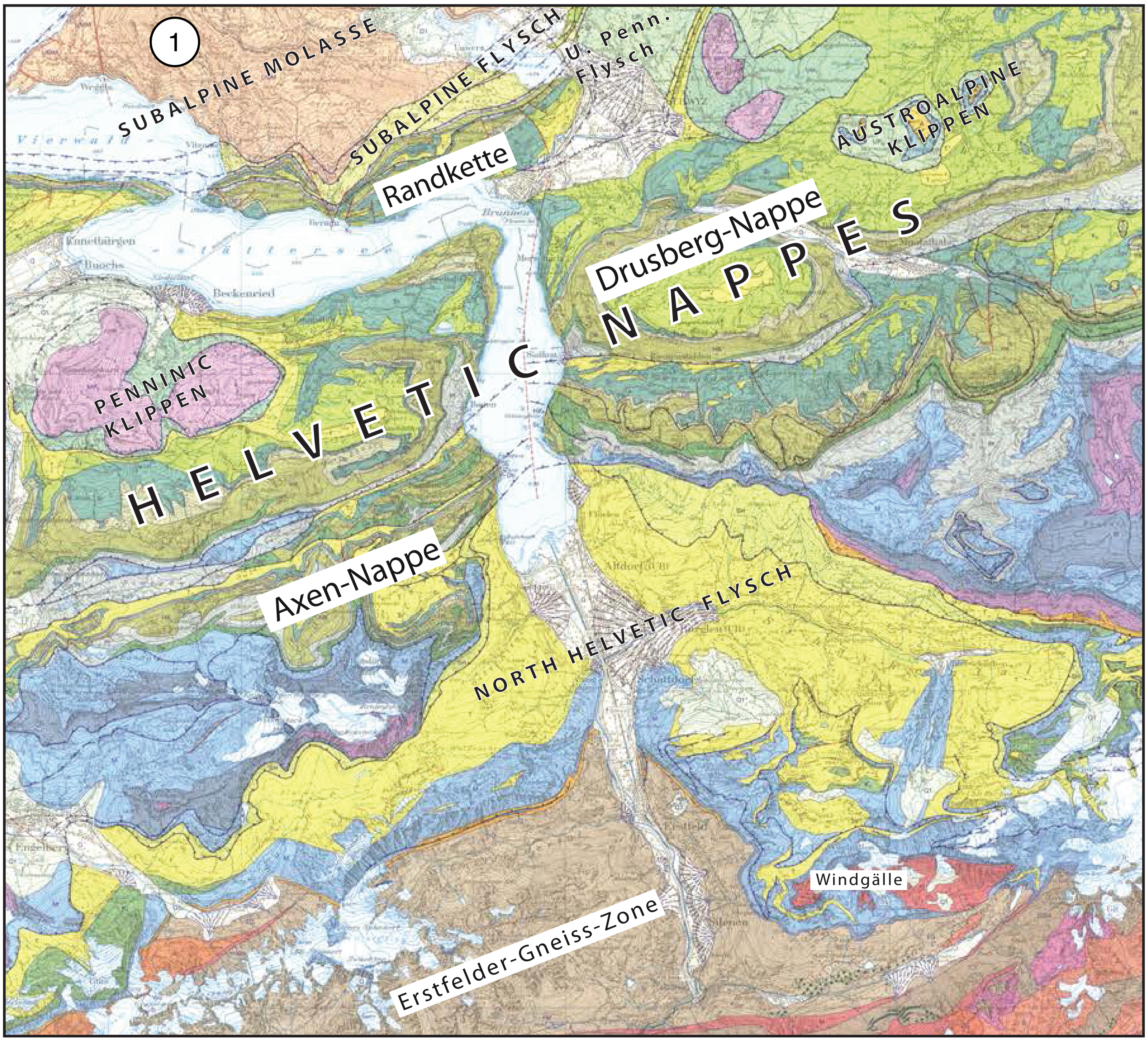


Fig. 4: Location of Rigi (1) in the Subalpine Molasse Basin, and the distribution of the Helvetic nappes and various tectonic klippen in the vicinity of Lake Lucerne.

The term **molasse** is derived from the French word *meule*, a soft sandstone used to form millstones. Modern usage of this term refers to a continental-fluviatile and marine sequence of clastic sediments with 'fining-upward' cycles and 'coarsening-upward' megacycles accumulated in a foreland basin of an uplifting orogen. At the Rigi, successions of conglomerates (*Nagelfluh*) can be seen that accumulated in the proximal part of the Rigi fan between the Oligocene to early Pliocene. Note that the Helvetic and Penninic foreland basins (containing flysch) were filled during the Eocene to Oligocene, and late Cretaceous to Eocene, respectively.

The Helvetic nappes to the South of the Rigi mark the beginning of the Alps. They have been displaced by up to 50 km and overlay the Infrahelvetic Complex with only moderate displacement during the Alpine orogeny. The origin of the Helvetic nappes lies in a region to the south or southeast of the Aar and Gotthard massifs which form the basement to the Infrahelvetic Complex.

At the Rigi, the Mythen may be seen in the SE which represent **tectonic klippen**: erosional remnants of higher-level nappes. The Mythen are klippen of mid-Penninic nappes that were thrust onto Helvetic flysch providing evidence for the fact that the Penninic (and Austroalpine) nappes once covered large parts of the Helvetic nappe system.

Note that the molasse units dip to the SE tectonostratigraphically below the Helvetic main thrust (Fig. 5). The flysch between molasse and thrust was transported from the SE during thrusting. The thrust forms a synform which is positioned above the Aar and Gotthard massifs to the SE and forms the basis of the strongly folded Helvetic nappes. The underlaying Triassic and mid-Jurassic sediments in the Geissberg area are hardly deformed.

312 +/- 10 Ma obtained from Rb-Sr age-dating of biotite within the Erstfeld Gneiss tectono-stratigraphically below the Helvetic main thrust (Fig. 5) correspond to late-Variscan cooling ages, indicating that metamorphic temperatures during Alpine

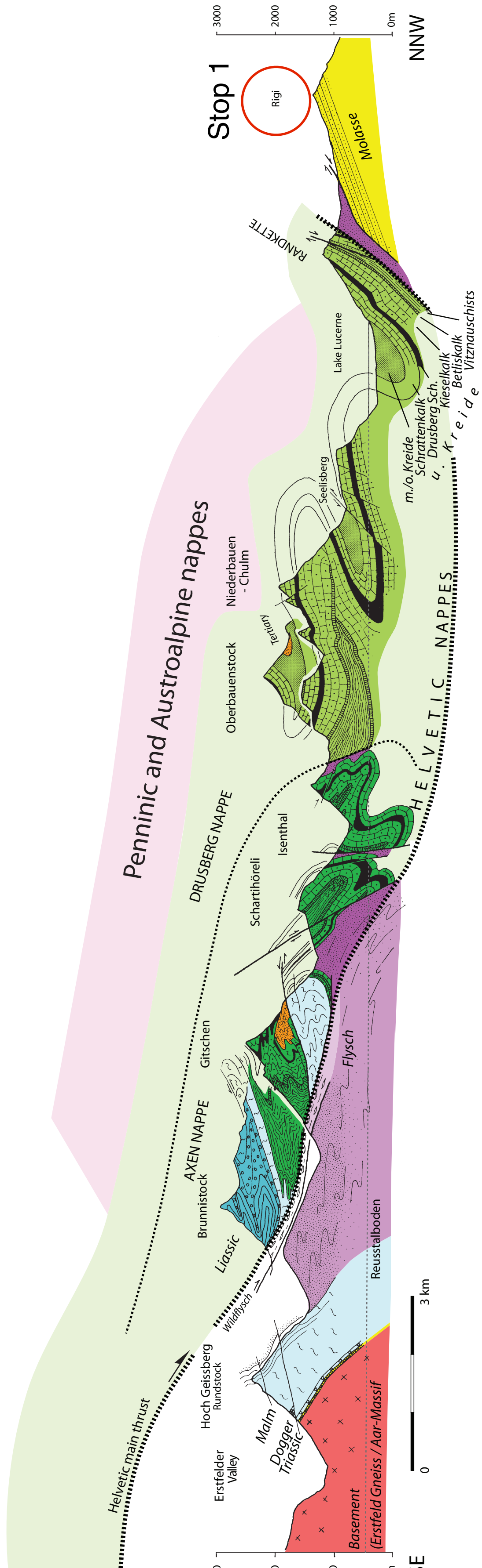


Fig. 5 Section across the Helvetic nappe system.

orogeny did not reset the Rb-Sr system (closure temperature ca. 300 - 350 C). Fluid inclusions in quartz and conventional geothermometry using the mineral reaction kaolinite + quartz = pyrophyllite + H_2O indicate peak metamorphic temperatures between ca. 210 and 300 C for the sedimentary cover of the Aar-Massif.

2. Gotthard Massif: Lithological units of the Variscan basement

The **Fibbia-gneiss** (Fig. 6) is composed of quartz, alkali-feldspar (up to 3 cm), plagioclase, biotite and white mica and dated at ca. 295 Ma using U-Pb zircon geochronology. A similar age was obtained for the **Rotondogranite** which was previously assumed to be of Alpine age given its weakly developed schistosity compared to that of the Fibbia gneiss. Ca. 37 Ma obtained from scarce white mica using the Rb-Sr system (closure temperature ca. 400 - 550 C) indicate that the Rotondogranite reached temperatures above ca. 550 C during the late Eocene. Rb-Sr cooling ages of ca. 15 Ma for biotite in the same rock suggest that the rocks of the Gotthard Massif were uplifted and cooled below 350 C in the mid-Miocene.

The **Glubine-Series** is composed of dark sericitic biotite (para-) gneisses alternating with lighter, quartz-rich gneisses and biotite schists. Calcsilicates containing grossular, zoisite, diopside and actinolite are also present in this series and are interpreted to reflect the result of metamorphic reactions between the gneisses and interbedded carbonate-bearing lithologies during the Variscan orogeny. The Glubine series is strongly deformed and is interpreted to be derived through the metamorphism of graywacke and quartz- and mud-rich sedimentary units that were

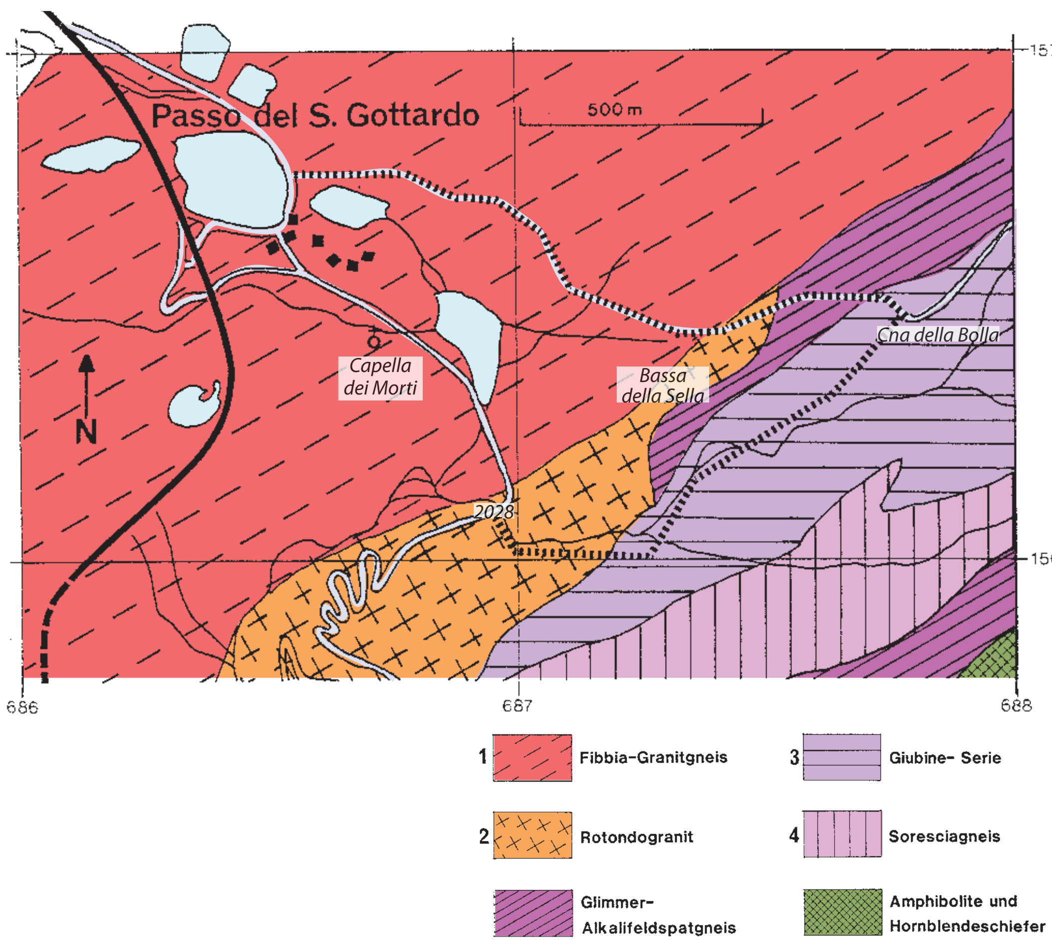
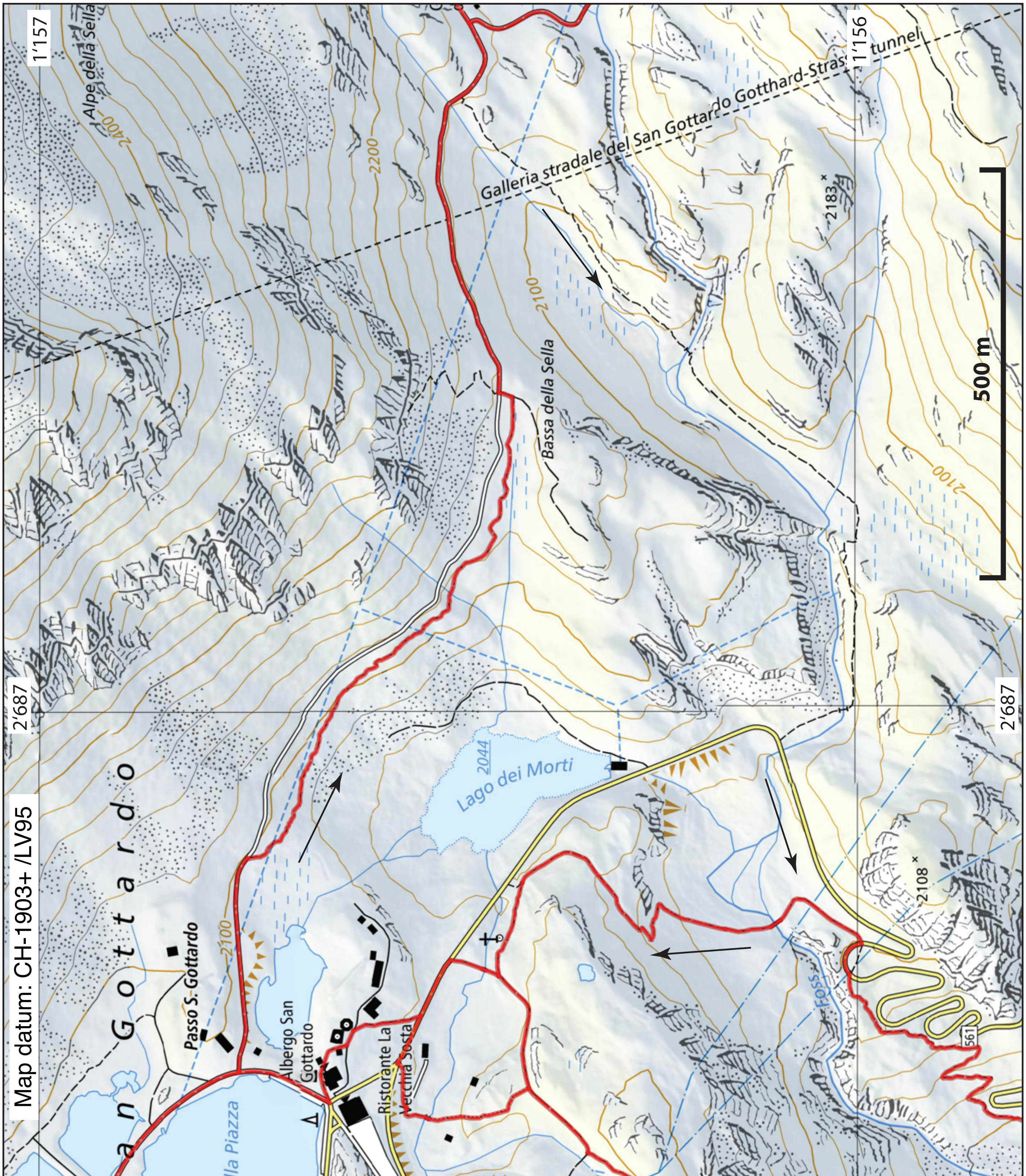


Fig. 6: Lithological units at the Gotthard pass.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1'157
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Galleria stradale del San Gottardo Gotthard-Strass tunnel
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Lago dei Banchi
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Albergo San Gottardo
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accumulated during the Proterozoic given detrital zircon ages of more than 1 Ga.

The protolith of the **mica alkali-feldspar gneiss** (“Streifengneis”) intruded the crust at ca. 440 Ma. Cross-cutting relationships with the Rotondogranite indicate that deformation of this gneiss occurred before Rotondogranite emplacement.

3. The Campolungo area

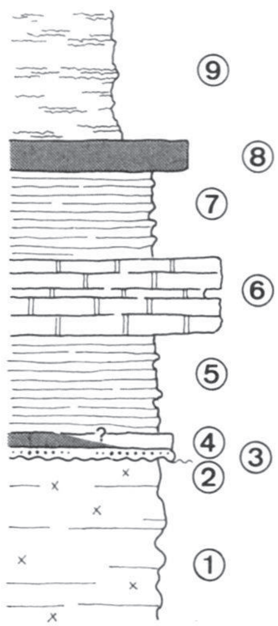


Fig. 7: Stratigraphic column at Campolungo.

This area is famous for its well-preserved Mesozoic stratigraphy ranging from basal Triassic quartzite (3 in stratigraphic column of Fig. 7), locally containing significant amounts of white mica, to Jurassic calcareous mica-schists (“Bündnerschiefer”; 9 in column) and spectacular folds developed in phlogopite-dolomite marble (5), massive white sugary dolomite marble (6), and grey laminated dolomite marble (7). Layers of carstified marble (4 and 8) separate the (locally tremolite-rich) marbles from the metamorphosed siliciclastica.

The Mesozoic sequence exhibits a series of overprinting Alpine structures and metamorphic mineral assemblages characteristic of the amphibolite facies. Staurolite-kyanite-tourmaline-garnet schists, with locally intercalating quartzite and meta-conglomerate units (2 in column) as well as ortho- and paragneisses (1 in column) form the pre-Alpine crystalline basement to the Mesozoic metasediments.

U-Pb SHRIMP geochronology of monazite in basement metapelites yielded pre-Alpine ages of ca. 330 Ma. Alpine monazite has not been identified. However, polyphase garnets with sharp discontinuities in major element

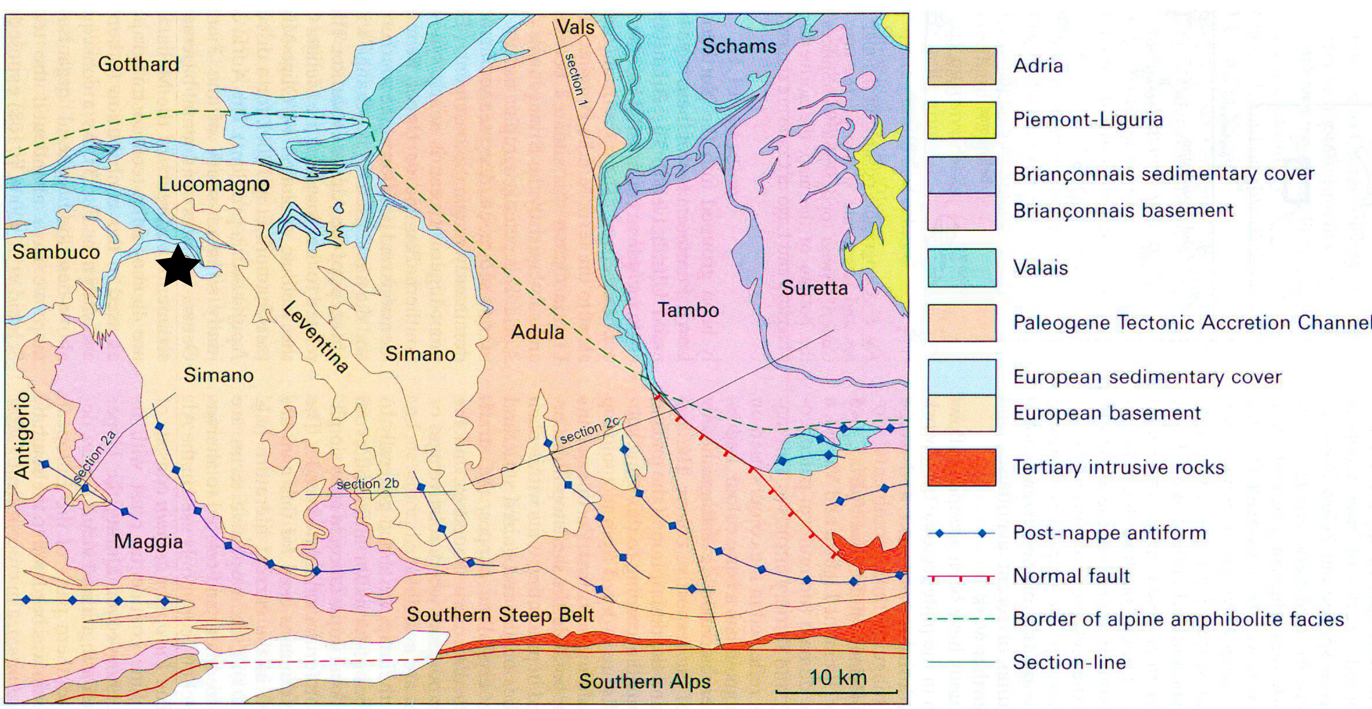


Fig. 8: Simplified tectonic map of the Lepontine dome (Berger et al., 2005) and location of the Campolungo area (star).

zoning between garnet core and rim are interpreted to indicate amphibolite-grade metamorphism during the Variscan and Alpine orogeny. The second growth phase of garnet in the basement mica-schists is chemically similar to the one-phase garnet occurring in the Bündnerschiefer.

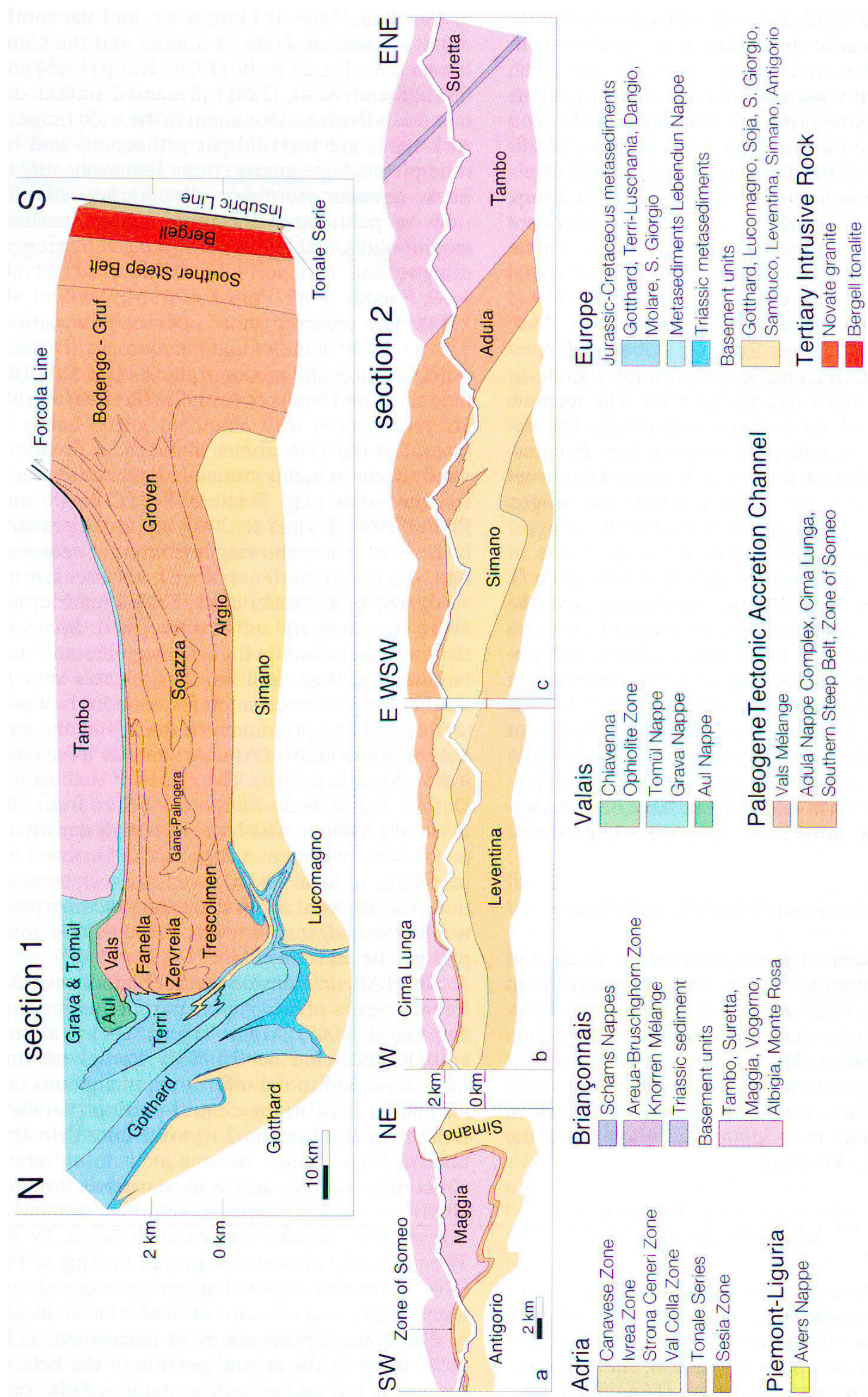
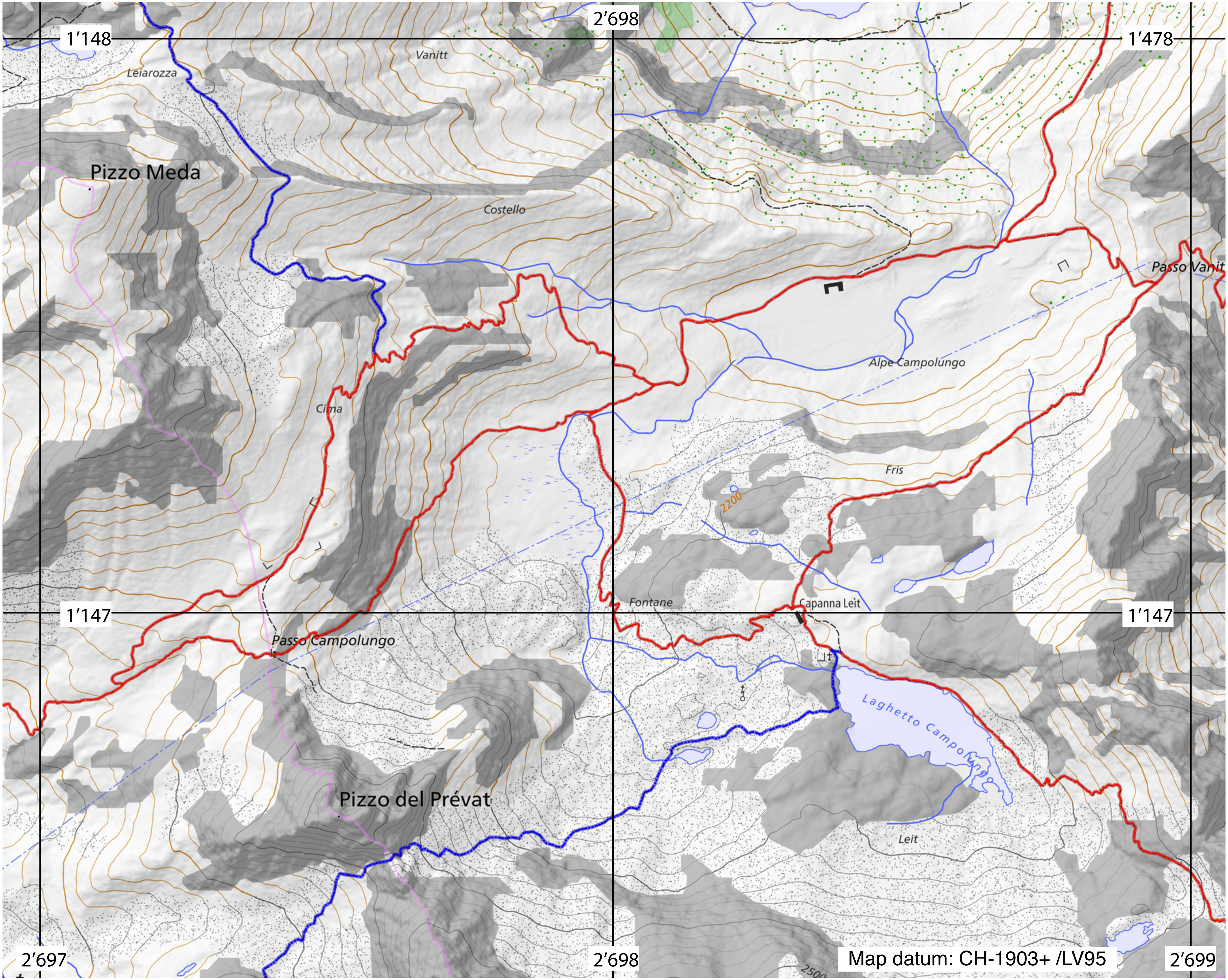


Fig. 9: N-S cross-section of the Lepontine dome (section 1 in Fig. 8; Berger et al., 2005). The Campolungo area is part of the Simano nappe.



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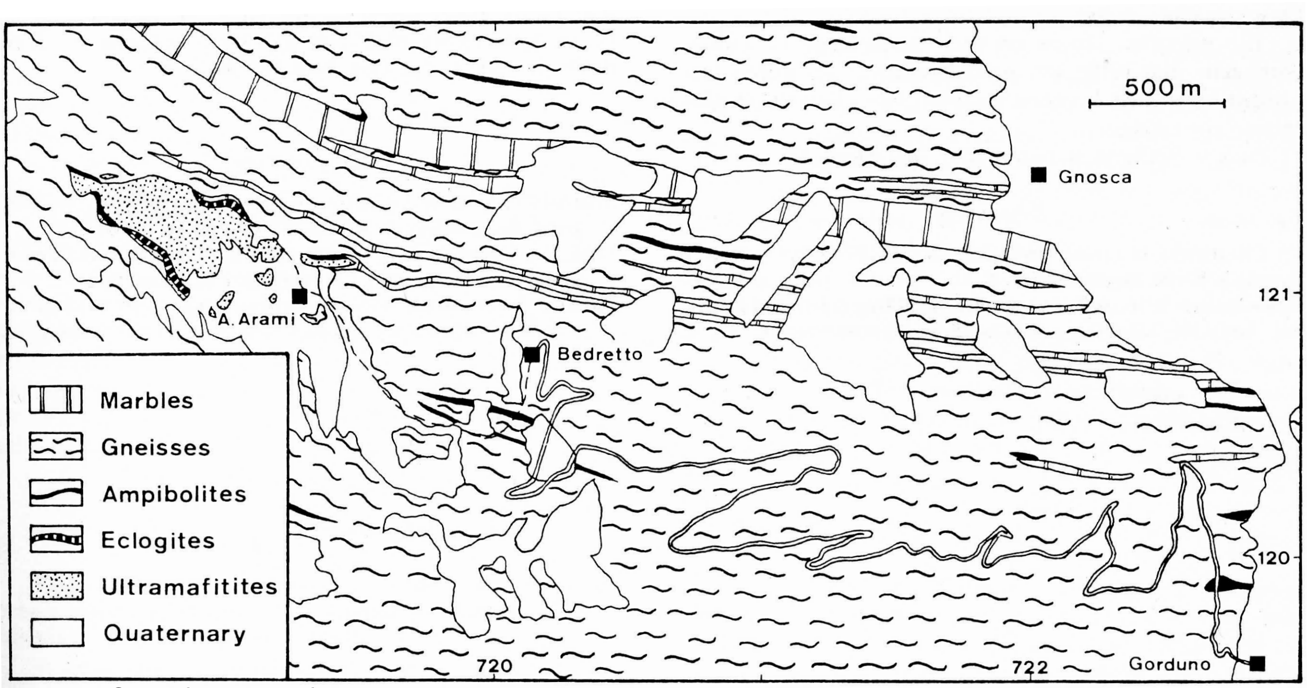


Fig. 10: Simplified map of the area around Alpe Arami.

Regionally, the Campolungo area is part of the Lepontine metamorphic dome and the rocks that will be observed during the field trip belong to the Simano nappe, paleographically a part of the European margin before the onset of tectonic convergence. Structurally above the Simano nappe is the Adula nappe, a Paleogene tectonic mélange unit. This unit is overlain by the Tambo and Suretta nappes which formed the basement of the Briançonnais micro-continent.

4. **Alpe Arami: Garnet peridotites and eclogites**

The rocks at Alpe Arami constitute a classic occurrence of ultramafic and mafic rocks situated in the Cima Lunga nappe. All the units at this site are steeply plunging south and strike E-W. Gneisses and marble envelop the ultramafic body (Fig. 10) which consists of chlorite peridotite and garnet peridotite and is accompanied along its margins by variably amphibolitized eclogite and locally by clinopyroxenite and hornblendite. Chlorite pseudomorphs after garnet are common, and are often flattened by the Alpine schistosity.

According to phase equilibria modelling, maximum metamorphic conditions experienced by the eclogite and garnet peridotite are ca. 800 C and 25 kbar, significantly higher than the Alpine sillimanite-grade documented for this area. It is inferred that these conditions reflect an older metamorphic history, and that the chloritization of the peridotite garnets and the amphibolitization of eclogite were caused by the younger Alpine metamorphic overprint.

5. **River outcrop Lavertezzo**

About 70 years ago, this spectacular outcrop was only known to a few naturalists. However, things changed and now the outcrop may be so crowded by bathers that geologists can hardly see the rocks. We will examine the rocks across the Roman Ponte dei Salti on the right hand bank of the Verzasca river. These rocks are part of the Simano nappe and show a steeply dipping, isoclinally folded banded (locally migmatitic) gneiss series, with synforms and antiforms spaced at a few meters distance and plunging gently towards SE. Leucrocratic gneisses alternate with mesocractic biotite gneisses, banded amphibolite, and locally with schollen of calcsilicate rock. Fold interference patterns may be observed (similar to the one shown in Fig. 11; view towards SE) pointing to three folding phases.

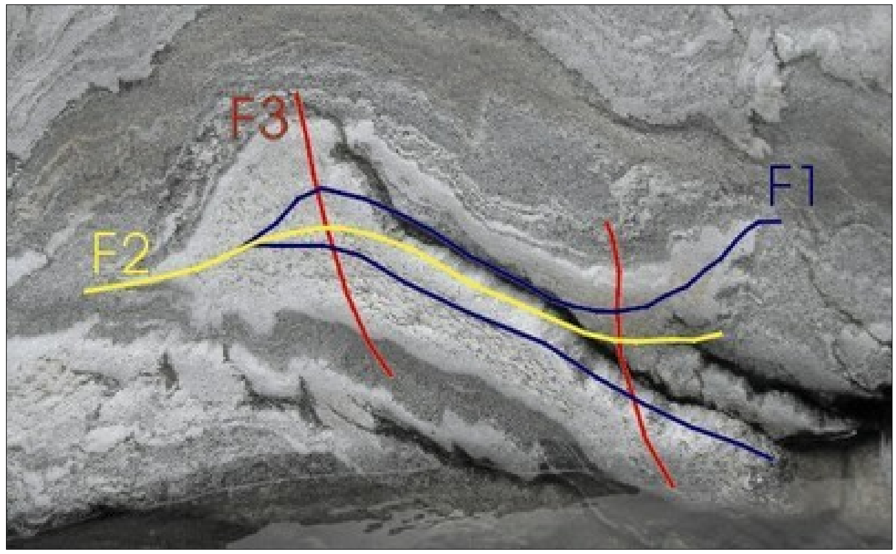


Fig. 11: Fold interference pattern at Lavertezzo.

An undeformed discordant pegmatitic dyke has been dated at ca. 20 Ma indicating elevated levels of heat flow in the crust during Alpine orogeny. However, recent dating of migmatitic gneisses at Lavertezzo, which have also been previously interpreted to reflect high levels of heat flow during the Alpine orogeny, yielded ages ranging between 280 and 290 Ma. This clearly suggests a Variscan origin for the migmatitic gneisses and metamorphic temperatures during Alpine orogeny not high enough for local anatexis in the Lavertezzo area.

6. **Verzasca dam: Southern Steep Zone (Wurzelzone)**

The Verzasca dam is close to the Insubric line (a section of the Periadriatic line) which has a steep northward dip in this area. It was mainly active during the Oligocene starting with relative uplift of the northern block (the Lepontine nappe pile) followed by dextral strike-slip movement. Depending on the geothermal gradient assumed, vertical uplift of 15 to 20 km can be inferred explaining the juxtaposition of rocks which experienced upper amphibolite-grade to lower granulite-grade in the north and unmetamorphosed rocks of the Southern Alps in the south.

The uplift of the northern side is either interpreted as indicating a back-thrust or, alternatively, an originally south-dipping normal fault rotated into its present, north-dipping orientation later on. Imme-


Fig. 12: Vertical F2 fold at the Verzasca dam.

diately north of the Insubric Line, the nappe units are in a steep position; this zone is described as the Southern Steep Belt or as the root zone (Wurzelzone) of the Lepontine nappes. Approaching from the north, one can nicely observe how the nappes and their internal foliation progressively steepen towards the south and finally disappear in the ground immediately north of the Insubric Line. Fig 12 shows a vertical F2 fold that can be studied at the western end of the dam.

To the west, the Lepontine nappes are bounded by the **Simplon Fault**, a SW-dipping normal fault which was mainly active in the Miocene. Instead of joining the Insubric Line to the SE, as one may expect from the large-scale geometry (and as has been erroneously assumed by some), the Simplon Fault turns to the NE towards the center of the Lepontine dome where it becomes less distinct and finally disappears. The eastern boundary of the Lepontine nappes is also formed by a Miocene normal fault, which displays a NE-dipping mirror-image orientation with respect to the Simplon Fault: the **Forcola Fault**. The Forcola Fault disappears to the south under the Quaternary fill of the Mera Valley and, just like the Simplon Fault, does not join the Insubric Line.

7. **Migmatitic orthogneisses at Ponte Brolla (entry to Valle Maggia)**

This outcrop is also part of the Southern Steep Zone and exhibits migmatitic orthogneisses. The light-colored material along the shear band in Fig. 13 (upper right to lower left; N is up) represents a quartz- and feldspar-rich melt (leucosome) crystallizing in the shear band. Such a field relationship results from simultaneous melting by anatexis and shearing, pointing to migmatization during the Alpine orogeny in this area. The sense of shear is sinistral, opposite to the dextral shear sense of the Insubric line. Note that the metamorphic temperatures during the Alpine orogeny were not high enough to cause migmatization near Lavertezzo.

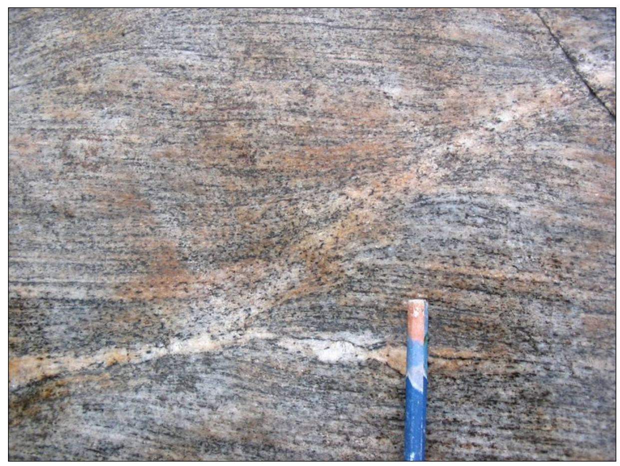


Fig. 13: Migmatitic orthogneiss at Ponte Brolla indicating coeval Alpine shearing and anatexis.

8. **Field trip Valmalenco**

The geology of Valmalenco marks not only the tectonic contact between Austroalpine Margna nappe and Penninic Malenco unit (Fig. 14, 15) but also the **Permian crust-mantle transition** exhumed during continental rifting associated with the opening of the Piedmont-Ligurian ocean in the Jurassic. During the Alpine orogeny and the closure of the ocean, these mantle rocks were subducted and integrated into the orogen, and finally exhumed again and exposed at the present day surface.

The Permian crust-mantle transition is interpreted to correspond to lithological contacts within the Malenco unit with the pelitic granulites (Fig. 15) reflecting the lower continental crust welded to the ultramafic subcontinental mantle rocks that dominate the rest of the Malenco unit by the 275 Ma Fedoz Gabbro. Geobarometric studies reveal that the gabbro intruded the lower crust at a depth of ca. 35 km. Exhumation and erosion of the former subcontinental mantle resulted in the hydration of the ultramafic rocks and widespread serpentinization. In addition, debris flows formed containing platform sediments and serpentinites, which were accumulated into local basins and fractures. Rocks that formed by the metamorphism of these sediments during the Alpine orogeny are referred to as **ophicarbonates**.

A 3 km wide **contact metamorphic aureole** in the vicinity of the early Oligocene **Bergell intrusion** overprinted the regional metamorphic mineral assemblages locally (Fig. 16). The metamorphic assemblage of the host rock consists of antigorite + diopside + olivine + chlorite + mag-

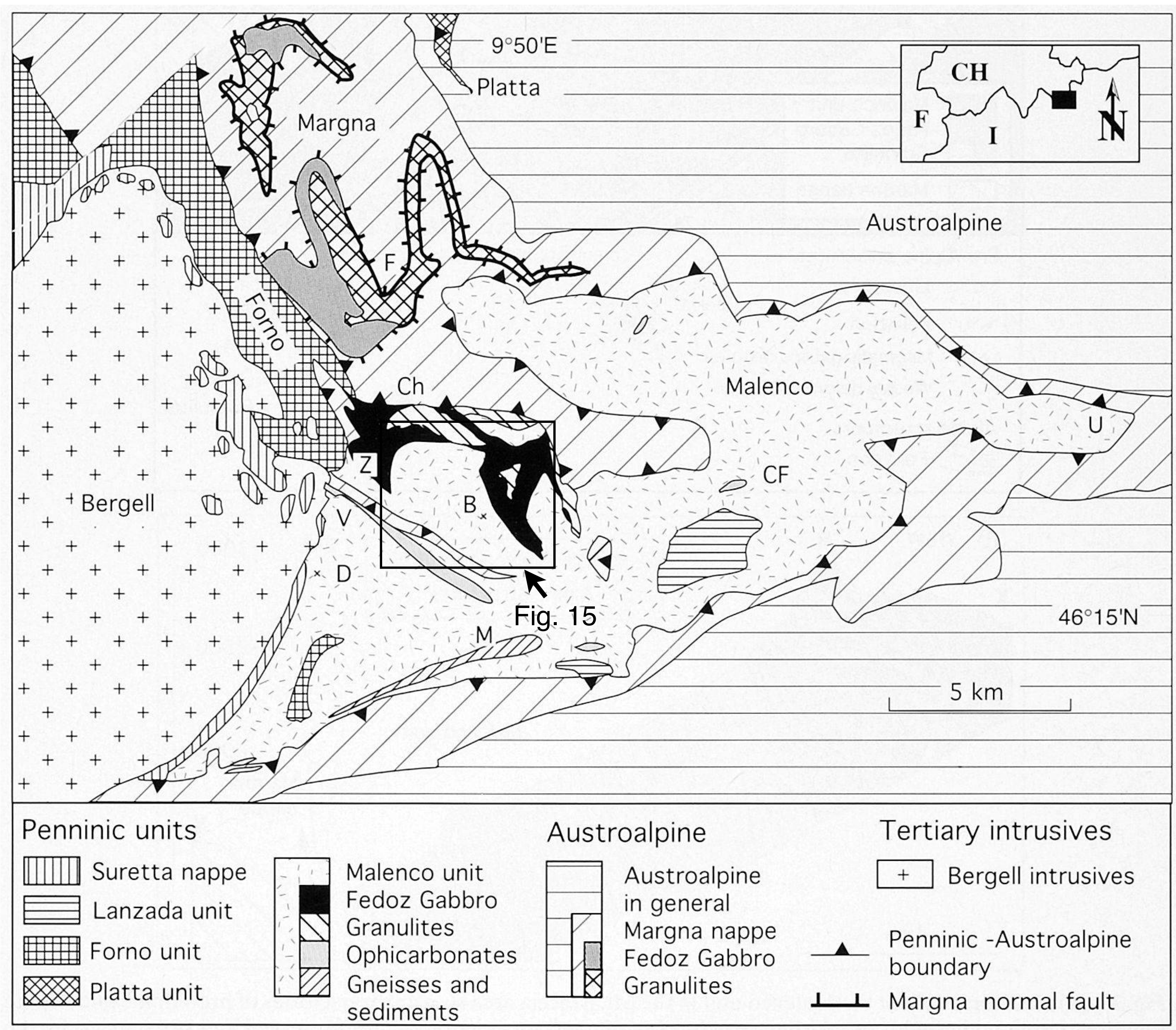


Fig. 14: Tectonic map of the Val Malenco region. The Margna normal fault separates lower from upper crustal rocks within the Margna nappe. The Fedoz gabbro and the granulites of the Mt. Braccia area are attached to the ultramafic rocks and belong to the Malenco unit. F = Piz Fora, Ch = Chiareggio, Z = Alpe Zocca, V = Val Ventina, D = Mt. Disgrazia, M = Mastabbia zone, B = Mt. Braccia, CF = Campo Franscia, U = Passo d'Ur.(Hermann & Muentener, 1996).

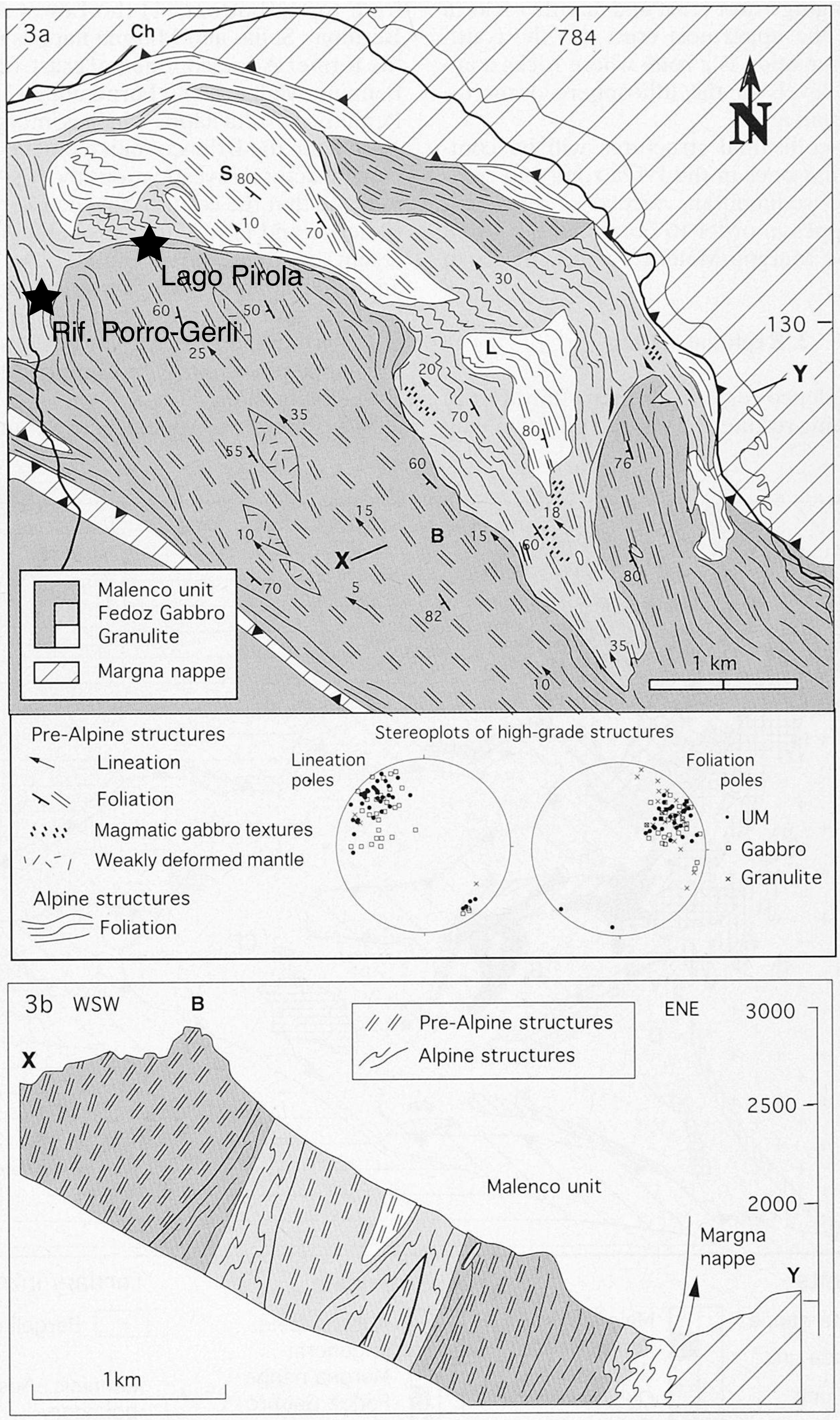
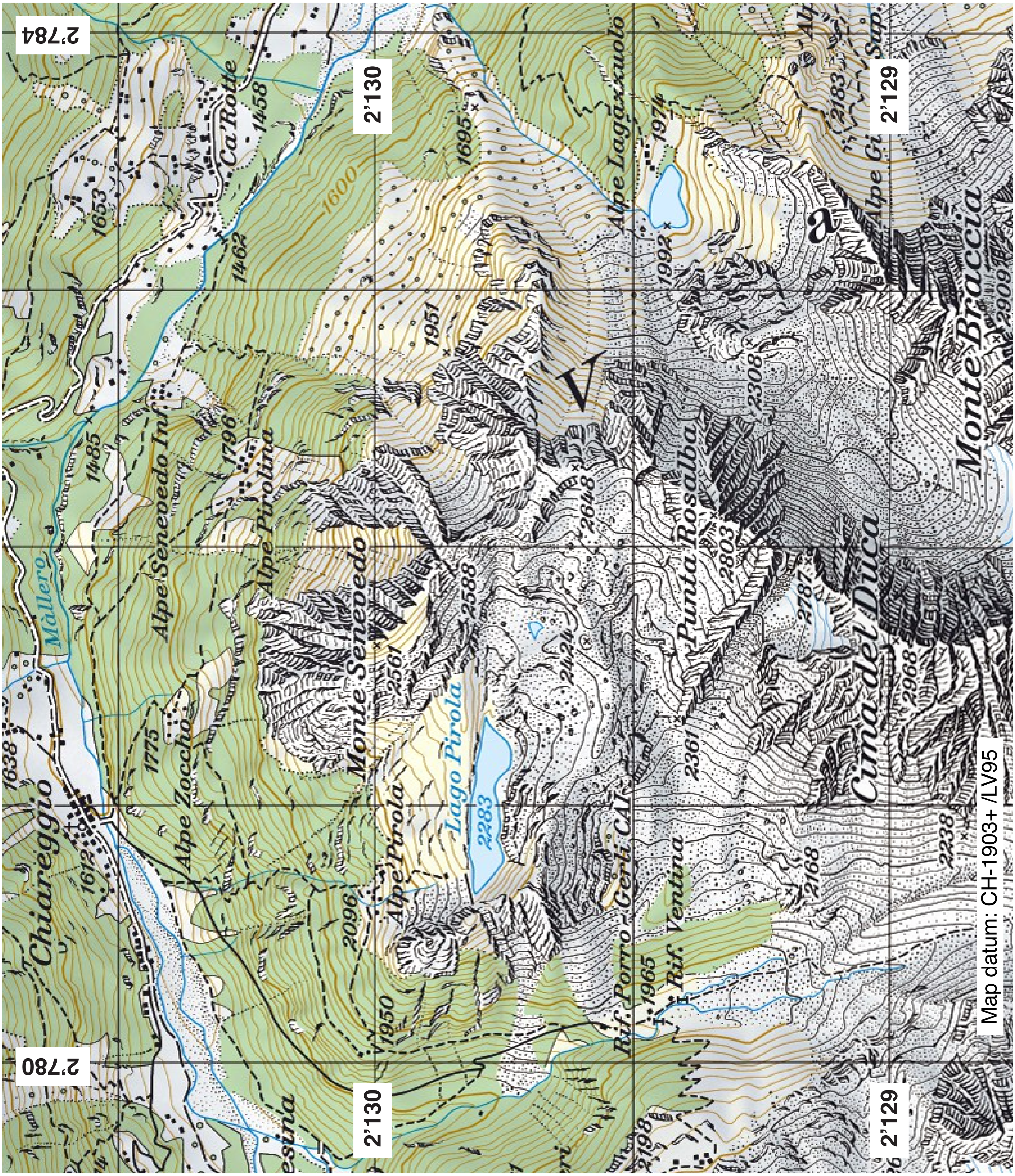


Fig. 15: (a) Structural map of the Malenco unit in the Mt. Braccia area showing trajectories of pre-Alpine and Alpine foliation. Large bodies with pre-Alpine structures with constant orientation are preserved and surrounded by the Alpine foliation. Points in the stereoplots lie in the lower hemisphere. UM = ultramafic rocks, B = Mt. Braccia, Ch = Chiareggio, S = Mt. Senevedo, L = Alpe Lagazzuolo.
(b) Section across the crust-mantle transition that lies within the Malenco unit. The rocks are slightly overturned due to the second backfolding event. (Hermann & Muentener, 1996).


2'784
2'780
2'130
2'129
Chiareggio
Mallero
Alpe Pirolina
Monte Senevedo
Lago Pirola
2283
Alpe Pirola
Rif. Porro
Rif. Gerli CAI
Rif. Ventina
Punta Rosalba
Cima del Duca
Monte Braccia
Alpe Lagazzuolo
Ca Rotte
2588
2561
2648
2803
2787
2968
2361
2168
1965
1950
2096
1775
1638
1485
1796
1653
1462
1458
1600
1695
1951
1992
2308
2183
Map datum: CH-1903+ /LV95

netite. The first mappable isograd in the country rock approaching its contact with the intrusion is the transition from diopside to tremolite. The disappearance of antigorite marks the second isograd which is offset by the Muretto Fault, a young brittle fault postdating the intrusion (not shown in Fig. 16). According to heat flow modelling by Trommsdorff and Connolly (1996), the ambient temperature in the country rock is estimated at ca. 350 C at the time of the pluton emplacement. During the intrusion of the tonalite at ca. 32 Ma, which forms an outer shell of the pluton around the 30 Ma granodiorite-granite core, rocks in the direct vicinity of the contact were heated to a maximum temperature of ca. 570 C. Rocks with a distance of ca. 2 km to the contact experienced maximum temperatures of up to 470 C according to these heat flow models.

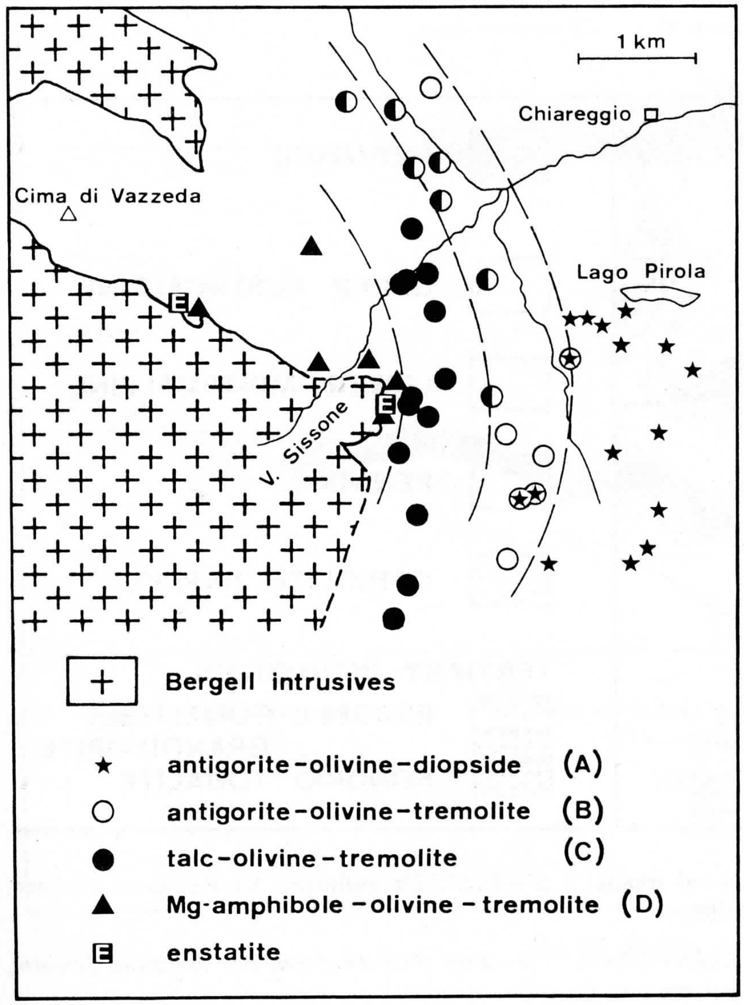


Fig. 16: Contact metamorphism in the vicinity of the Bergell intrusion. Mg-amphibole is anthophyllite.

9. **The contact between Austroalpine and Piedmont-Ligurian ocean at Julier Pass**

According to Eberli (1988), listric E-dipping normal faults developed during the Jurassic in the lower Austroalpine nappes as part of the continental margin of the Adriatic plate (Fig. 17). In the western portion of the continental margin, normal faults developed dipping in the opposite direction towards the Piedmont-Ligurian ocean. As a result, a submarine rise existed at this time.

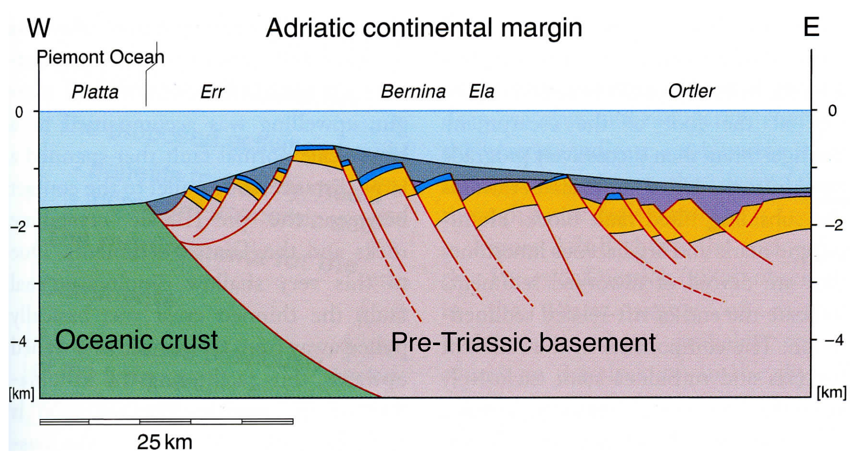
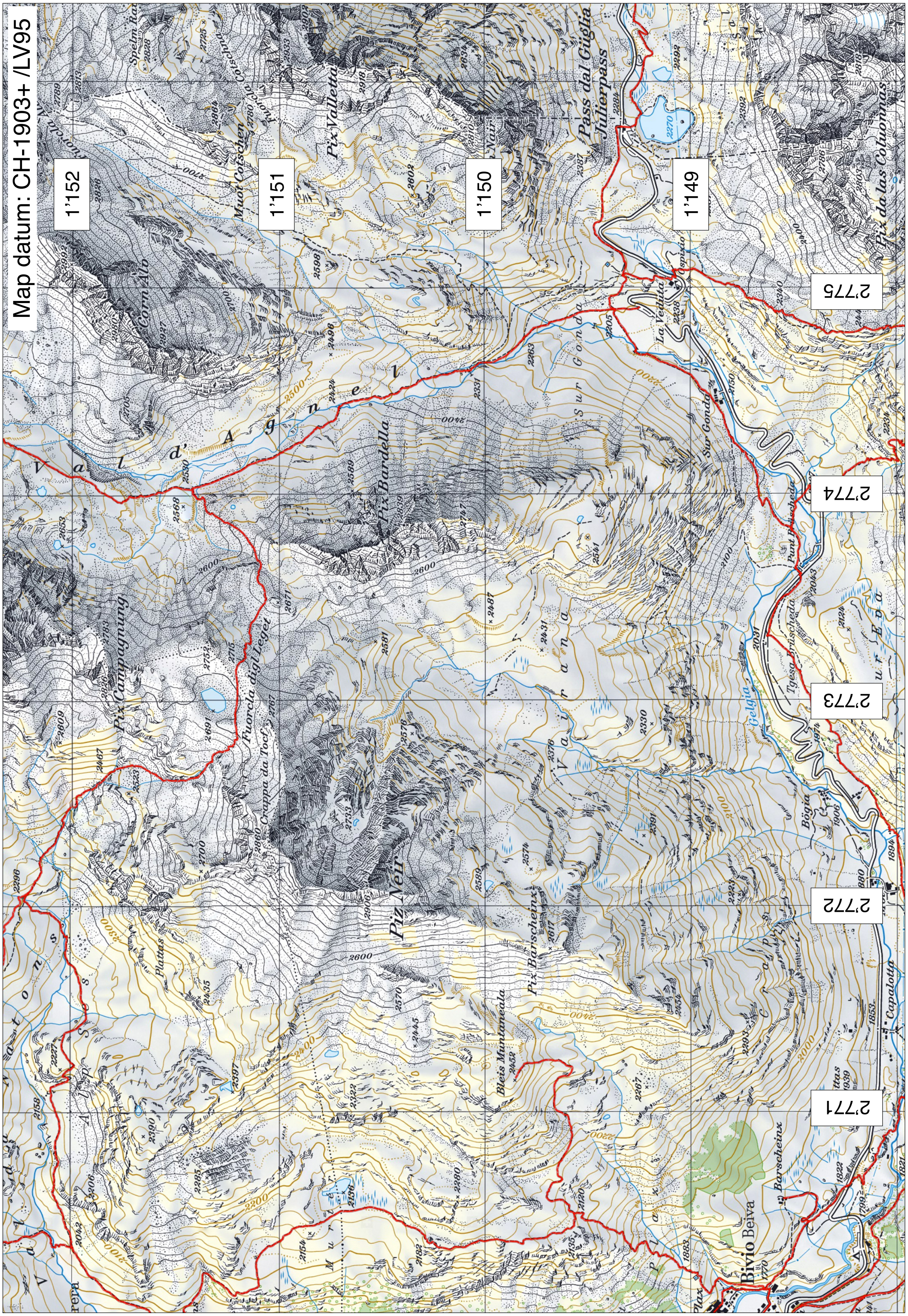


Fig. 17: Model of the passive Adriatic margin.

During the opening of the Piedmont-Ligurian ocean, thinning of the crust and upwelling of the mantle exposed the largely peridotitic rocks to the ocean floor where they were hydrated and transformed to serpentinite. During our field trip we will try to localize the contact between the Austroalpine Err nappe complex, which represents the Adriatic continental margin, and the ophiolite-bearing Penninic Platta nappe.


Map datum: CH-1903+ /LV95
1'152
1'151
1'150
1'149
2'775
2'774
2'773
2'772
2'771
Pass dal Güglia
Julierpass
Piz Valletta
Piz Bardella
Piz Neir
Val d' Agnel
Fuorcla digl Leget
Piz Barscheinx
Bleis Muntanela
Bivio Beiva
Capalotta
Piz da las Coluonnas

10. **The Glarus Thrust**

The Alps of the Glarus area (Fig. 18) are considered the birthplace of the nappe theory. As one of the first scientists, Hans Conrad Escher noted in 1809 that apparently older rocks (Permian sediments of the Verrucano Group) overlie younger rocks (Late Jurassic limestones of the Quinten Formation) in the Tschingelhoren. This hypothesis contradicted all ideas at the time, and in 1866 Hans Conrad's son, Arnold Escher, developed the model of a recumbent double fold, in the reverse limb of which the older rocks overlay the younger ones. This idea was adopted by

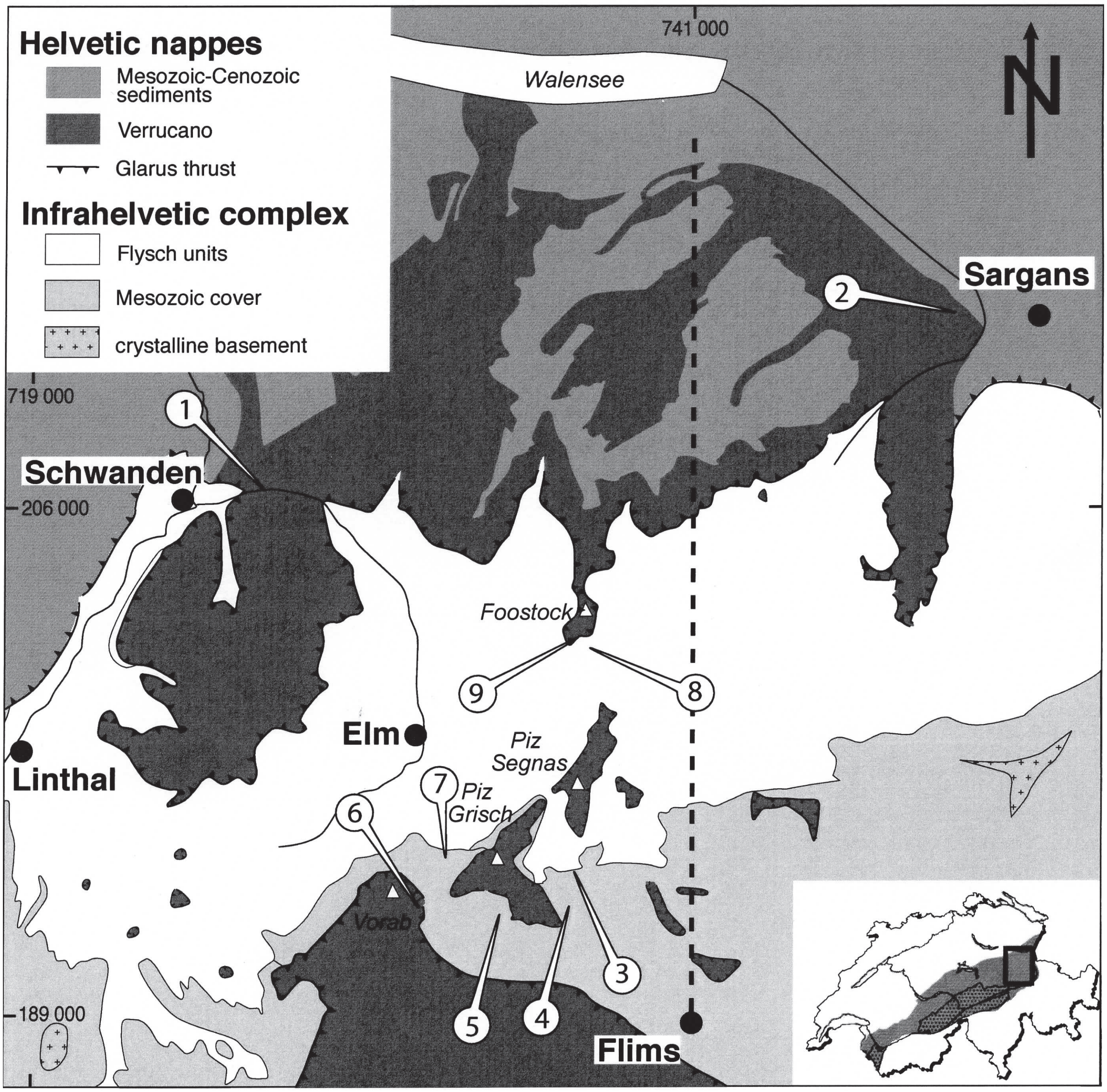


Fig. 18: Schematic tectonic map of the Glarus area. Dashed line refers to cross section in Fig. 19. Numbers 1 and 6 refer to the locations that will be visited during the field trip: Lochsite and Vorab, respectively. From Herwegh et al., (2008).

Albert Heim, and his famous drawing from 1894 of the double fold in the Glarus area is shown in Fig. 19. Murchison, who visited the Glarus area together with Arnold Escher a few years earlier, suggested already the presence of an enormous overthrust but it was not until 1901 that Heim finally accepted the existence of thrust faults in the Alps.

Fig. 20 (A) is a watercolor painting of the Tschingelhoren in the Glarus area by Hans Conrad Escher (1812) which clearly shows the separation of the Verrucano and Quinten rocks by a sharp line. Fig. 19 (B) is a recent photograph taken at the same location.

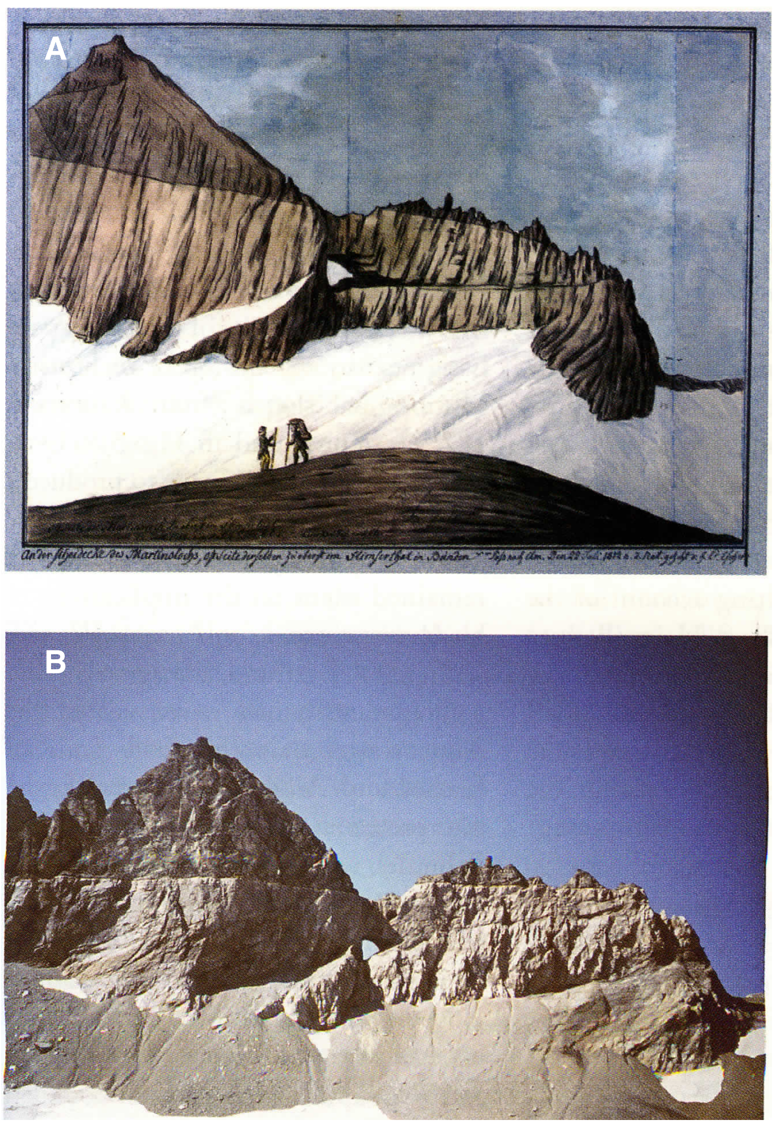


Fig. 20: (A) Glarus Thrust and Martins' Hole in the Tschingelhoren. Aquarelle by H.C. Escher (1812). (B) Photograph taken at the same location as (A).

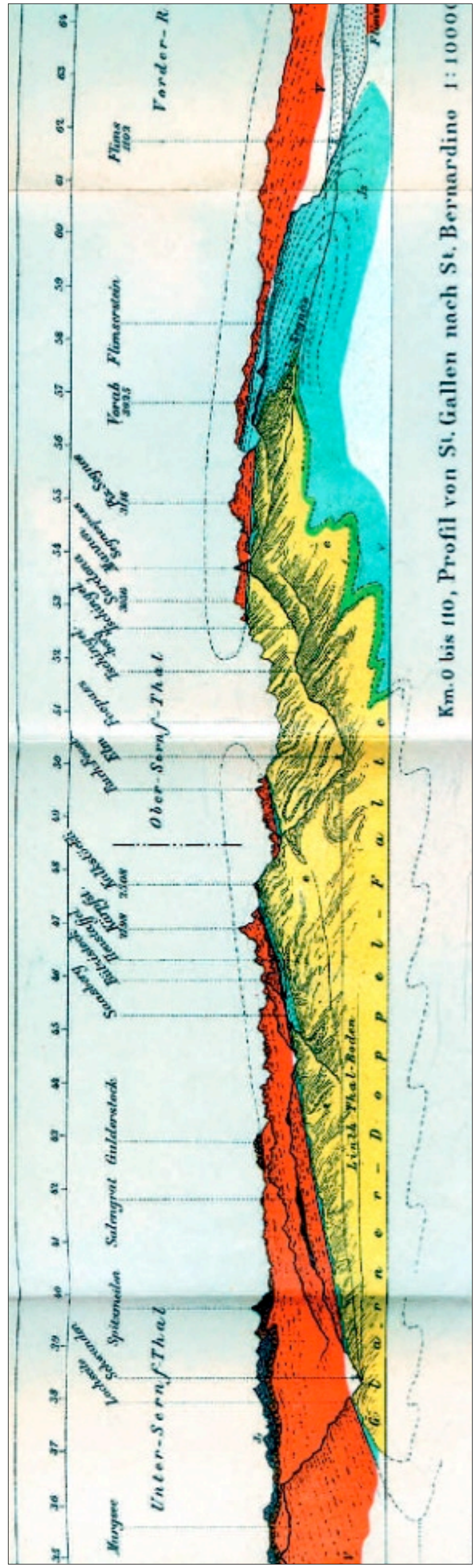


Fig. 19: The Glarus double fold model after A. Escher and A. Heim. Heim (1894).

The Tschingelhoren is part of the Tectonic Arena Sardona which was included in the UNESCO list of World Natural Heritage Sites in 2008. The Glarus Thrust, which we will see at different locations during our trip, provides insight into the process of mountain building, and was the main reason for the inclusion of the area as a World Heritage Site.

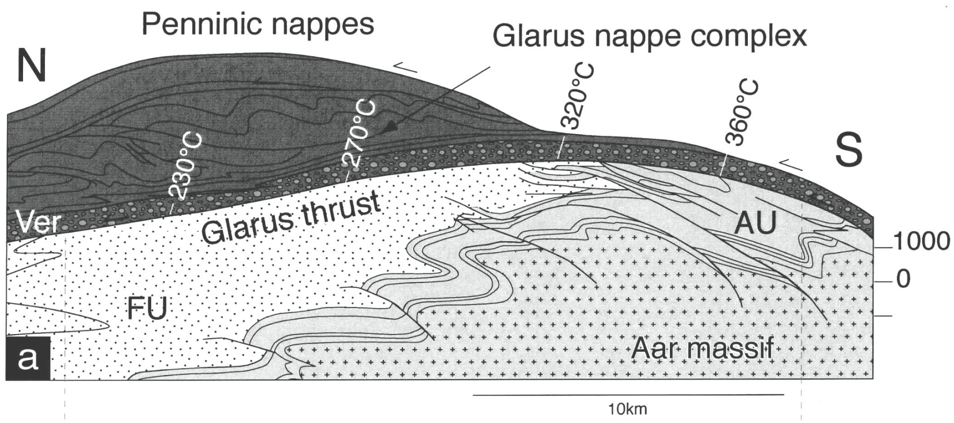


Fig. 21: Cross section parallel to the dashed line in Fig. 19 with flysch units (FU), Verrucano (Ver) and Mesozoic sediments (AU). Temperatures correspond to peak metamorphic conditions. Herwegh et al., (2008).

A recent interpretation of the tectonics in the Glarus area (parallel to the dashed line in Fig. 18) is shown in Fig. 21 (Herwegh et al., 2008). Since some of the units that make up the Mesozoic sediments in the footwall of the thrust are derived from an area further south than the overlaying Glarus nappe complex, the Glarus area represents a classic example of out-of-sequence thrusting.

Probably the most famous locality of the Swiss Alps is the Lochsite (location 1 in Fig. 18) - *no hammers!* The green and purple Verrucano conglomerates (4 and 5, respectively; Fig. 22), Eocene flysch (1), Lochsite limestone tectonite (2), as well as the planar fracture plane, referred to as septum (3), are well exposed. The tectonite is characterized by intensely deformed veined calcite, and deformation occurred by viscous and cataclastic processes in the presence of fluids. The transition from the green to the typical purple Verrucano is attributed to an increased oxidation of iron away from the calcareous tectonite. Systematic chemical and isotopic bulk rock variations across the septum are interpreted as evidence for upwards-directed fluid flow perpendicular to the thrust plane. The cuspate-lobate geometry that can be seen at the contact between flysch and tectonite is interpreted to reflect the contrasting mechanical properties of the lithologies involved during thrusting. Since cusps of the mechanically weaker material are thought to penetrate into the mechanically stronger material, the geometry developed at Lochsite indicates that the tectonite accommodated the high shear strains yet was mechanically stronger than the flysch.

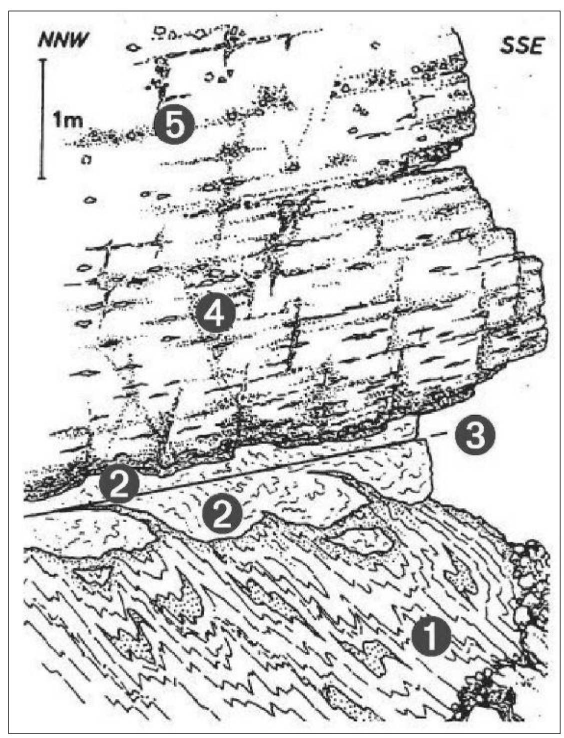


Fig. 22: The Lochsite locality. Truempy (1988).

Stratigraphic timetable

after Haq and the “International Commission on Stratigraphy”

Era	Period	Epoch		Stage*	Ma
Cenozoic	Quaternary	Holocene			0.0117
		Pleistocene		Gelasian	2.58
	Neogene	Pliocene		Piacenzian	
				Zanclean	5.3
		Miocene		Messinian	
				Tortonian	
				Serravallian	
				Langhian	
				Burdigalian	
				Aquitanian	23
	Paleogene	Oligocene		Chattian	
				Rupelian	
				Priabonian	33.9
		Eocene		Bartonian	
				Lutetian	
				Ypresian	55.8
		Paleocene		Thanetian	
				Selandian	
				Danian	65.5
Mesozoic	Cretaceous	Late	«Senonian»	Maastrichtian	
				Campanian	
				Santonian	
				Coniacian	
				Turonian	
				Cenomanian	99.6
		Early		Albian	
				Aptian	
				Barremian	
			«Neocomian»	Hauterivian	
				Valanginian	
				Berriasian	145.5
	Jurassic	Late	Malm	Tithonian	
				Kimmeridgian	
				Oxfordian	161.2
		Middle	Dogger	Callovian	
				Bathonian	
				Bajocian	
				Aalenian	175.6
		Early	Lias	Toarcian	
				Pliensbachian	
				Sinemurian	
				Hettangian	199.6
	Triassic	Late		Rhätian	
				Norian	
				Carnian	228
		Middle		Ladinian	
				Anisian	245
		Early		Olenekian	
				Induan	251
Palaeozoic	Permian	Late		Thuringian	270.6
		Early		Saxonian	
				Autunian	299
	Carboniferous	Late		Stephanian	
				Westphalian	318.1
		Early		Namurian	
				Visean	
				Tournaisian	359.2
	Devonian				416
	Silurian				443.7
	Ordovician				488.3
	Cambrian				542
Proterozoic					2500
Archean					3800