Field guide

A Transect of the Eastern and Southern Alps

September 8th – 12th 2018

SPP 2017 "Mountain Building in 4-Dimensions" (4D-MB)

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INTRODUCTION

The transect from Salzburg to the Veneto is a good place to see Alpine orogenic processes because it exposes all main components of the Alpine collisional belt (**Fig. 1-1**), from the northern and southern peripheral basins, to nappes derived from the upper (Adriatic) and lower (European) plates and the Adria-Europe suture, to recent thrusts in the Southern Alps where active seismicity reflects ongoing Adria-Europe convergence.

<u>Tectonic units exposed at surface from N to S along the transect</u> (**Figs. 1-1,1-2**):

1. **Northern Alpine (Molasse) basin** – Oligocene to mid-Miocene sediments on the European foreland and derived from the exhumed Alpine nappe stack
2. The **Northern Calcereous Alps** – far-travelled nappes comprising mostly Mesozoic sediments from the southern Adriatic margin
3. The **Tauern Window** – subducted and exhumed nappes and cover rocks of the European margin and Alpine Tethyan ocean framed by the Austroalpine Nappes that originate from the northern Adriatic margin
4. The **Periadriatic Fault System** (or lineament) – an Oligo-Miocene fault that accommodated late orogenic motion
5. The **Southern Alps** thrust-and-fold belt - Mesozoic sediments detached from their no-longer-visible Adriatic basement subducted beneath the Eastern Alps
6. **Southern Alpine (Veneto, Po) Basins** – Oligocene-to-recent sediments on the Adriatic foreland derived mostly from the Southern Alps, northern Apennines and (in the east) from the northern Dinarides
7. I addition, we will visit the **Giudiacarie fold-and thrust belt** that accommodated sinistral offset of the Alpine edifice in Miocene time.

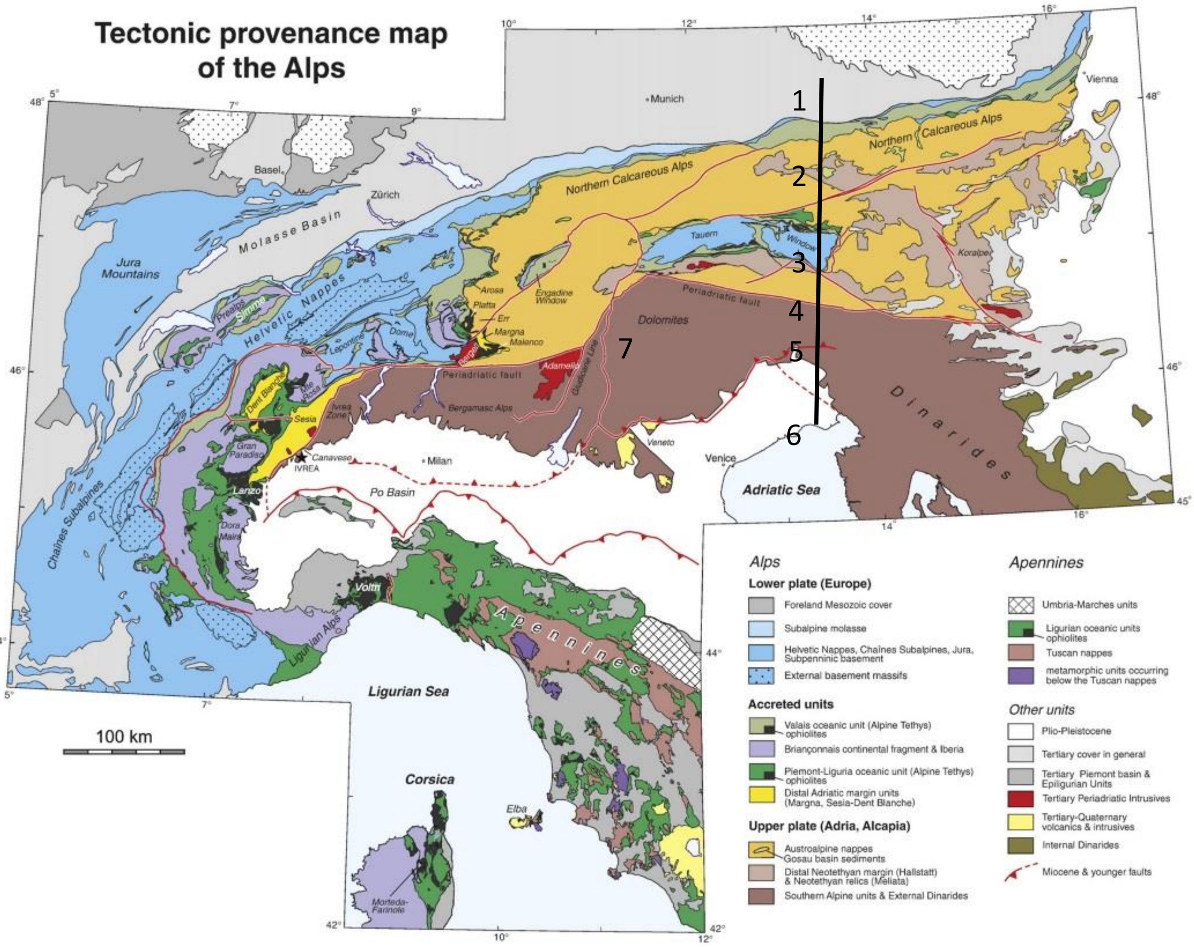


Figure 1-1: *Tectonic map of the Alps (Handy et al. 2010, simplified from SCHMID ET AL. 2004) with colours indicating upper & lower plate affinities and Jurassic paleogeographic origin of nappes Numbers correspond to units numbered in text.*

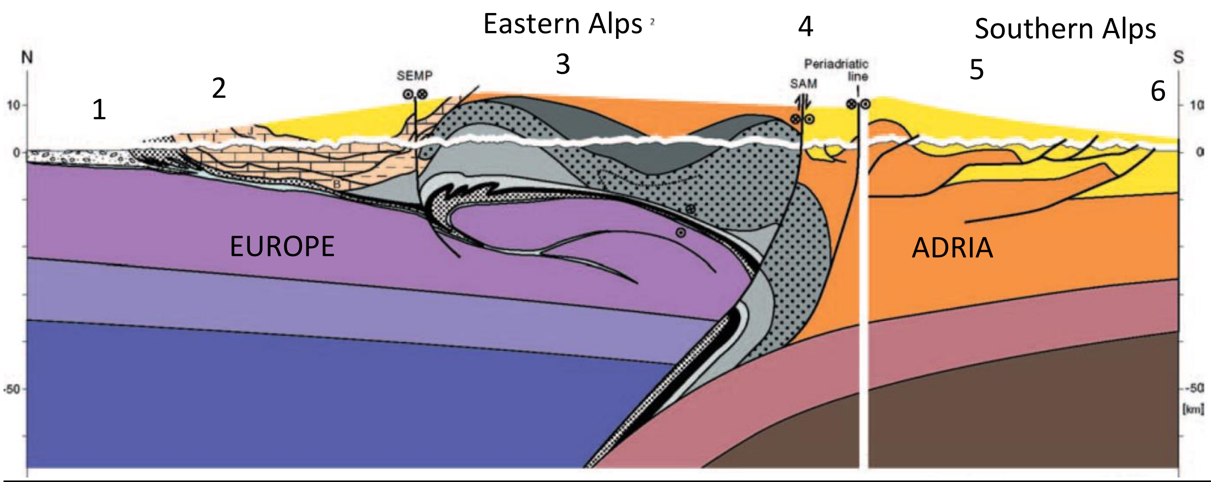


Figure 1-2: *Cross section of the Eastern & Southern Alps (trace shown in Fig. 1-1), modified from SCHMID ET AL. (2004)*

Deep Structure

The transect in our field trip crosses two first-order geophysical anomalies (**Figs. 1-3,1- 4**): (1) a +Vp slab anomaly that dips vertically to NE-ward (BABUŠKA ET AL. 1990, LIPPITSCH ET AL. 2003; PLOMEROVA ET AL. 2015) and is variously interpreted as subducted Adriatic (HANDY ET AL. 2015, HETÉNYI ET AL. 2018) or European lithosphere (MITTERBAUER ET AL. 2011); this slab anomaly weakens or is non-existent beneath the W part of the Tauern Window (**Fig. 1-3a**). W of the Tauern Window, under the Central Alps, another +Vp dips SE-ward and is interpreted as subducted European lithosphere (**Fig. 1-3b**); (2) a weakly defined Moho from 12-15°E (**Fig. 1-4**, white area in Spada et al. 2013). Unlike the Western and Central Alps which overlie an Adriatic lower crustal wedge, the Tauern Window overlies no such pronounced wedge, but does coincide with a large positive gravity anomaly (EBBING ET AL. 2006). The latter is enigmatic, as there is no corresponding positive velocity anomaly at relatively shallow crustal depths beneath the Tauern Window. Another anomalous feature (**Fig. 1-3d**) is the large gap in the +Vp slab anomaly beneath the Dinarides, indicating loss of the Adriatic slab preserved further S beneath the Hellenides.

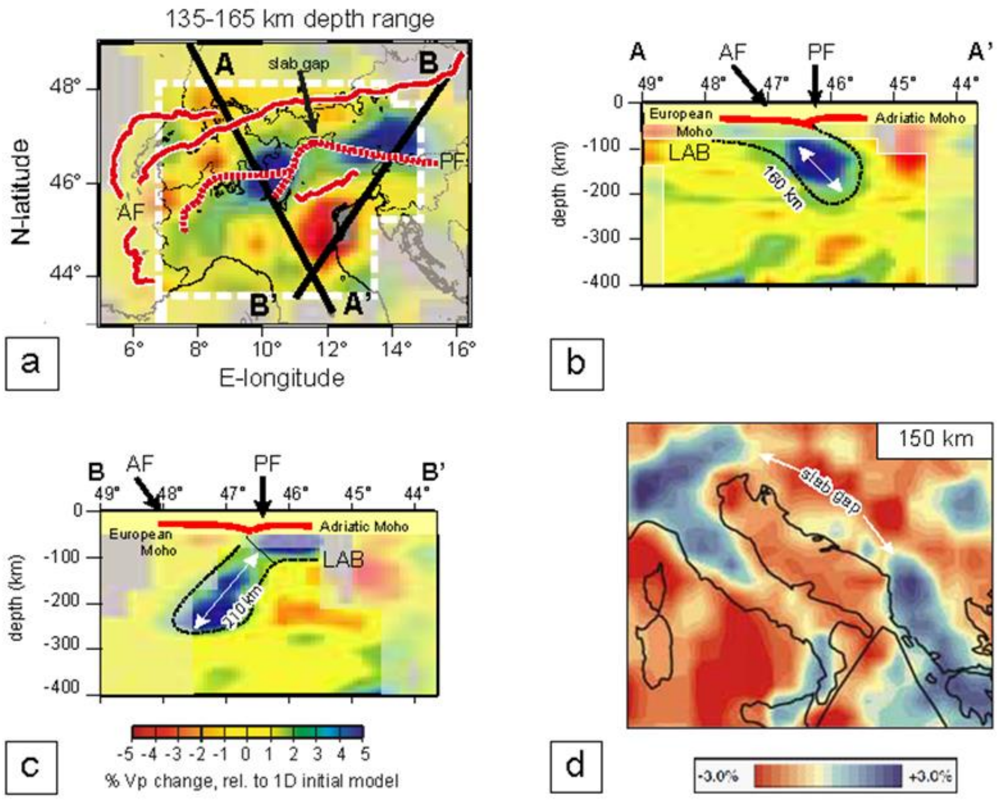


__Figure 1-3__: P-wave tomographic map (a) and cross sections (b) and (c) of the central and eastern Alps modified from LIPPITSCH ET AL. (2003). P-wave tomographic map of the Adriatic region (d) from BIJWAARD & SPAKMAN (2000) showing slab gap beneath the northern Dinarides. AF – Alpine thrust front, PF – Periadriatic Fault System

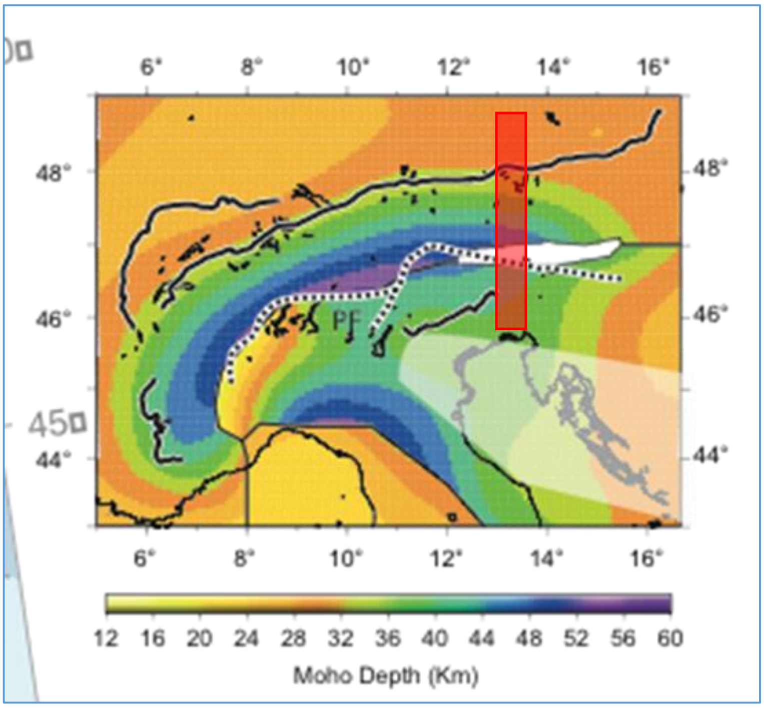
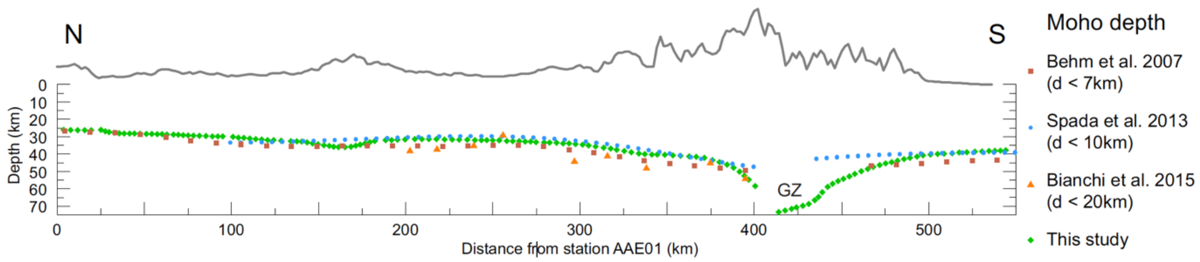
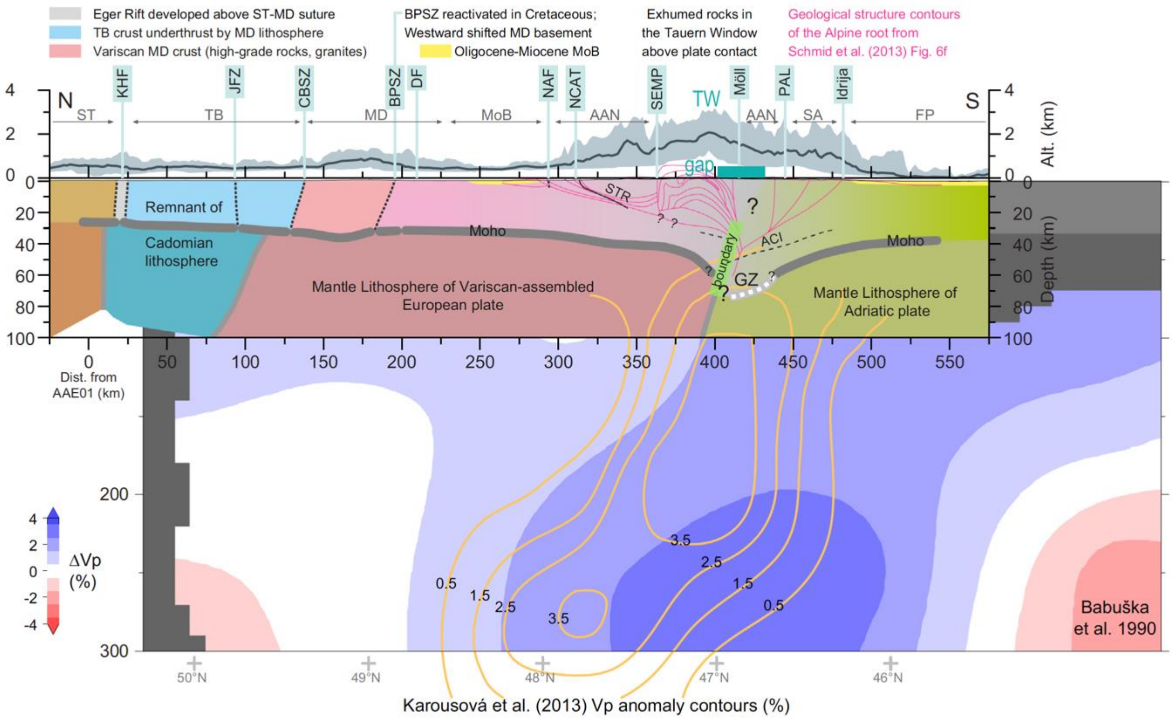


***Figure 1-4**: Moho map of SPADA ET AL. (2013) with Periadriatic Fault (PF), Alpine thrust fronts (black lines) and trace of EASI section (red) shown below in* HETÉNYI ET AL. 2018*.*



Moho and mantle structure along 13-13.5°E summarized in HETÉNYI ET AL. 2018



Paleotectonics

The tectonic units in the Alps shown in **Figure 1-1** are crustal slivers from the Mesozoic *European and Adriatic* (Alcapia) continental margins, as well as relics of the intervening ocean, *Alpine Tethys*. Rifting began in latest Triassic-early Jurassic time and lead to oblique sinistral spreading from mid-Jurassic to mid-Cretaceous time (**Fig. 1-5**).

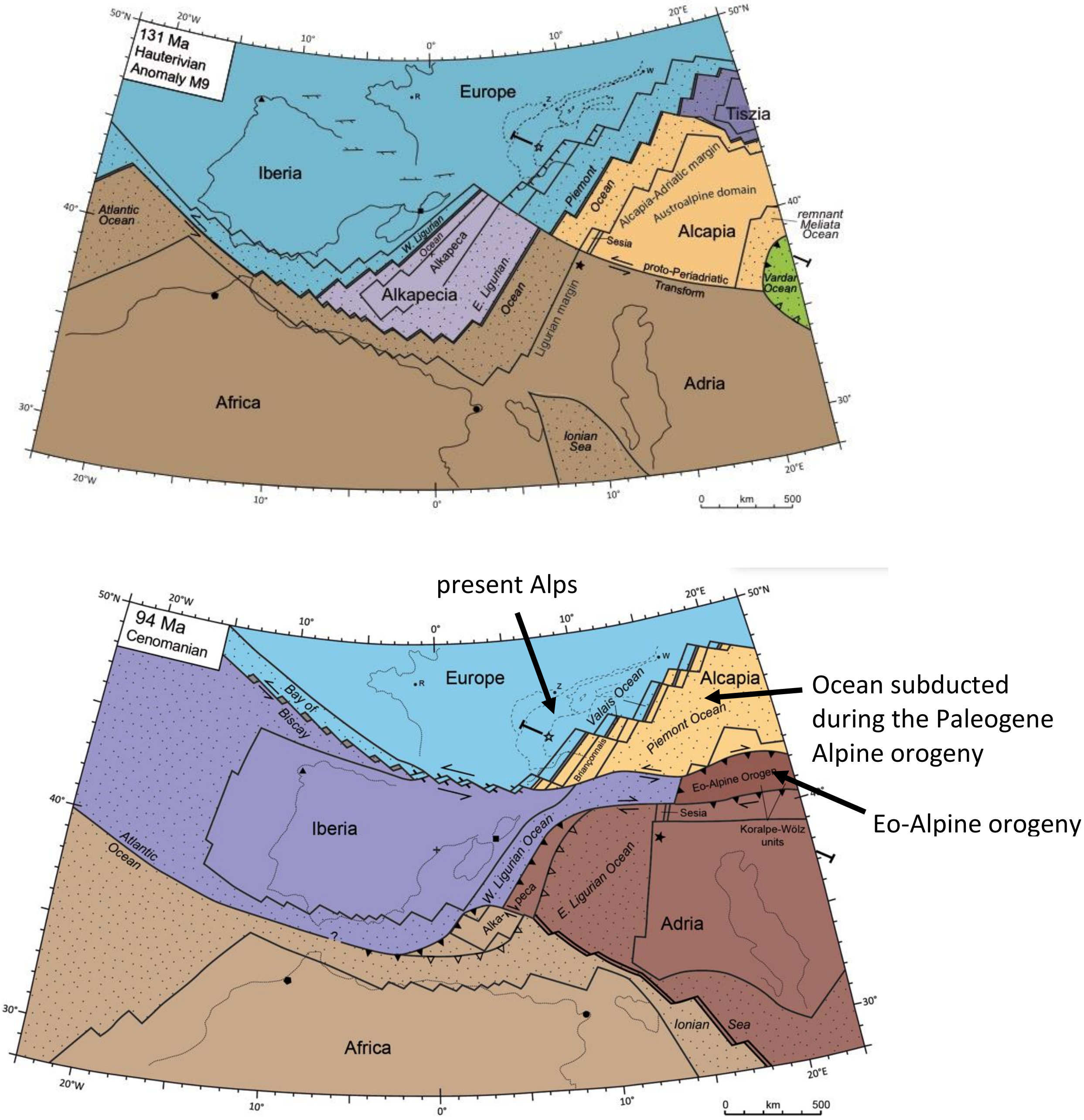


Figure 1-5: Plate tectonic reconstruction of Alpine Tethys at the end of spreading of the Piemont-Liguria part of Alpine Tethys (top) and near the end of spreading of the Valais part of Alpine Tethys during the Eo-Alpine orogeny (bottom; HANDY ET AL. 2010).

DAY 1: Northern foreland basin (Molasse) to the core of the Alpine orogen

Route: Salzburg-Rossfeld-Großglockner (map with route)
Themes: Northern foreland basin, two stages of Alpine orogeny

Stop 1-1: Panorama at Gaisberg (47°48'11.96°N, 13°6'40.46°E) or Kapuzinerberg (47°48'7.57°N, 13°3'24.61°E) in Salzburg

Theme: basin fill north of the Alps, thrusting of nappe stack onto the basin

Molasse Basin: The northern foreland or Molasse basin comprises a subhorizontal to gently folded sequence of Oligo-Miocene (33-5 Ma) marine and freshwater clastics that onlaps European basement to the north (Variscan-metamorphosed basement of the Schwarzwald and Bohemenia) and attains up to 4500m thickness in the south. There, it is coarse-grained (Nagelfluh conglomerate of the Subalpine Molasse, SM) and has been folded and thrusted to form the most external nappe of the Alpine collisional belt. Thrusting slong the eastern part of the SM ended about 17 Ma, with evidence for only minor shortening since then (Ortner et al. 2011). The basin is usually divided stratigraphically into four subunits or -facies: (1) *Lower Marine Molasse* (Untere Meeresmolasse, UMM, Rupelian-Chattian); (2) *Lower Freshwater Molasse* (Untere Süßwasser Molasse, USM, Chattian-Aquitanian); (3) *Upper Marine Molasse* (Obere Meeresmolasse, OMM, Burdigalian); (4) *Upper Freshwater Molasse* (Obere Süßwasser Molasse, OSM, Serravalian-Tortonian); Unconformities and disconformities within the basin document the northward migration of a foreland bulge that is attributed to the advance of the Alpine nappes.

Panorama at Gaisberg (courtesy of F. Neubauer, Univ. Salzburg)**:** The Gaisberg panorama (**Fig. 1-7**) is an impressive overview of the northern margin of the Alps and its transition to the Alpine foreland. The plain to the N is the Molasse basin. The hilly area is the base of the Alpine thrust wedge containing Cr.-Eocene Rhenodanubian flysch and Cr.-Eocene Helvetic-Ultrahelvetic hemipelagic limestone units. The basal thrust of the Northern Calcareous Alps onto the Molasse is at the northern base of the Gaisberg and extends W through Salzburg, where it forms the northern base of the Kapuzinerberg and the Hohensalzburg castle. The Gaisberg and the southerly adjacent Osterhorn group of mountains comprise u. Tr.-l.Cr. limestones of the Tirolic nappe of the Northern Calcareous Alps (see overview for stop 1-2 below). To the SW, we see the overlying Lower Juvavic nappe with its Hallstatt limestone derived from the S continental margin of Adria near its transition to the Neotethyan ocean. The Lower Juvavic nappe is overridden by the Upper Juvavic nappe exposed in the Untersberg Mountains.

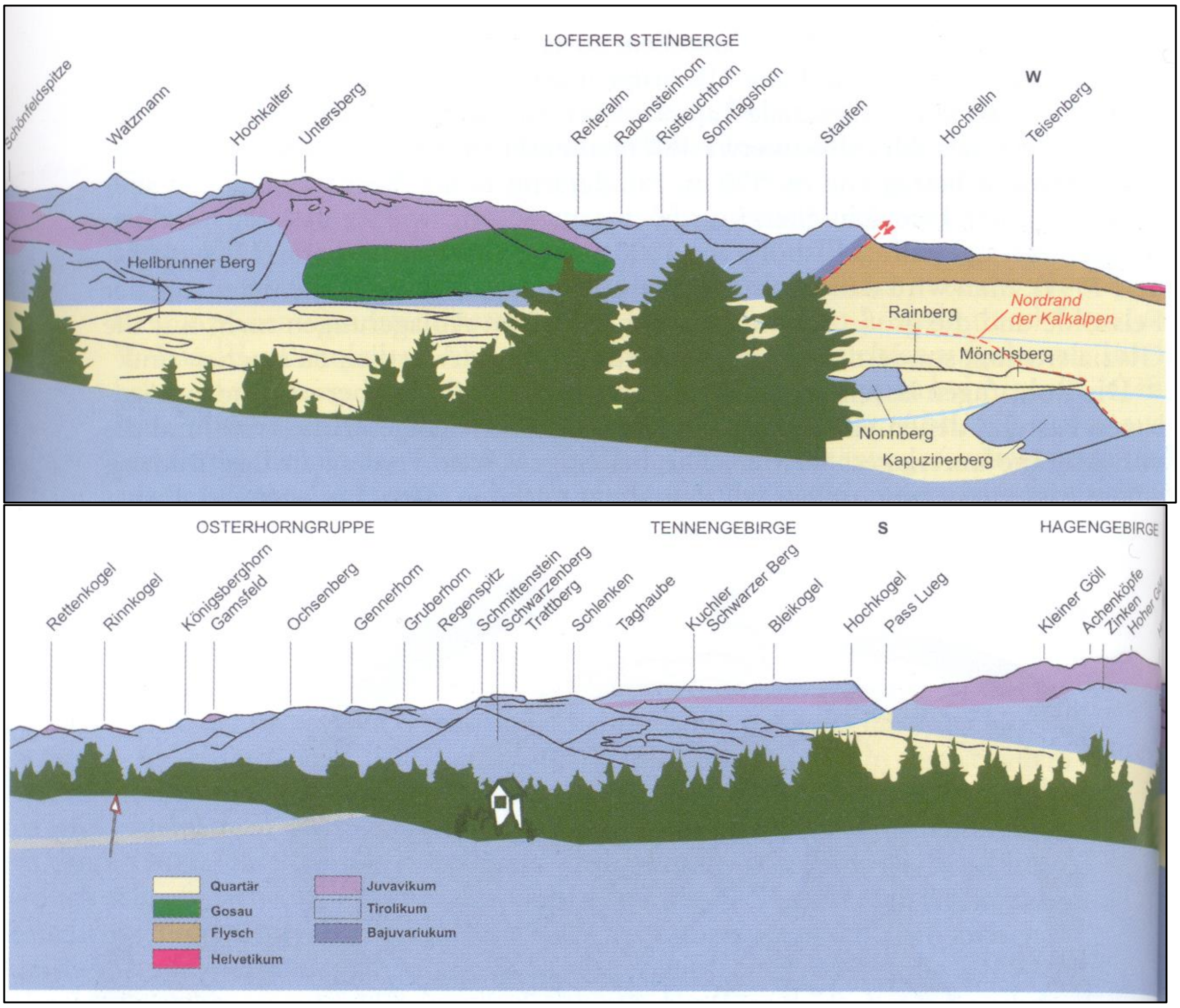


***Figure 1-7**: Geological units from the Gaisberg as viewed to the W (top) and S (bottom). From GENSER, NEUBAUER & TICHY, courtesy of H.-P. STEYRER (2009)*

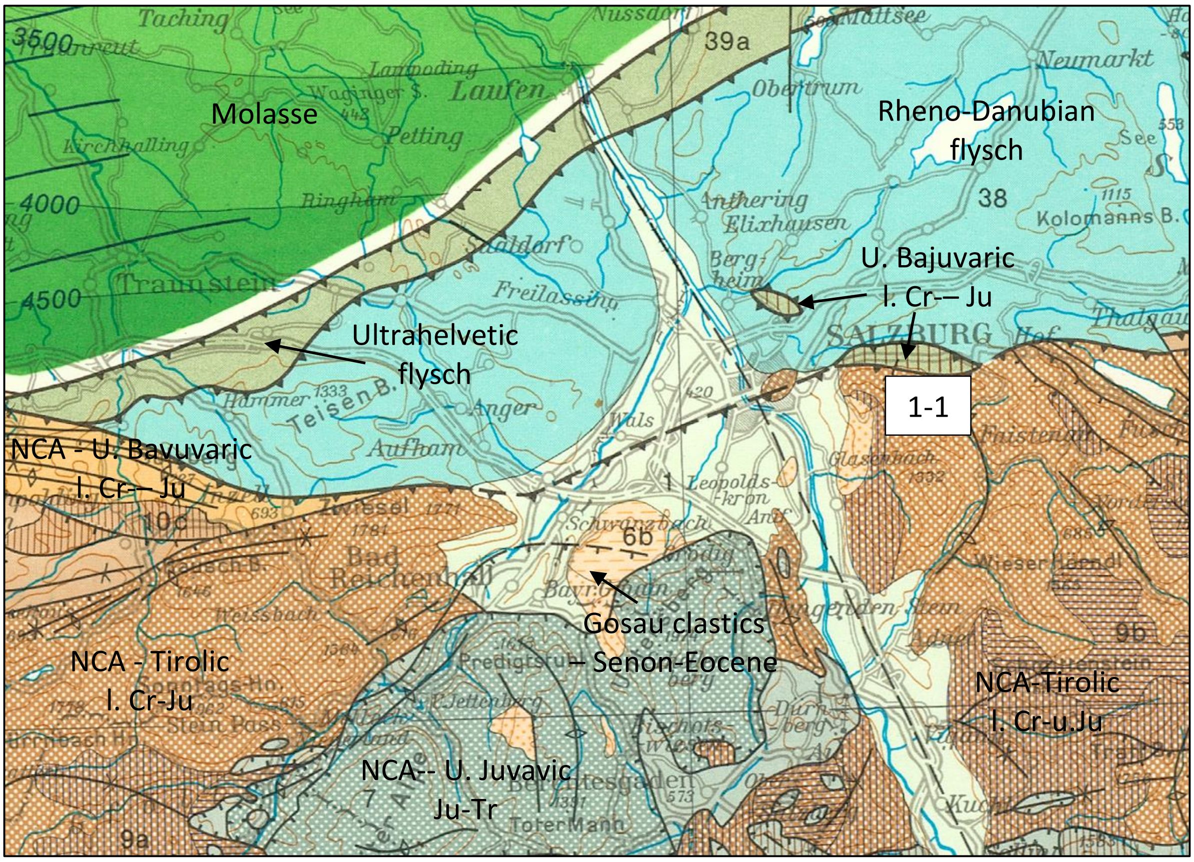


***Figure 1-8**: Tectonic units along the Alpine front near Salzburg in Structural Map of Italy, Bigi et al. 1981; Note that a post-orogenic Gosau-type basin is included in the hangingwall of the NCA thrust (NEUBAUER, 2002; UHLIR and VETTERS, 2009).*

<u>Stop 1-2</u>: Rossfeldstrasse (N47° 37' 25.2'', E13° 05' 22.8'')

Theme: Eo-Alpine orogeny, nappe structure of the Northern Calcereous Alps

Northern Calcereous Alps (NCA): The NCA are far-travelled nappes comprising Permian and mostly Mesozoic cover rocks of Austroalpine basement from the southern margin of the Adriatic microplate adjacent to the Vardar branch of the Neotethyan ocean (**Fig. 1-5**). The NCA is subdivided from top to bottom into the *Juvavic, Tirolic, and Bajuvaric* nappes. The stratigraphic base of the Tirolic nappes is the Greywacke Zone or Grauwackenzone. The Juvavic nappes were detached from their basement, which is generally agreed to be located to the S and E of the Tauern Window in units that experienced subduction metamorphism (**Fig. 1-1**). The NCA are important because they contain the sedimentary record of the Eo-Alpine orogeny, which lasted from mid- to late Cretaceous time (135-90 Ma, FAUPL & WAGREICH 2000). Generally, nappes are emplaced "in-sequence", i.e., along thrusts that propagate from internal (hinterland) to external (foreland) parts of the orogen and in a sense opposite to that of the subduction. In this case, however, out-of-sequence thrusting (propagation towards the hinterland) lead to a local inversion of the nappes, with nappes from more external domains overlying internal ones (GAWLICK ET AL. 1999).

Outcrop: Exposures of deep-water conglomerates with ophiolitic detritus (FAUPL & WAGREICH, 2000) that were deposited on the southern continental margin (Halstatt) of Adria in Valanginian to Aptian time (140–125 Ma, e.g., GAWLICK ET AL., 1999; FAUPL AND WAGREICH, 2000). The Rossfeld Formation is interpreted to represent the infilling of a deep-sea trench in front of the advancing Eo-Alpine thrust sheets (FAUPL & TOLLMANN, 1979; FAUPL AND WAGREICH 2000). During Aptian time (125–112 Ma), this syn-orogenic sedimentation shifted progressively further to the northwest into units presently preserved in successively lower tectonic units of the NCA. This shift in sedimentation marked the migration of the thrust front at the base of the advancing Eo-alpine orogenic wedge that, however, had not yet reached the Piemont part of the Alpine Tethyan Ocean by this stage.

Panorama of the NCA nappes and the Dachstein paleosurface: This and other paleosurfaces are karstified surfaces of u.Triassic Dachstein limestone at altitudes of 1800 to 2500m in the central and eastern parts of the Northern Calcereous Alps (**Figs. 1-9, 1-10**). They are covered by "Augenstein" sediments -sands, pebbles and conglomeratic components- that correlate with l. Oligocene deposits at the base of the so-called "Inntal Tertiary" and the Molasse Basin (of which the Inntal Tertiary was an embayment). This indicates that they were deposited coevally at a similar base level in the Alpine foreland basin at the beginning of the Oligocene. The contact of the Augenstein sediments with the underlying u. Triassic limestone has been interpreted as the erosional remnant of a pre-Oligocene depositional surface (or paleo-surface) that was originally situated just above sea-level and was subsequently uplifted (FRISCH ET AL. 2001).

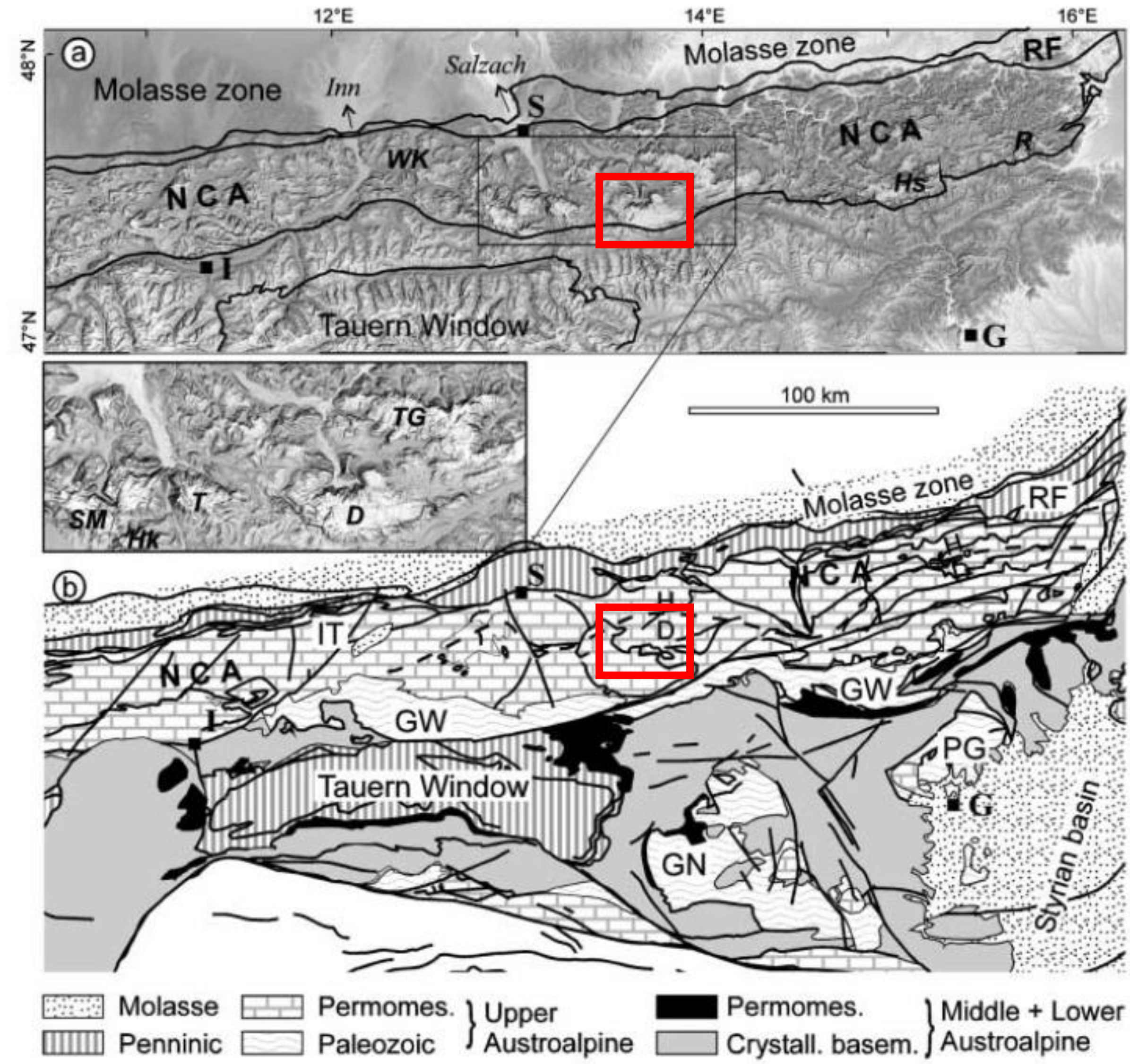


***Figure 1-9**: Satellite view (a) and geological overview (b) of Eastern Alps with location of elevated paleosurfaces and Augenstein sediments in the Northern Calcereous Alps, NCA (modified from FRISCH ET AL. 2001). D - "Dachstein" paleosurface within red box.*

Bad weather outcrop: Rhenodanubian Flysch along Salzach River near Salzburg (N47° 50' 08.7'', E13° 01' 25.7'') - Late Cretaceous to Eocene turbidites formed in the European foredeep before or during Adria-Europe collision

Note: On the way to the Tauern Window, we cross a major sinistral fault, the Salzack-Ennstal-Mariazell-Puchberg Lineament (SEMP, **Fig. 1-10**) that forms the northern boundary of the Tauern WIndow. The Miocene age of this lineament is constrained by syn-rift sediments in the Wagrain pull-apart basin along the SEMP (**Fig. 1-10**).

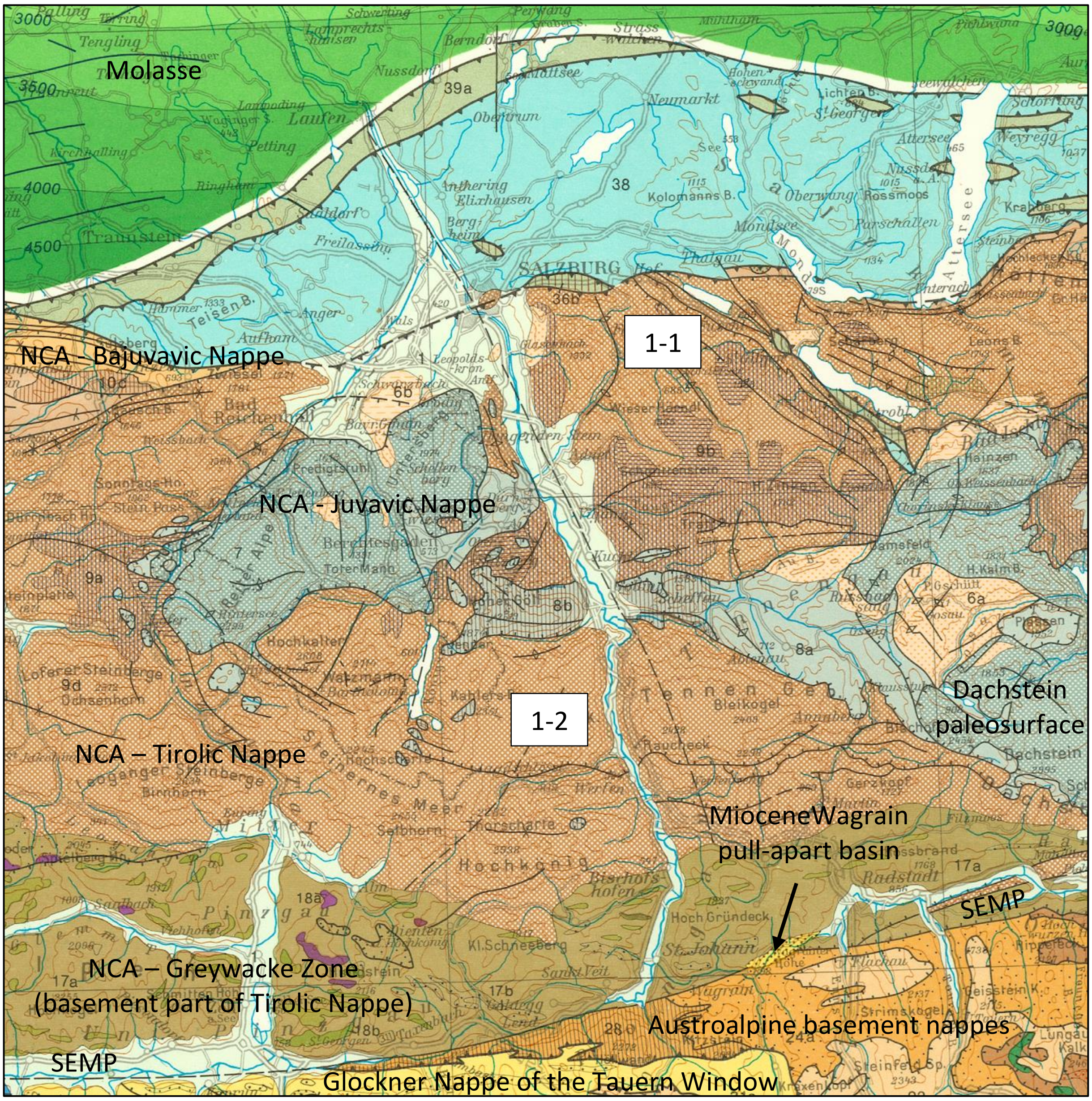


***Figure 1-10**: Nappes of the NCA shown in Structural Map of Italy, Bigi et al. (1981); SEMP – sjnistral Salzack-Ennstal-Mariazell-Puchberg Fault. European units – Rhenodanubian, Ultrahelvetic & Helvetic flysch, Adriatic units - NCA*

Stop 1-3: Edelweissspitze, 2572 m (47°7’24.60°N, 12°49’52.32°E)

Themes: Eocene nappe formation, subduction metamorphism of the main (meso-) Alpine Orogeny

The **Tauern Window** is a Miocene structure that contains exhumed Paleogene nappes of the formerly lower European plate in its core, surrounded by older exhumed Austroalpine nappes of the upper Adriatic plate. The nappes in the Tauern Window formed during the main stage of Alpine subduction (Late Cretaceous to late Eocene) and collision (early Oligocene-early Miocene). The Paleogene suture between lower and upper plate units consists of metamorphosed ophiolites and sediments of the former Alpine Tethyan Ocean. The Tauern Window is bounded by Miocene normal

(Brenner, Katschberg) and strike-slip (SEMP, DAV, Mölltal) faults that severely modified the nappe pile and accommodated lateral orogenic extrusion of the Alpine orogenic core to the E. They represent a radical change in kinematics due to Miocene-Recent indentation of the Adriatic microplate, when subduction polarity changed and Adria became the lower plate subducting beneath the Eastern Alps.

We will traverse the Tauern Window from north to south, passing from structurally highest to lowest units in the core (**Fig. 1-11**). After an introductory scenic stop (stop 1-3), we will visit the folded thrust of Alpine Tethyan oceanic crust onto the distal European margin, then hike across a stratigraphic sequence of the most distal part of this margin. If there is time tomorrow, we will take a further walk in the Pasterze glacial valley to one of the structurally lowest units of the Venediger Duplex.

Structure of the Tauern Window: The nappes in the Tauern Window formed during convergence of the Adriatic and European plates in Late Cretaceous to Cenozoic time. From top to bottom, this nappe stack comprises the following units (**Fig. 1-11**):

- **Austroalpine** units are derived from the Adriatic margin
- **Penninic** units (Matrei Zone, Reckner Ophiolite Complex, Glockner Nappe System) derived from Alpine Tethys
- **Subpenninic** units (Modereck Nappe System, nappes of the Venediger Duplex, Wolfendorn Nappe, Eclogite Zone) from the European margin

The Austroalpine units frame the Window. They experienced Late Cretaceous "Eo-alpine" deformation and metamorphism (e.g., HOINKES ET AL. 1999; FROITZHEIM ET AL. 1994; VILLA ET AL. 2000; SCHUSTER 2003) before being thrust onto the Penninic units along the active Adriatic margin. We will not deal with this Eo-alpine stage, as it is not directly related to the subduction of Alpine Tethys and subsequent Adria-Europe collision.

The nappes within the Tauern Window are nested and can be divided into two nappe complexes shown in **Figure 1-12**: an upper complex (Glockner Nappe system, Modereck Nappe system with the Seidlwinkl sheath fold) and a lower complex (Venediger Duplex with four nappes). These complexes are separated by a roof thrust at the top of the duplex. The eastern end of this nappe stack was sheared by the Katschberg Normal Fault.

Tectonic-Metamorphic History (deformational phases, D1-D5)

- D1 - crustal accretion (86-35 Ma)
- D2 - nappe stacking below the Austroalpine units (86-34 Ma);
- D3 - high-pressure metamorphism and isoclinal recumbent folding of Penninic nappes in the central part of the Tauern Window (e.g., KURZ ET AL. 2008). The age of high-pressure metamorphism is controversial, with both Eocene (Ratschbacher et al. 2004) and Oligocene ages (GLODNY ET AL. 2005; NAGEL ET AL. 2013) proposed so far.
- D4 - Collision and accretion of Europe-derived nappes (34-30 Ma), formation of a duplex with 4 nappes, thermal peak of metamorphism (30-25 Ma)
- D5 – Miocene upright folding, E-W orogen-parallel extension, rapid exhumation (23-7 Ma)

Exhumation is greatest at the western and eastern ends of the Tauern Window, where upright D5 folds and domes deform basement rocks with Barrow-type, greenschist- to amphibolite-facies assemblages (Eastern- and Western Tauern subdomes in **Fig. 1-11**). This thermal peak metamorphism, termed the "Tauernkristallisation" (Sander 1914), induced widespread static recrystallization that overprints all nappes, including the D4 Venediger Duplex (LAMMERER & WEGER 1998). The duplex is itself overprinted by mylonite of the D5 Brenner- and Katschberg Normal Faults at opposite ends of the Tauern Window. The age of the Tauernkristallisation ranges from 30-25 Ma (Rb/Sr on garnet-bearing assemblages, CHRISTENSEN ET AL. 1994; Rb/Sr white mica of VON BLANCKENBURG ET AL. 1989; KURZ ET AL. 2008; U-Pb allanite, CLIFF ET AL. 1998; INGER AND CLIFF 1994; Sm-Nd garnet isochron age of FAVARO ET AL. 2015).

<u>Note on access to outcrops in the Hohe Tauern National Park</u>: Field trips, especially with 5 or more participants, should obtain permission to do field work from the local park authorities. Three Austrian states adjoin on National Park grounds (Kärnten, Salzburg, Tirol), so check your maps carefully to see where field area and park boundaries overlap, and seek written permission from the appropriate office(s) well in advance of your visit. See "Important Addresses" below.

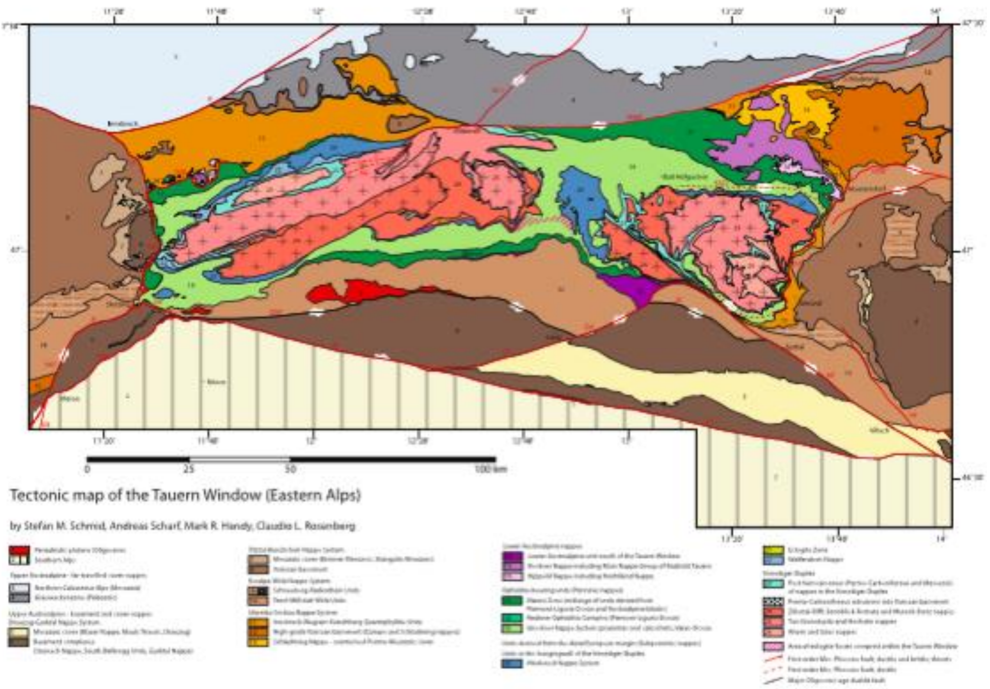


Figure 1-11: *Geological Map of the Tauern Window (modified from SCHMID ET AL. 2013).*

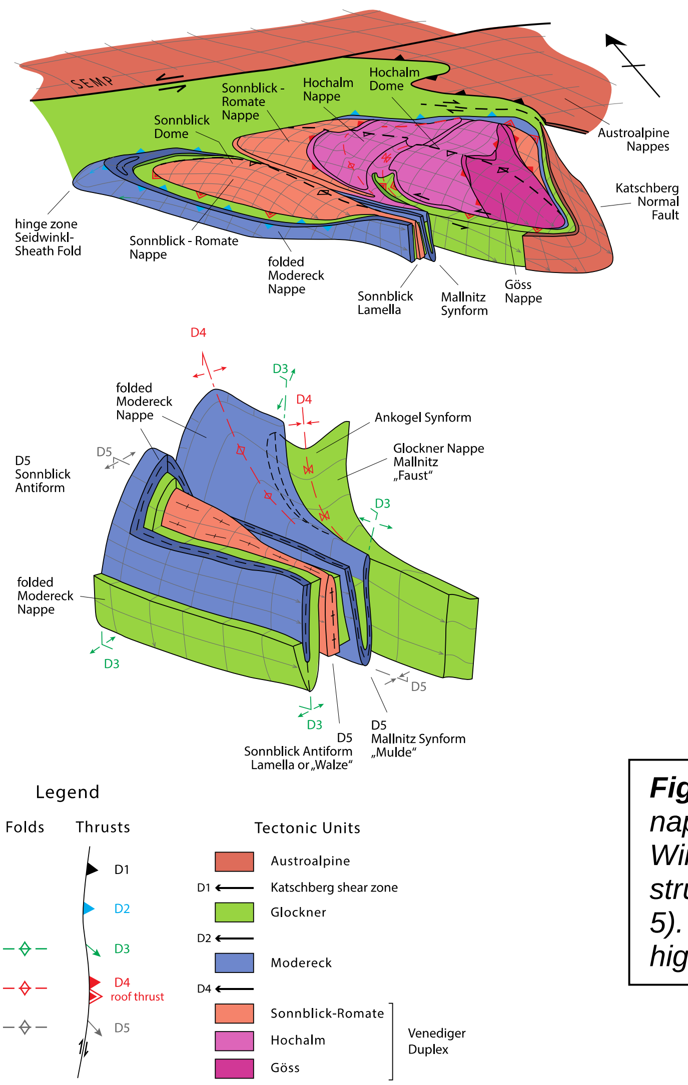
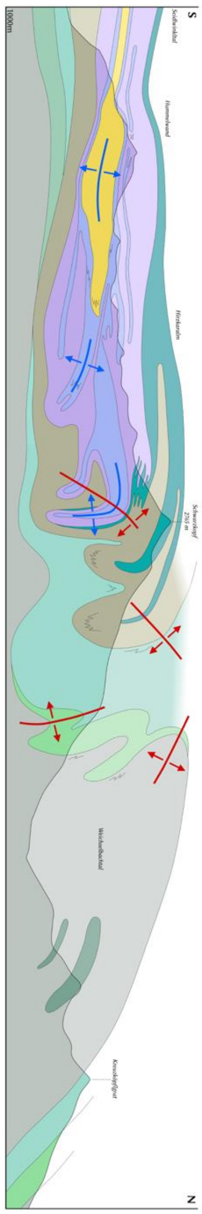


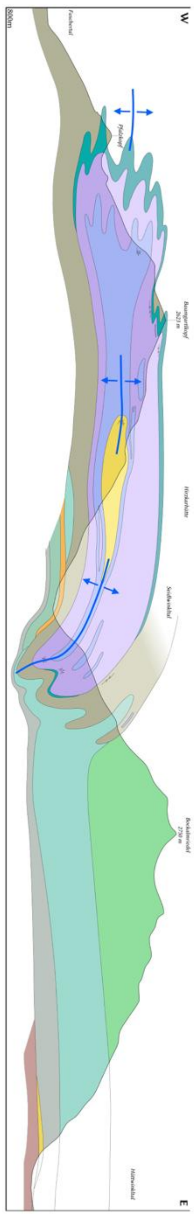
Figure 1-12: *Block diagram (top) with main nappes and thrusts of the eastern Tauern Window. Detailed diagram (middle) of nappe structure in in the Obervellach area (Stop 2-5). Legend shows structural position, from highest to lowest in the nappe pile.*

Cross sections parallel to (a) and perpendicular to (b) the N-S transport direction of the Modereck nappe and the Seidlwinkl fold formed during subduction and exhumation prior to collision:

(a)

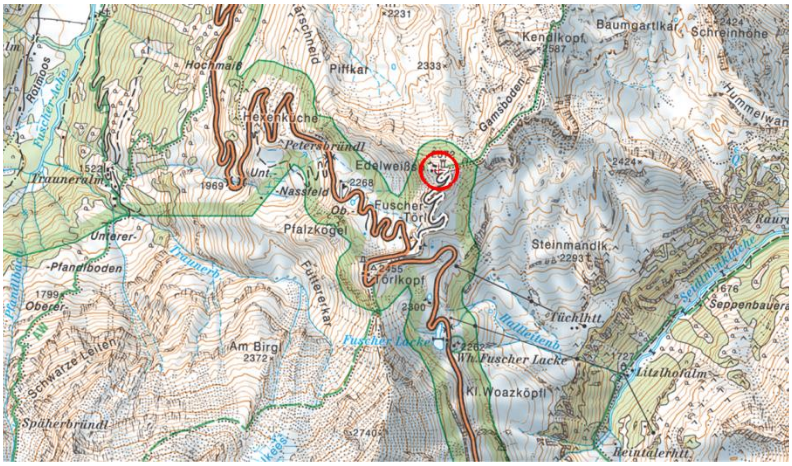


(b)



Blue – axial trace of the F3 Seidlwinkl Fold nappe; Red – axial traces of the F4 folds

Route:



***Stop 1-3**: Edelweissspitze (circle)*

Panorama: The Edelweißspitze affords a 360° panorama from the central part of the Tauern Window (**Figs. 1-13 to 1-15**). To the N and NE, we see in the distance the structurally highest Austroalpine nappes, including the Northern Calcereous Alps that frame the Tauern Window (**Fig. 1-1**). To the E, the landscape is dominated by large tracts of Tr. marbles (especially m.Tr. Seidlwinkl marble) and lower Cretaceous schist (Brennkogel schist) of the Modereck Nappe system. This is dominated on the horizon by the prominent peaks of the Hocharn (3254 m) and Sonnblick (3106 m) which form the basement core of the D5 Sonnblick Dome (**Fig. 1-12**). The mountain to the S (Brennkogel, 3018 m) comprises lower Cretaceous metasediments of the Modereck Nappe system (see Stop 1-2). To the W we have the Große Wießbachhorn (**Fig. 1-14**) with its Penninic units (ophiolites and calc-schist, "Bündnerschiefer") and the sub-Penninic granitic basement units of the Venediger Duplex. The Edelweißspitze itself is made up of u.Tr. dolomitic marble and marble, as well as m.-u.Tr gypsum-bearing cellular dolomite (Rauhwacke) of the Seidlwinkl fold nappe (see Stop 1-4).

***Figure 1-13**: View to the N of the Tauern Window seen from the Weissenbachscharte. Lower left: late Permian “Wustkogel” strata forming core of the isoclinal Seidlwinkl fold nappe (originally distal European margin); Pyramidal peak on left: lower Jurassic Schwarzkopf shales; Right: Edlenkopf with contact of early Cretaceous Brennkogel schist with light calcl-schist of Glockner Nappe. Middle: Seidwinkl Valley and Northern Calcereous Alps (originally SE Adriatic margin) in the distance.*

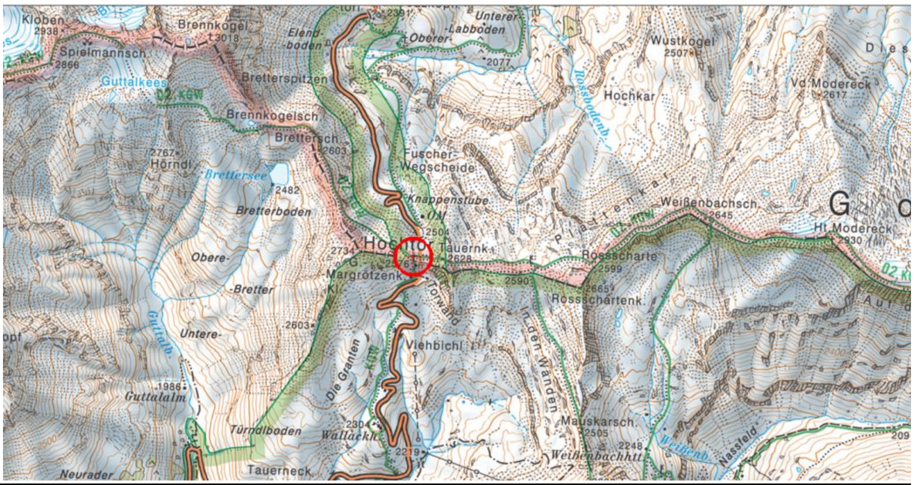
***Figure 1-14**: The Große Wiesbachhorn (3564 m) seen to NW from the Edelweißspitze. This mountain comprises calc-schist (Bündnerschiefer) and has the greatest topographic relief in the Eastern Alps (2300 m from peak to base in the Ferleiten Valley). The Boggeneiskees on its eastern flank (right side of mountain) is a special type of glacier fed only by avalanches during snow-rich winters.*

***Figure 1-15**: View to the SW of Austria's highest mountain, the Großglockner (3798 m) comprising ophiolite and calc-schist (Bündnerschiefer) of the Glockner Nappe. Mountain flank on left belongs to the Brennkogel.*

Stop 1-4: Hochtor parking lot (47°4'51.96°N, 12°50'32.28°E)

Theme: Stratigraphy and structure of the distal European margin (Modereck Nappe)

Route:



***Stop 1-4 (circle)**: Hochtor*

View: The hike from the parking place to the Hochtor, Tauernkopf (2628 m), Roßschartenkopf (2665 m), and in good weather to the Weißenbachscharte (2645 m), affords a view of all peaks and units in the area: to the W the Margrötzenkopf (2734 m, contact of Brennkogel schist of the Modereck Nappe system with prasinite- and eclogite-bearing calc-schist of the Glockner Nappe, Penninic ophiolites of Alpine Tethys), to the SSW the Austroalpine Schober Group and the Lienzer Dolomites (NW part of the Adriatic margin adjacent to Alpine Tethys), to the E the Goldberg Group with Subpenninic units of the Venediger Nappe Complex (SE margin of the European continent adjacent to Alpine Tethys) and to the NNE the Totengebirge, Steinernes Meer, and Dachstein Groups of the Northern Calcereous Alps (SE margin of the Adriatic continent adjacent to Neotethys)

Structure: The dominant structure in the area is the Seidlwinkl fold nappe (blue unit in **Figs. 1-11, 1-12**), a multi-km scale recumbent, isoclinal fold that faces northward and closes in the Seidlwinkl Valley (FRANK ET AL., 1987). The core of this fold comprises Permian siliciclastics of the Wustkogel Fm (see below). An axial plane foliation carries a N-S oriented stretching lineation that is usually parallel to the fold axes (F3), except in the “eye” of the fold in the Seidlwinkl Valley (**Fig. 1-11**). This large-scale fold is interpreted as a sheath fold (**Fig. 1-12**) that formed during or just after the attainment of peak pressure conditions (see below). Exposures of the Glockner Nappe on the Margrötzenkopf to the W of the Hochtor all structurally overly the Modereck Nappe, i.e., occupy the normal, upright limb of the D3 Seidlwinkl fold. Eclogite relics are exposed on the ridge of the Margaretzenkopf; the Glockner Nappe is largely overprinted by greenschist-facies deformation.

Stratigraphy: The hike traverses an almost complete, though deformed stratigraphic section of the distal European continental margin, preserved in the upright limb of the Seidlwinkel Fold nappe. The base of the section exposed in the Wustkogel and on the Weißenbachscharte comprises continentally derived siliciclastics (arkosic and sandstone gneisses partly derived from quartz porphyry, foliated white-green-red “Buntsandstein” sandstones) that range in age from upper Carboniferous-Permian to lower Triassic. Upsection these are followed by foliated evaporites and shallow-water carbonates, including schistose gypsum-bearing dolomite (Rauhwacke, l.-m. Tr) and greenish-silver phyllite (former volcanic layers?). The middle part of this sequence features a prominent band of well-bedded light-grey sugary dolomite (m. Tr., Anisian?) that serves as an excellent structural marker for tracing the fold nappe. This is followed upwards by gray banded dolomite containing Dasycladaceen (*Diplopora annulata*, Ladinian, see TOLLMANN, 1977, p. 22) and a thick sequence of yellow sericitic cellular dolomite (Rauhwacke, Carnian?) topped by a thin white siliclastic layer with silvery Al-silicate micaschist (Piffkar Fm, u. Tr., Norian and Rhät). In the local literature, this predominantly carbonate sequence is termed the Seidlwinkl Fm (FRASL & FRANK,1964, 1966; FRANK, 1969). Its primary thickness is c. 200 m, but shearing has locally reduced the thickness to a meter or even less.

The section continues upward with black schist (l.J. Schwarzkopf Fm) and a thick sequence of flaggy dark brown-rusty schist (l.Cr. Brennkogel Fm). At the Hochtor, the base of the Brennkogel Fm contains 5-20 cm thick quartzite layers (**Fig. 1-16**, PESTAL & HEJL, 2009) that are often graded and even breccious, lending them a turbiditic character. However, the base of the Brennkogel Fm varies in composition in the Tauern Window, usually reflecting the composition of the immediately underlying rocks in the section. This has been attributed to a lower Cretaceous erosional unconformity that formed during the late stages of rifting just before the opening of Alpine Tethys (SCHMID ET AL., 2013).

***Figure 1-16**. Brennkogel schist at the Hochtor Pass with quartzite layers (left) and breccia (right) at the base of the sequence.*

The contact of the sequence above with calc-schist (Bündnerschiefer) of the structurally higher Glockner Nappe system is tectonic and represents the isoclinally folded D2 Alpine subduction thrust.

Metamorphism: The calc-schists (Bündnerschiefer) of the Glockner Nappe system contain lenses of mafic rock (usually prasinite*) with the eclogite-facies assemblage garnet-omphacite-zoisite-glaucophane-paragonite-quartz-rutile. Post-D4 overprinting by the Tauernkristallisation is marked by the assemblage plagioclase-amphibole-chlorite-titanite-hematite (FRANK ET AL., 1987). The platy light quartzite and schist of the Piffkar Fm sometimes contains chloritoid, recognizable as mm-long black needles, also typical of the Tauernkristallisation.

The Brennkogel schist has the assemblage phengite-paragonite-margarite-chlorite-calcite-dolomite-chloritoid-zoisite or -clinozoisite (FRANK ET AL., 1987). Anomalously aluminous layers contain zoned garnets with lawsonite pseudomorphs (chlorite-paragonite-clinozoisite) and inclusions (chlorite-chloritoid-quartz-apatite zircon-rutile). The assemblages of both units indicate subduction to high-pressure conditions prior to and/or during D3 top-N exhumation in the subduction channel.

We recently discovered Brennkogel schist of the Modereck nappe from the Margrethat contains syn- to post-D3 garnets with early (syn- to post-D2) pseudomorphs of lawsonite (**Fig. 1-18**). By combining thermodynamic modelling of zoned garnets with Raman microspectroscopy of quartz inclusions in these garnets, we obtain a steep decompression path during D3 shearing (**Fig. 1-18**). The Tertiary exhumation history of the various subducted units in the Tauern Window is shown in **Figure 1-19** (after KURZ ET AL., 2008). When taken together with existing studies, it becomes clear that both distal continental and oceanic units were involved in the Alpine subduction.

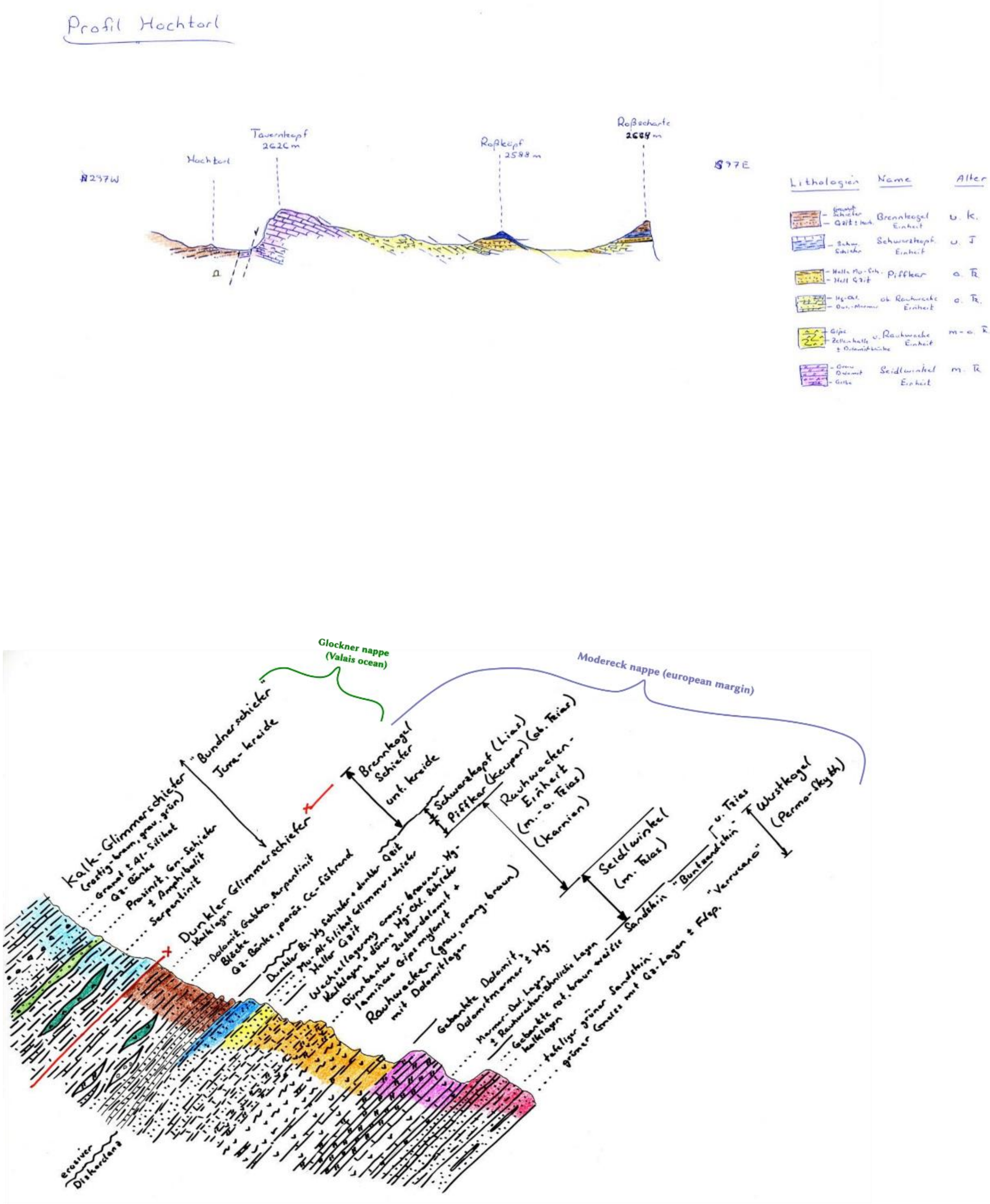


Figure 1-17: *Rough W-to-E cross section of the Hochtor area (top) and composite stratigraphic section of the Modereck Nappe near Hochtorl (bottom)*

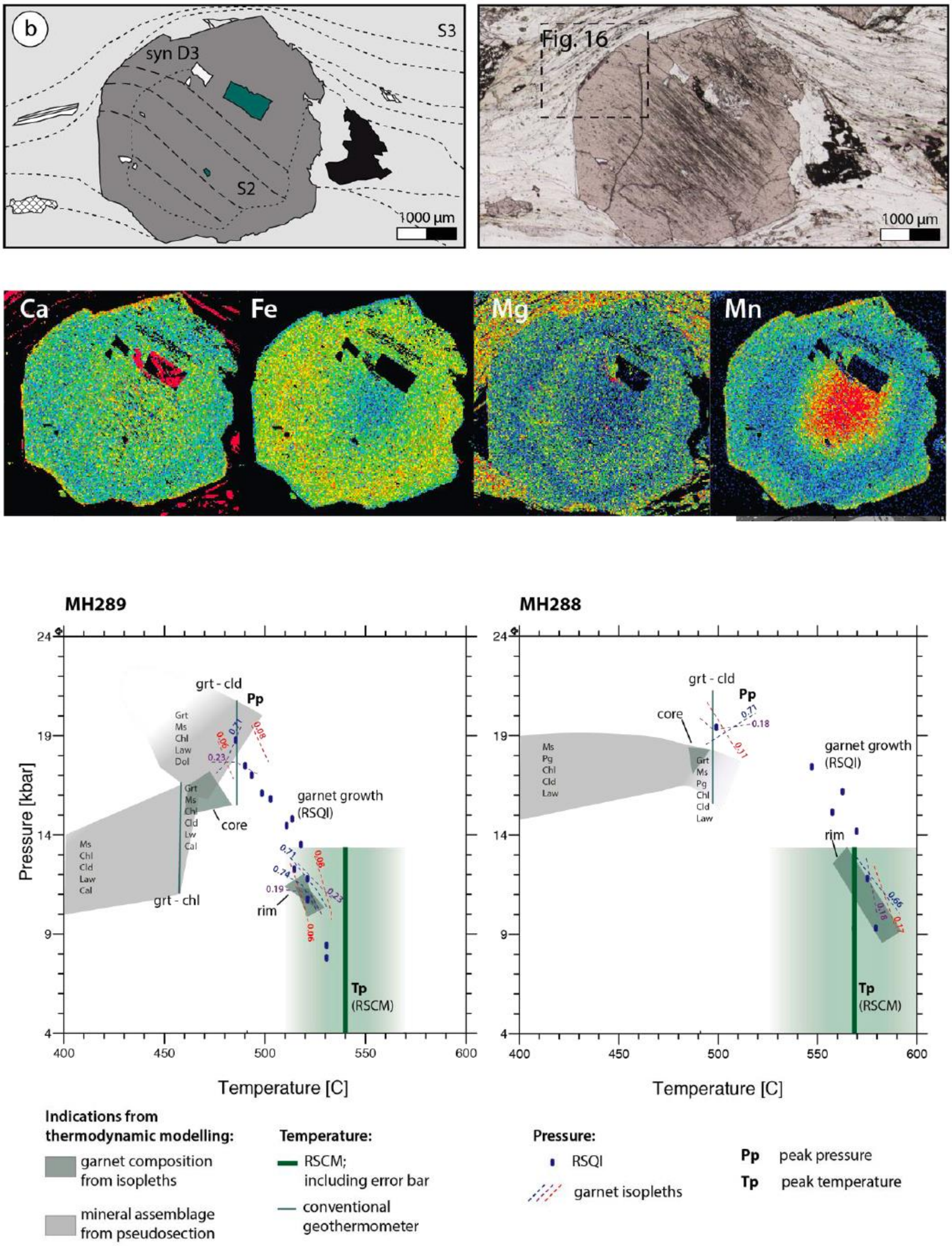


***Figure 1-18**: Garnet from Brennkogel schist of the Seidlwinkl fold nappe: (a) microstructure with curved inclusions documents post-D2 (core) and pre- to syn-D3 growth (rims); (b) compositional zonation with lawsonite pseudomorphs; (c) P-T evolution for D2 thrusting and subduction and D3 exhumation, preserved in the hangingwall of the roof thrust of the Venediger Duplex (K. SCHMIDT, 2015, MSc thesis).*

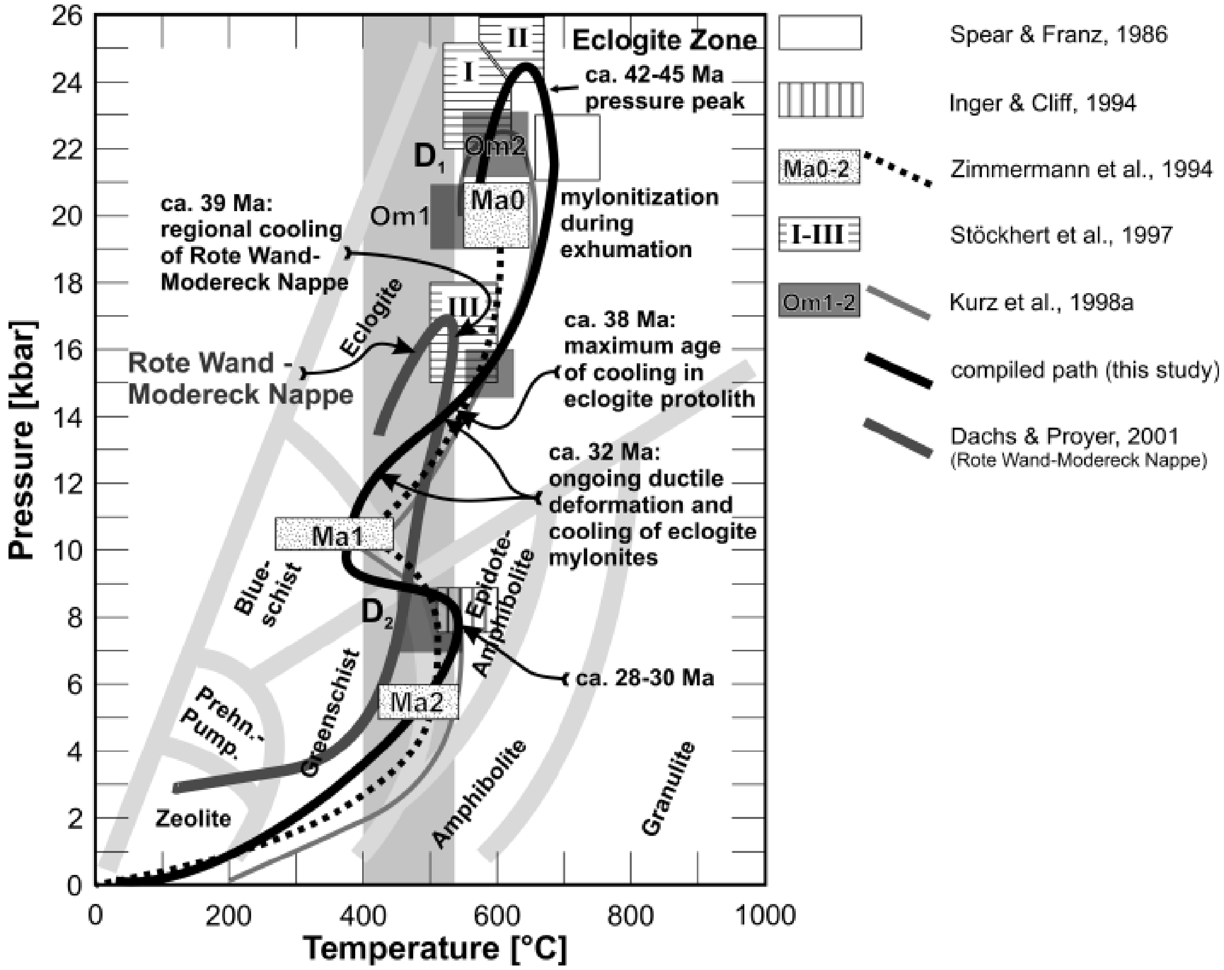


***Figure 1-19**: P-T curves showing subduction and exhumation of continentally derived nappes in the Tauern Window (from Fig. 4 of Kurz et al. 2008): the Eclogite Zone of the W Tauern Window (**Fig. 1-11**) and the Rotewand-Modereck Nappe (here simply termed the Modereck Nappe).*

Pleistocene Geology: The carbonates form a high plateau pocked by karst sinkholes („Dolinen“). The slow downhill migration of loose carbonate rocks is attributed to solifluction, with surges occurring yearly in the spring and early summer. The abundance of springs near the quartzites and gneisses of the Wustkogel Fm indicates that these lithologies form a barrier to water flowing in the porous carbonate. These springs are important sources of water for the local alps (Tüchl Hütte and Hummelwand) during the summer months.

Overnight in the Wallackhaus, Großglockner Pass or in Heiligenblut (see Important Addresses)

Day 2: Adria-Europe indentation tectonics

Route: Wallackhaus to Gmünd via Heiligenblut, Obervellach (Mölltal)
Themes: Miocene indentation, lateral escape tectonics, exhumation

Stop 2-1: Serpentinite of the Glockner Nappe system (47°3’34.92°N, 12°47’38.76°E)

Theme: Oceanic crust (lithologies of the Glockner Nappe system)

Directions: Stop at the curve “Pockhorner Wiese” just beyond the Schienewand, on the road between Kasereck und Franz-Josefs-Höhe, about 2 to 2.5 km ESE of the Glocknerhaus (Stop 6 of HÖCK & MARSCHALLINGER 1988).

***Stop 2-1 (circle)**: Pockhorner Wiesen.*

Description: The rock is predominantly antigorite (the massive variety of serpentinite) and is bordered by small lenses of ophicalcite. The serpentinite is overlain by S-dipping calc-silicate sometimes containing garnet. Blocks of the calc-silicate have the paragenesis tremolite/actinolite-calcite-diopside-epidote as well as (dolomite-chlorite) and tremolite/actinolite-calcite-epidote-chlorite and (dolomite-diopside). The minerals in parenthesis do not coexist stabley with the other phases. The Cc-Dol geothermometer yields temperatures in the range 480-500°C (FRANK et al., 1987).

Stop 2-2: Glockner Nappe at Franz-Josefs-Höhe (47°4’20.64°N, 12°45’21.96°E)

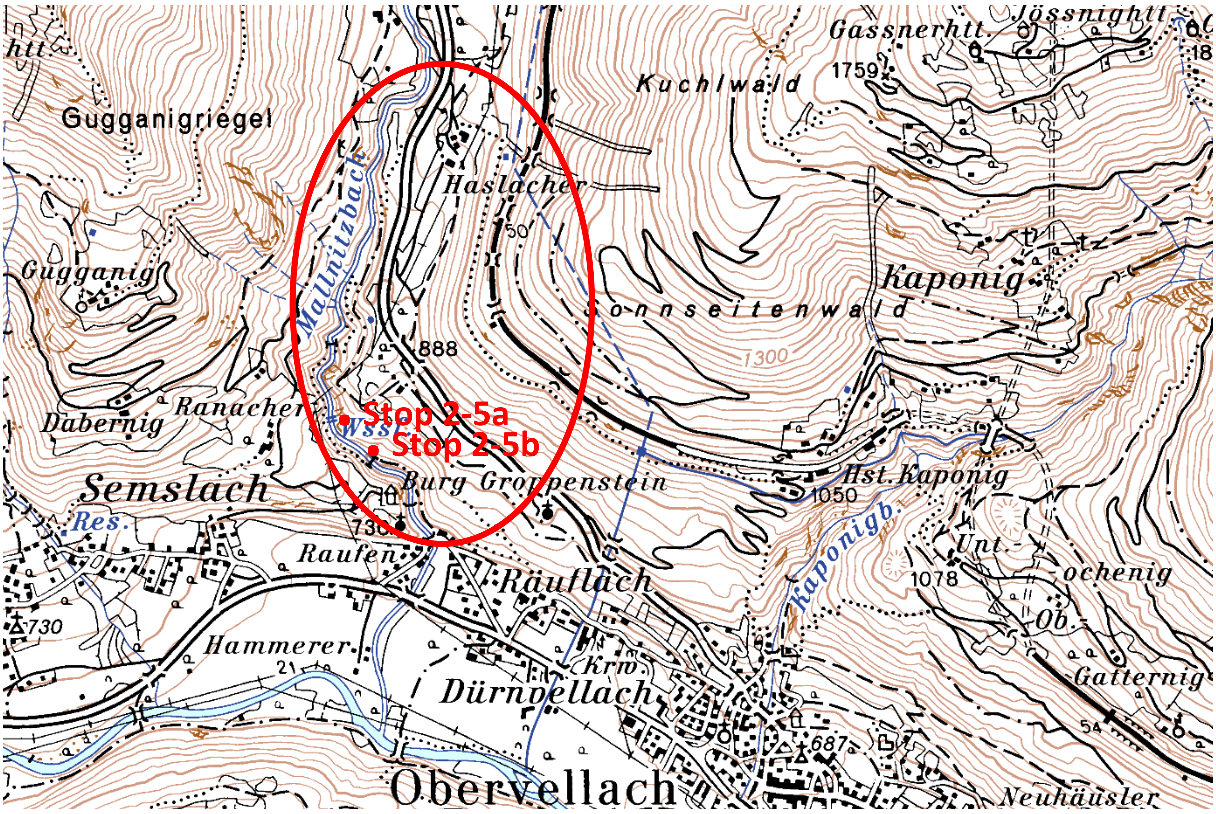
Themes: Metamorphism during subduction, collision and exhumation of Penninic units (especially Glockner Nappe system); Pleistocene geology of the Pasterze Glacier

Directions: Park at the Franz-Josefs Höhe and consider the two options below, depending on weather and the time available.

Stop 2-5: Groppenstein Gorge – Groppensteinschlucht (parking lot at entrance to the Groppenstein Gorge, 46°56’36.24°N, 13°10’49.44°E, elevation: 810 m)

Themes: Multiply folded nappe stack of the eastern Tauern Window, strike-slip shearing and lateral escape related to Katschberg normal faulting

Directions: From Schladming follow the A10 to Spittal a. d. Drau. A few km before arriving at Spittal, turn west onto the A9. After 3 km the autobahn ends as the main road 106. Drive to the town of Obervellach and continue up the Möll Valley until you see a small road branching off to the right with a sign labelled “Groppensteinschlucht”. After c. 200 m, park the cars in a lot in front of a small hut where a receptionist will request a fee of 5€ per person to enter the gorge. If you have visited the mayor’s office beforehand and said that you are geologists, then you can enter without paying (that’s how much we are worth!). The path along the gorge goes all the way up to Mallnitz, but you need walk only as far as the emergency exit path. Walk from the hut about 200m along the northeastern side of the Mallnitz stream (passing a large outcrop and rockfall of Brennkogel quartzite) until you reach a footbridge that crosses the gorge. The first outcrop is on the ledge above the stream just to the north (right) of the northern end of the bridge.



Stop 2-5 - *Topographic map and stop locations in the Groppenstein Gorge*

General Structure: The remaining outcrops today and tomorrow are devoted to D5 structures that formed during exhumation and eastward lateral escape of the orogenic crust in response to late-orogenic (Miocene) indentation of the Adriatic microplate. Exhumation and lateral escape were accommodated by a system of crustal-scale shear zones that bound the Eastern Tauern Dome (**Fig. 1-11**). A similar system of shear zones at the Brenner Normal Fault delimits the western end of the Tauern Window (**Fig. 1-11**). The main part of the eastern system is the Katschberg Normal Fault (Day 3) which is linked to two subvertical branches of strike-slip mylonitic shear. Stops 2-5 and 2-6 are to the southern of these branches that skirts the SW boundary of the Hochalm Subdome. Stop 2-7 is at an exposure of the brittle Mölltal fault which runs parallel with this southern branch, but affects the Austroalpine crustal indenter (Scharf et al. 2013a, Favaro et al. 2016).

Outcrop description: In the lower part of the Groppenstein Gorge (Himmelbauer), we observe the following sequence of lithologies situated on the southern limb of the D5 Sonnblick Dome (**Fig. 2-9e**): (1) quartzite and slightly carbonaceous dark schists of the lower Cretaceous Brennkogel Formation in the Modereck Nappe System; (2) white quartzite of the Piffkar Fm in the Modereck Nappe System; (3) biotite-white mica schist and gneiss forming the pre-late Paleozoic Sonnblick basement; (4) late Paleozoic augengneiss of the Sonnblick basement. Note that the Mesozoic cover of the Sonnblick unit is missing, both here and elsewhere. It was presumably detached prior to D5 shearing (D2 or D3?). The profile ends at Haslacher, near the northern end of the red ellipse in **Figure 2-1**.

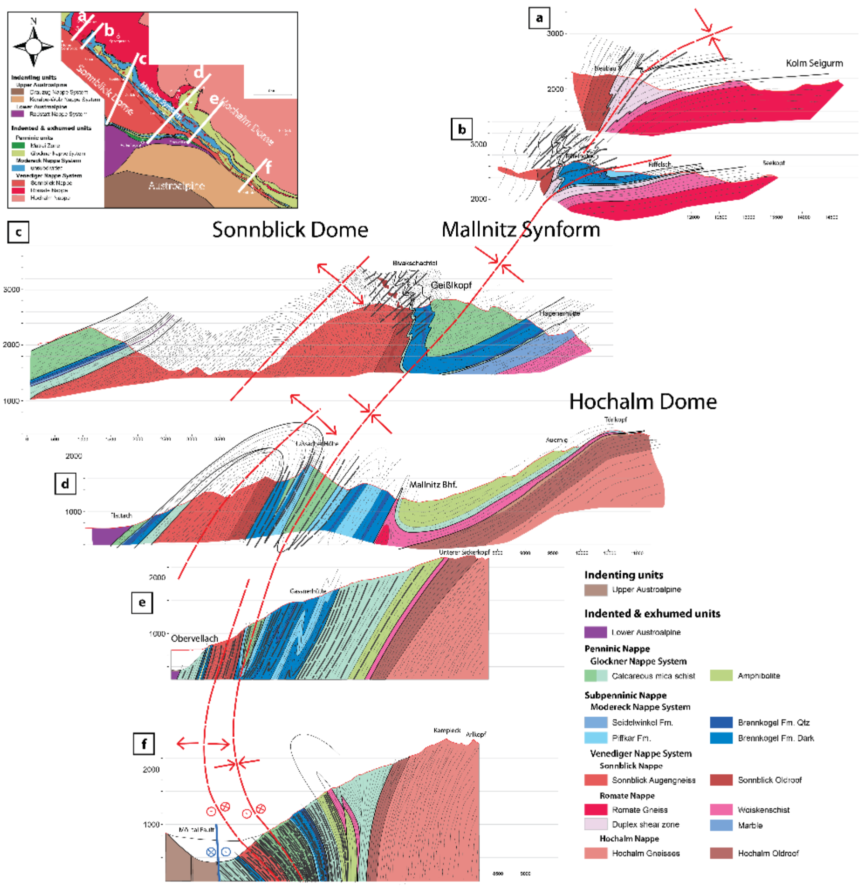


__Figure 2-9__: Cross sections of Mallnitz Synform, Sonnblick and Hochalm Domes (inset map): Red dashed lines - traces of the F5 axial planes; black dashed lines - main S5 foliation. Older foliations indicated with grey lines. Note in (f) the opposite shear senses of indenting Austroalpine crust along the Mölltal Fault (dextral, blue circles) and of indented orogenic crust along the steep southern branch of the Katschberg Normal Fault (sinistral, red circles). Adapted from FAVARO ET AL. (2017)

Figure 2-9 shows an acylindrical D5 synform (Mallnitz Synform) and two doubly-plunging antiforms (Sonnblick, Hochalm Domes) as well as the steepened isoclinal D3 anticline overlying the roof thrust of the Venediger Duplex. The D3 structures were all highly sheared, mostly during D4 (in the east) and D5 (in the west) events. The geometry of these highly sheared units in the Obervellach area is depicted schematically in the block diagram in **Figure 1-12**. The Mallnitz Synform tightens from NW to SE (**Fig. 2-9**). Its core contains the upper part of the Glockner Nappe System and its limbs comprise the Modereck Nappe System, which itself forms the core of a D3 anticline (**Fig. 2-9**).

The first stop next to the bridge across the gorge is at subvertically dipping, mylonitic schist and quartzite of the Brennkogel Fm. The foliation azimuth is about N20°E and the stretching lineation pitches gently to the SE. The outcrop shows several cm- and dm-scale shear bands that are consistent with a predominantly sinistral sense of shear. Raman spectra from carbonaceous material in these rocks yield a peak temperature of 503 °C, which we interpret to be related to the "Tauernkristallisation" that preceded the mylonitization. The conditions of deformation are inferred to be greenschist-facies based on the syntectonic stability of white-mica and chlorite and the predominance of subgrain-rotation and grain-boundary migration recrystallization in quartz aggregates. This intensive D5 deformation is responsible for the impressive thinning of the Sonnblick Dome to the Sonnblick Lamellae running along the northeastern side of the Möll Valley, **Figs. 1-11, 1-12**). We relate this thinning to northward indentation of the rigid Austroalpine Drau-Möll Block exposed on the southwestern side of the Möll Valley (**Fig. 1-11**).

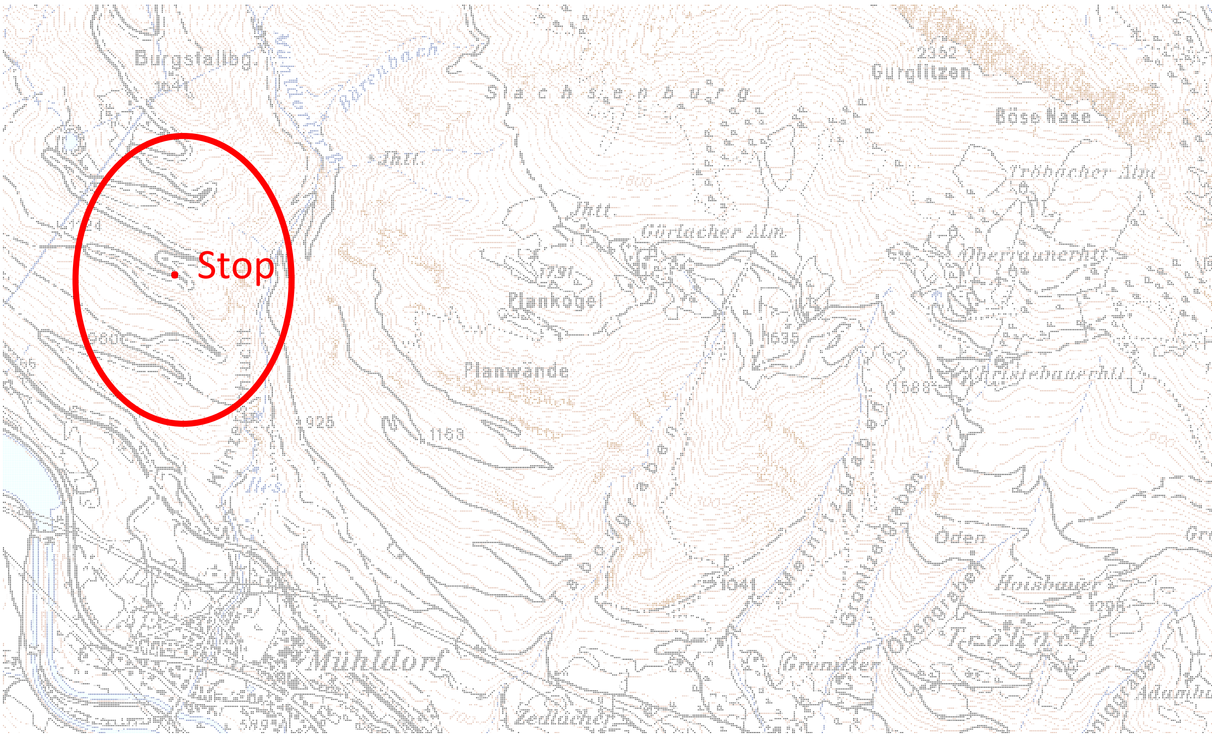
Cross the bridge and continue up the steep, winding path along the southern bank of the Mallnitz stream. Where the path steepens, one crosses the subvertical contact of schists of the Brennkogel Fm with the gneisses and schists of the Sonnblick basement. This contact is the roof thrust of the D4 Venediger Nappe System that was reactivated during D5 mylonitization. This reactivation evidently excised a thin lamellae of calc-schist ("Bündnerschiefer") which is exposed along strike between the Brennkogel Fm and the Sonnblick basement, and formed the lower unit of the Glockner Nappe System. Continue climbing past the waterfall on your right until you reach a broader expanse of streambed outcrop, our second stop.

The second stop in the streambed comprises one lithology, a medium-grained, mylonitic biotite-white mica augengneiss and clastomylonite whose protolith was a granite of late Paleozoic age by analogy with similar rocks in the tectonic slices of the Venediger Nappe Systems in the western part of the Tauern Window. Like the previous outcrop, the mylonitization is D5 and is typical of the strain found along the entire length of the Sonnblick Lamellae. The sense-of-shear indicators in this outcrop indicate both dextral and sinistral motion, which we attribute to a highly coaxial D5 strain field (KURZ & NEUBAUER, 1996). The feldspars are dynamically recrystallized and locally fractured, whereas quartz underwent dynamic recrystallization by a combination of subgrain rotation and fast grain-boundary migration; together, these mechanisms are indicative of upper greenschist-facies conditions for D5. Medium- to fine-grained leucocratic veins truncate the main foliation at low- to moderate angles and are themselves cut by late discrete fractures locally filled with lower greenschist-facies minerals; these brittle structures are presumably related to late stages of D5.

Climbing to the north along the gorge path, we pass the northern tectonic contact between the Sonnblick basement and the dark, slightly carbonaceous schist of the Brennkogel Fm. Again, the calc-schists of the lower unit of the Glockner Nappe System are missing (faulted out) and the contact represents the isoclinally folded D4 roof thrust of the Venediger Nappe System. We thus enter the southern limb of the D5 Mallnitz Synform (**Fig. 2-9**). The core of this synform comprises calc-schists with occasional layers of marble (imbricated m.-Tr. Seidlwinkl Fm?) and quartzite (u. Tr. Piffkar Fm?).

<u>Stop 2-6</u>: Road outcrop on the Burgstallberg (46°52'32.88°N, 13°20'37.68°E, elev: 1200 m)

Theme: Shear sense of the southern branch of the Katschberg Shear Zone System



***Stop 2-6**: Topographic map and stop location near the 6th curve from the bottom of the road to Burgstallberg*

Directions: Drive southeast along the main road 106 to Mühldorf. Shortly before reaching the town, turn left off the main road onto a small road. Continue under the railway line, then turn left again. A useful landmark for knowing where to look for the exit off the main road is when you see two large water pipes running down the northern side of the Möll Valley. Where there is a "no driving" sign, the road begins to climb in a seemingly never-ending series of hairpin curves. Note that this road carries heavy truck traffic related to construction and maintenance of the hydroelectric tunnels at the top of mountain (why it is forbidden to drive a car), so that one should ask for permission to drive on the road from the head of the building firm. Drive until the 6th hairpin (hairpin curves all conveniently numbered with signs) and park the cars out of the way of the trucks. The outcrop is down the road just 50 m from the curve.

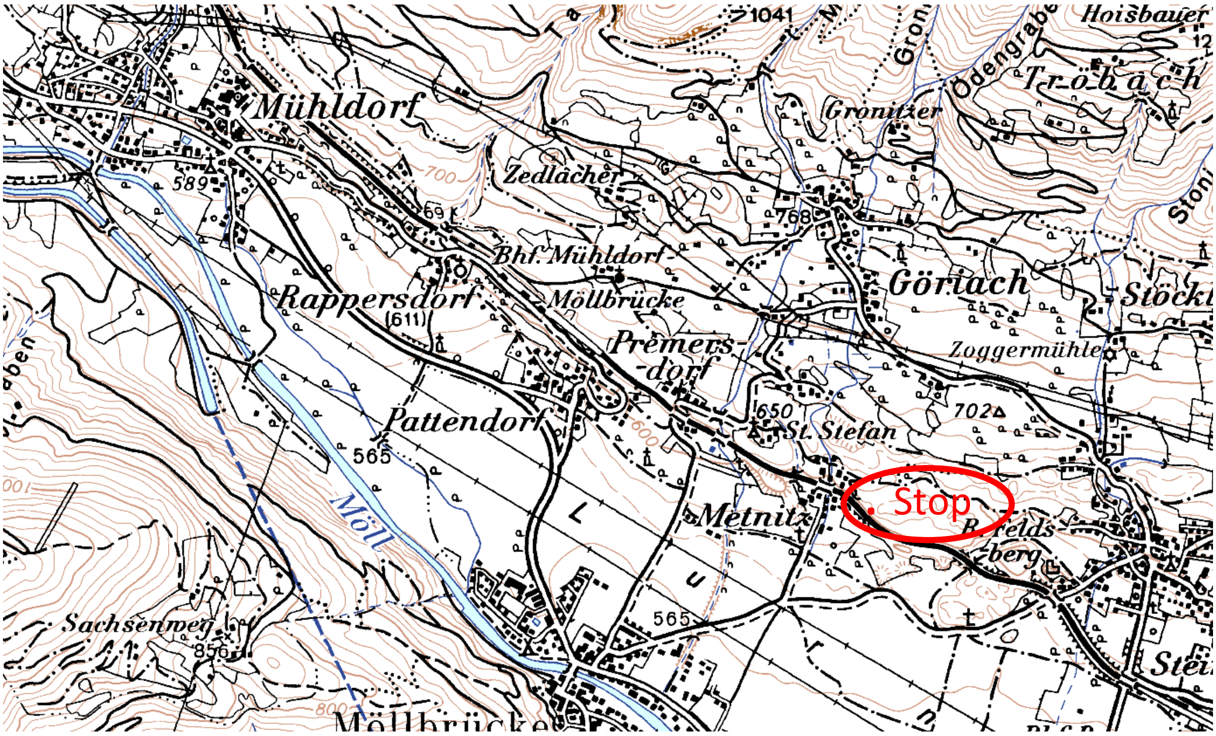
Description: Aside from the base of the section where the Sonnblick Lamellae is very poorly exposed, the road section exposes only one lithological association: variegated chlorite-white-mica bearing, greenschist-facies calc-schists with occasional lenses and layers of quartzite and prasinite. This association belongs to the lower unit of the Glockner Nappe System in the southeastern prolongation of the northern limb of the Mallnitz Synform; it is directly correlated along strike with the fist-like occurrence of calc-schist and ophiolitic rocks (amphibolites, meta-gabbros, serpentinized ultramafics) seen in map view at Mallnitz (Fig. 26). The outcrop reveals sinistral shear-sense indicators (**Fig. 2-10**) on surfaces parallel to the XZ-fabric plane that contain the stretching lineation (perpendicular to the subvertical foliation). Sinistral mylonitic shear is typical of the entire southern branch of the Katschberg Normal Fault, in contrast to the dextral shear along the northern branch (see Introduction above, Scharf et al. 2013a).

***Figure 2-10**: (A) Intrafoliational boundins with asymmetry and rotation indicating sinistral shear sense in calc-schist (Bündnerschiefer) of the Glockner Nappe system; Outcrop along road to Burgstallberg on NE side of the Möll Valley; (B) Rotated feldspar clast in granitoid of the Sonnblick Lamellae; Outcrop on the NE side of the Möll Valley.*

Note that the southern branch exposed here is the site of a minor trough in the peak temperatures (20° C lower than the general value of 500° C) as documented by Raman spectroscopy on carbonaceous material in calc-schists (section H-H´ in Figs. 24 and 25; Scharf et al. 2013b). This trough is attributed to the preservation of lower peak temperatures of the pre-KNF "Tauernkristallisation" in the upper Glockner Nappe System that was infolded during D5 deformation. The age of Katschberg shearing is bracketed between c. 23-21 Ma and 17 Ma (Scharf, 2013a, Favaro et al. 2016).

Stop 2-9: Embankment along Tauern railway line at Metnitz (46°50’36.24°N, 13°23’7.08°E, elevation: 613 m)

Theme: Brittle deformation related to late lateral escape tectonics, cataclasites of the Mölltal Fault



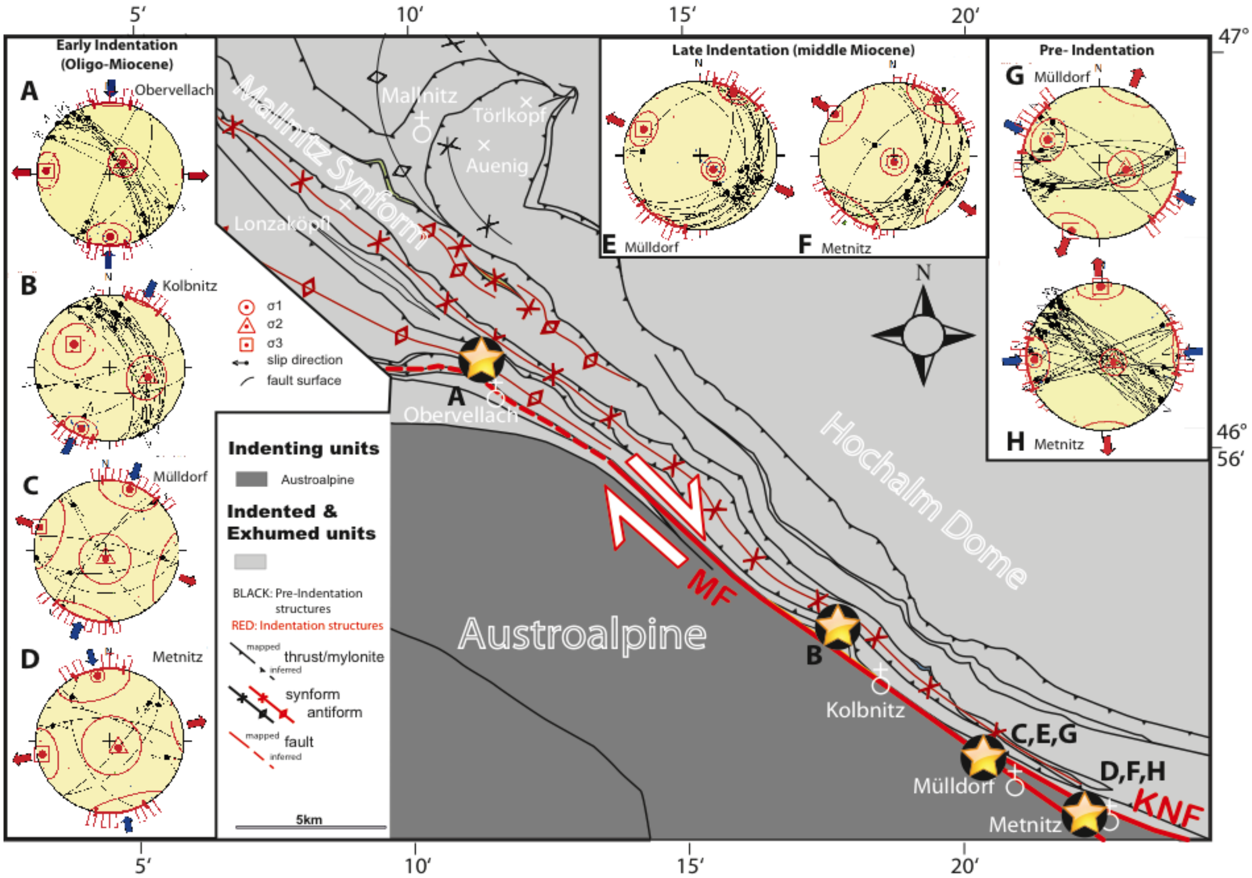
***Stop 2-8**: Topographic map and stop location*

Directions: Continue on the main road 106 heading southeast towards Spittal-an-der-Drau until the village of Möllbrücke. Just after reaching the center of village, turn left at the sign marked “Metnitz” and follow the road until the Tauern railway line. Drive underneath the line, then turn sharply right and drive another 50 m, where you can park cars. The outcrop is just in front along the railway line.

Figure 2-11*: View to SE along the Möll Valley, a glacial valley running parallel to the dextral Mölltal strike-slip fault separating the Austroalpine crust (right) from the exhumed Penninic Sonnblick Lamella and Venediger Nappe complex (left).*

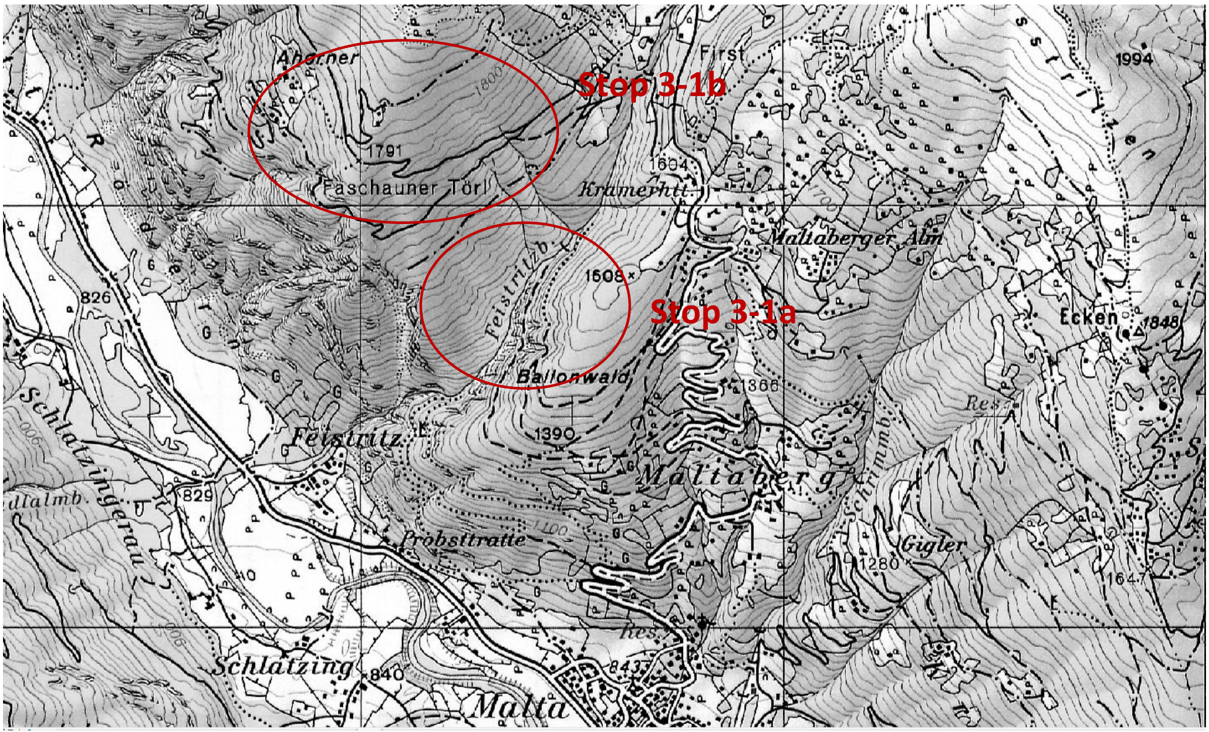
Description: The outcrop comprises gneiss of the Austroalpine Millstatt Complex, a member of the Koralpe-Wölz unit, which is marked by Eo-alpine amphibolite-facies metamorphism and Late Cretaceous eclogite-facies assemblages (though there are no eclogites at this locality). The rocks here are strongly fractured and retrogressed under sub-greenschist facies conditions. Their moderately to subhorizontally dipping schistosity is severely disrupted by at least two fracture systems coated with secondary hydrous and ore minerals: (1) steeply dipping, partly conjugate fractures with surfaces locally carrying gently plunging striae; (2) moderately southeast-dipping fractures, sometimes carrying down-dip striae, and locally associated with subvertical synthetic Riedel fractures. The latter fractures are younger as they usually offset all other surfaces with a consistent top-down-to-SE sense of motion.

The first fracture system is interpreted to have formed during activity of the Mölltal Fault. Palaeostress analysis (PTB method in **Fig. 2-12**) indicates strike-slip kinematics with shortening axes oriented E-W. This is inconsistent with dextral motion on a NW-SE trending Mölltal Fault as determined from the offset of units in map view and from the PTB method applied to other outcrops. This inconsistency is attributed to reactivation of the subvertical fracture surfaces during the second phase of faulting. This second phase accommodated SE-directed extension (subvertical principle shortening direction in the PTB analysis of **Fig. 2-12**). This is related to late extension, possibly during the final stage of Katschberg normal faulting at the SE end of the Tauern Window.



> ***Figure 2-12**: P-T-B analysis of brittle fault planes along the Mölltal Fault that overprint mylonite of the southern branch of the KNF. (A) Brittle deformation of Sonnblick Lamella near Obervellach; (B) brittle deformation in the Glockner Nappe System near Kolbnitz: (C, E, G) cataclasites in lower Australpine Unit, railroad near Mülldorf; (D, F, H) cataclasites in lower Australpine Unit, railroad cut near Metnitz. Figure modified from FAVARO ET AL. 2017*

Description: This stop consists of two sections of several small outcrops along a forestry road. It involves about 3 hours of easy walking and ends with a beautiful view of the Katschberg Normal Fault and the Hochalm Dome. The outcrops are of structures related to Miocene E to SE-directed shearing of Subpenninic and Penninic units in the footwall of the Katschberg Normal Fault (KNF). The entire stop is described in the explanatory pamphlet to Map 182 “Spittal a. d. Drau”, scale 1:50.000 (SCHUSTER ET AL. 2006).



Directions: From Gmünd, follow the road L12 into the Malta Valley and turn right (north) at the village of Malta. Drive up to the Maltaberg (the end of the road) and park at the Almhütte there at c. 1600 m (they serve cakes, coffee and Almdudler). From there, walk back to a forestry road branching off at an elevation of c. 1500 m (i.e., before the first U-bend). Follow this road to the southwest to the "Ballonwald".

Stop 2-10a: ("Ballonwald" (46°58'5.88°N, 13°30'23.76°E, altitude: 1500 m)

Themes: Katschberg Normal Fault

Description: Several small outcrops along the forestry road (1.5 km) oriented perpendicular to the strike of the Katschberg Normal Fault (KNF) reveal the lithologies in the footwall of the KNF: Calc-schist and prasinite of the Glockner Nappe System and Subpenninic rocks (siliciclastic albite-bearing gneiss of the Modereck Nappe System, pre-Variscan paragneisses of the Storz Nappe). The tectonic contact of the Modereck Nappe System with the underlying Storz Nappe (part of the Sonnblick-Romate unit) marks the roof thrust of the Venediger Duplex (**Figs. 1-11, 1-12**). All units dip moderately to the ESE and preserve top-ESE kinematic indicators typical of D5 mylonitization along the KNF. Peak temperature estimates obtained from Raman microspectroscopy on carbonaceous material (RSCM) in the metasediments above the aforementioned roof thrust yield temperatures of 515 ± 10° C in the structural lowest units and 460 ± 8° C in the structurally highest units (**Fig. 2-14**; SCHARF ET AL. 2013b). This enormous field-gradient (70°C/km) corresponds with the zone of greatest tectonic omission in the footwall of the KNF.

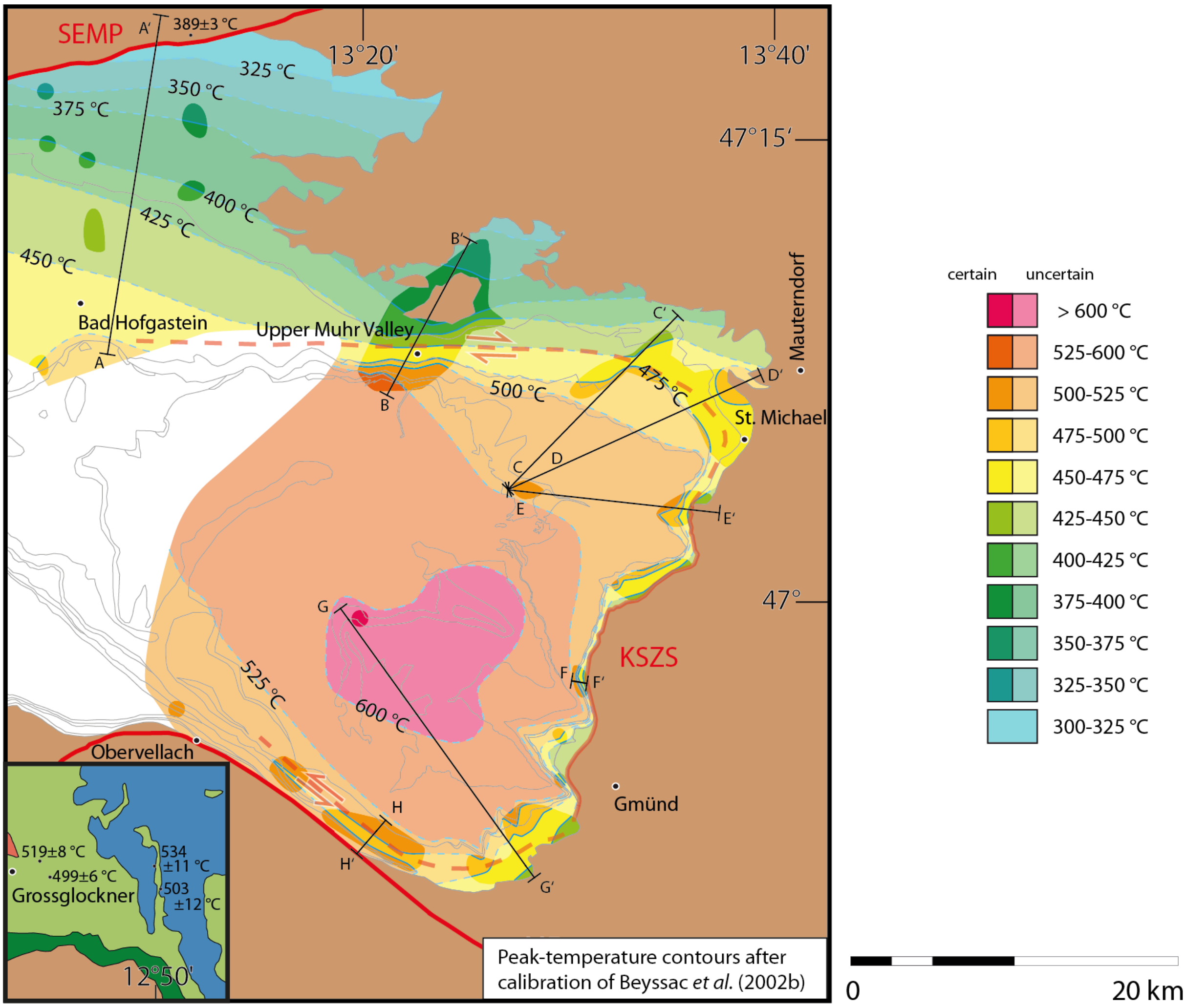


***Figure 2-14**: Peak-temperature contours of SCHARF ET AL. (2013b) based on the calibration of BEYSSAC ET AL. (2002b) for CM. Transparent colours and dashed lines indicate areas and contours where the sample density is low. Brown = Austroalpine units. Grey lines = tectonic contacts separating units of the Tauern Window. The peak-temperature contours are marked in light blue. Inset shows estimated peak temperatures of 4 samples in the only area of high-pressure metamorphism.*

Stop 2-10b: Faschauer Törl (46°58’36.12°N, 13°29’30.12°E, altitude: 1791m)

Themes: East-directed Miocene normal faulting and footwall exhumation

Directions: Return to the cars parked at the Almhütte and follow the path crossing the Feistritz Valley to the west. This path (2 km long with an altitude difference of 200 m) has exposures of the Variscan granitic intrusions that intruded the pre-Variscan paragneisses seen along the path in the “Ballonwald”. All these rocks belong to the Storz Nappe below the roof thrust of the Venediger Duplex (**Figs. 1-11 & 1-12**). The asymmetry of the feldspar augen in the intrusive rocks indicates top-ESE sense of shear. The end of this path provides a beautiful view of the Faschauer Törl (1791 m), where one can see the large-scale culmination of the Hochalm Dome, as well as the moderate eastward dip of all thinned Penninic- and Subpenninic units in the footwall of the KNF.

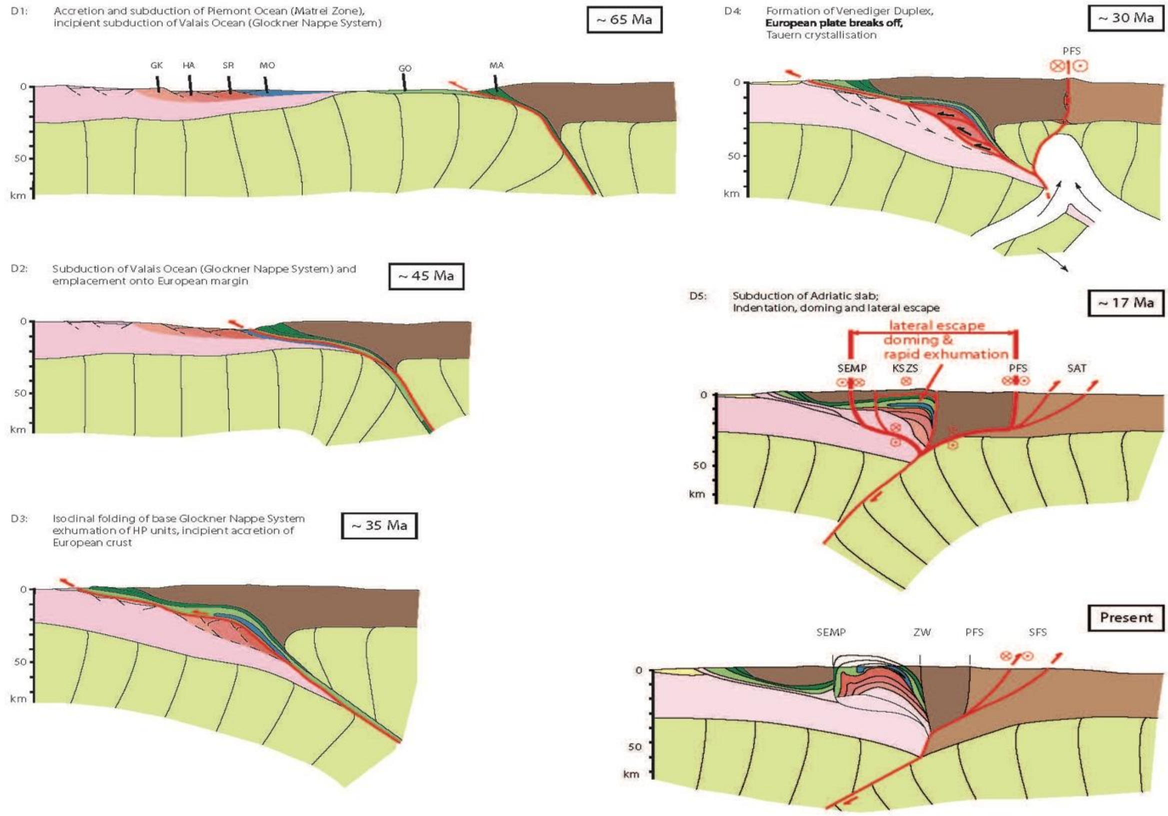


Figure 2-15: *Tectonic synthesis of the Alpine orogen along a N-S cross section odf the transect on this field trip (modified from HANDY ET AL., 2015 and SCHMID ET AL., 2013). Crustal units have same colours as in Figs. 1-11, 1-12.*

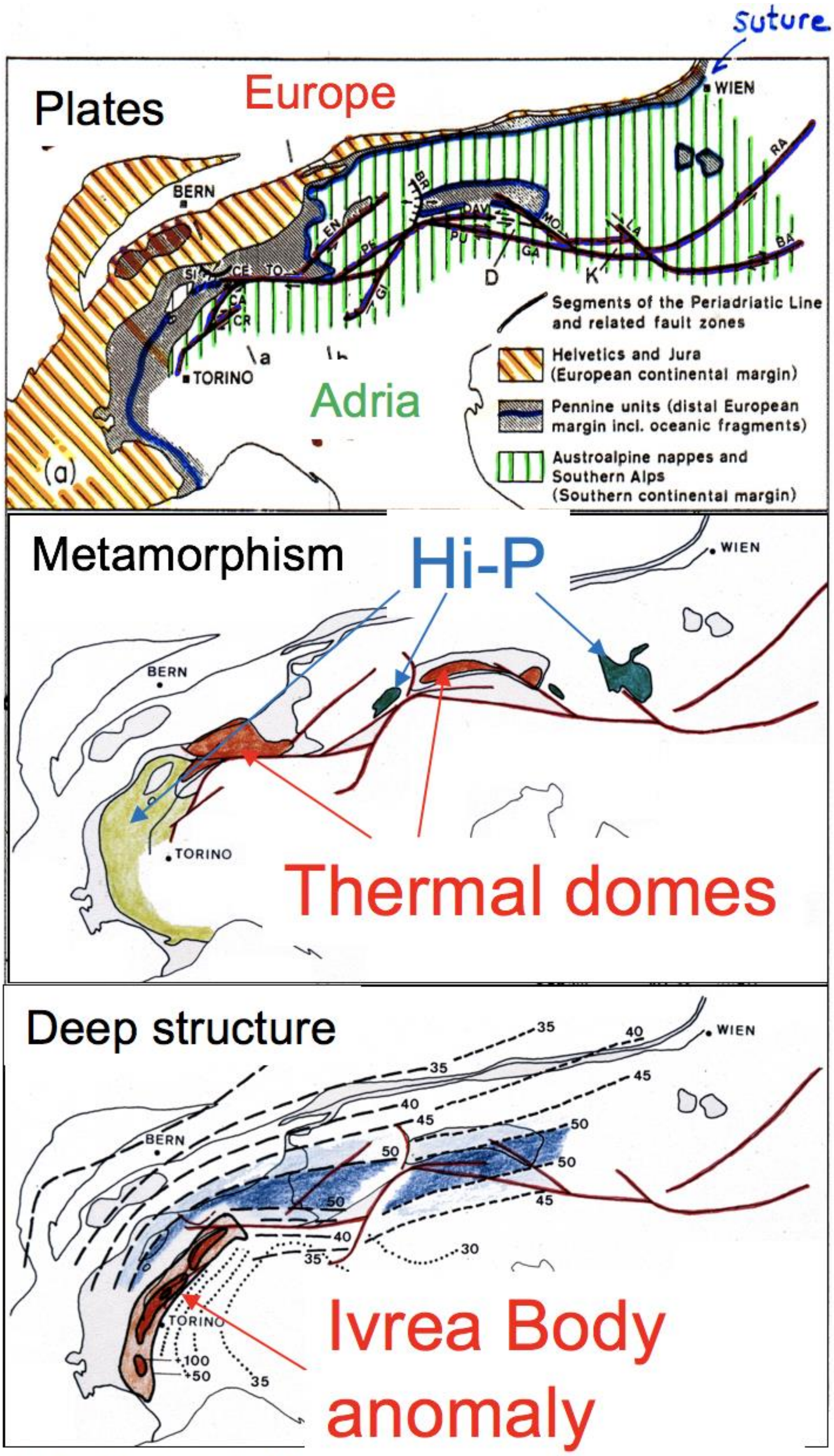
Overnight in Gmünd (see below, “Important Addresses”)

Day 3: Periadriatic Faulting, active Adria-Europe convergence

Route: Gmünd to Maniago via the Pustertal and Tagliamento Valley
Themes: Indentation tectonics, Miocene-recent plate boundary, Periadriatic Fault System, active tectonics of the Southern Alps and Veneto area

Stop 3-1a: Periadriatic Lineament along Nassfeld road near Tröpolach (46°36'17.40°N, 13°17'17.70°E elevation: 724m)

Periadriatic Fault System or Lineament: The Periadriatic fault system (PFS) runs from N and W of Turin, Italy in the W to beneath the Plio-Pleistocene fill of the Pannonian Basin, Hungary in the E (**Fig. 3-1**). It has a two-stage history: (1) *Oligo-Miocene dextral transpression* and pronounced refolding of Paleogene nappes (S-directed "backfolding) in the Central and Western Alps (SCHMID ET AL: 1989), and differential strike-slip motion beneath the Pannonian Basin (CSONTOS ET AL. 1992, FODOR ET AL. 1998); this first phase of activity involved calc-alkaline magmatism, represented by the so-called "Periadriatic" magmatic suite, that is interpreted to record European slab breakoff in late Eocene-early Oligocene time (VON BLANCKENBURG & DAVIES 1995, ROSENBERG 2004); (2) *Miocene dextral strike-slip faulting* between the Eastern and Southern Alps (i.e., E of the Giudicarie Fault) that, together with the conjugate strike-slip (SEMP) and normal faulting (Brenner, Katschberg), induced eastward stretching, exhumation and lateral extrusion of the metamorphic core of the Alps, as seen on Days 1 and 2. Earlier (pre-Alpine orogenic) activity of the Periadriatic Line as a Mesozoic transfer fault during the opening of Alpine Tethys is indicated by the offset Mesozoic (Triassic-early Cretaceous) facies boundaries in adjacent parts of the Eastern and Southern Alps (SCHMIDT ET AL., 1991).



Schmid et al. 1989

Figure 3-1: *Periadriatic Fault System (dark red) and its relationship to the Mesozoic-Paleogene plates (top), Alpine metamorphism (middle) and deep structure (Moho and gravity anomaly, bottom) after SCHMID ET AL. 1989.*

Note: At no time was the PFS a suture in the sense of a plate boundary marking a former subducted ocean; this plate boundary is marked by the Paleogene contact between the Austroalpine (Adriatic upper plate) and Penninic oceanic nappes (ophiolites subducted with the downgoing European plate). Rather, during stage 1 the PFS accommodated the lateral component of oblique-slip motion between Adria and Europe, with displacement estimates ranging from 50-240 km; during stage 2, it decoupled Adria-Europe N-S convergence and subduction from E-W crustal motion in the upper plate of the retreating Carpathian orogen (HANDY ET AL. 2015). The Adria-Europe plate boundary since latest Paleogene times has been located at the tip of the Southern Alpine thrust wedge (**Fig. 1-1**). In existing seismological studies, the Periadriatic Fault System does not offset the MOHO (see **Fig. 1-4**), indicating that since the late Oligocene, the PFS in the Alps has been transported to the S as an allochthonous structure in the hangingwall of Southern Alps units accreted to the upper (European) plate, as shown in **Figure 2-15.**

Directions: Follow the main road to the west in the Pustertal until the town of Tröpolach, then turn S onto the secondary road (route 90) to Pontebba until reaching the bend in the road at Nassfeld.

Outcrop: Mylonitic marble of Oligocene age along Periadriatic fault. The protolith is u. Ordovician limestone (Dinantian), part of the sedimentary cover of the Southern (Carnic) Alps and one of the few places in the Alps where the Paleozoic cover is preserved. Mylonitization (dynamic recrystallization) in marble indicates a syntectonic temperature of at least 180°C. The Structural Map of Italy (**Fig. 3-2**) shows map-scale N-vergent thrusts and NW-SE trending Riedel-type shear surfaces indicative of dextral transpression in map view.

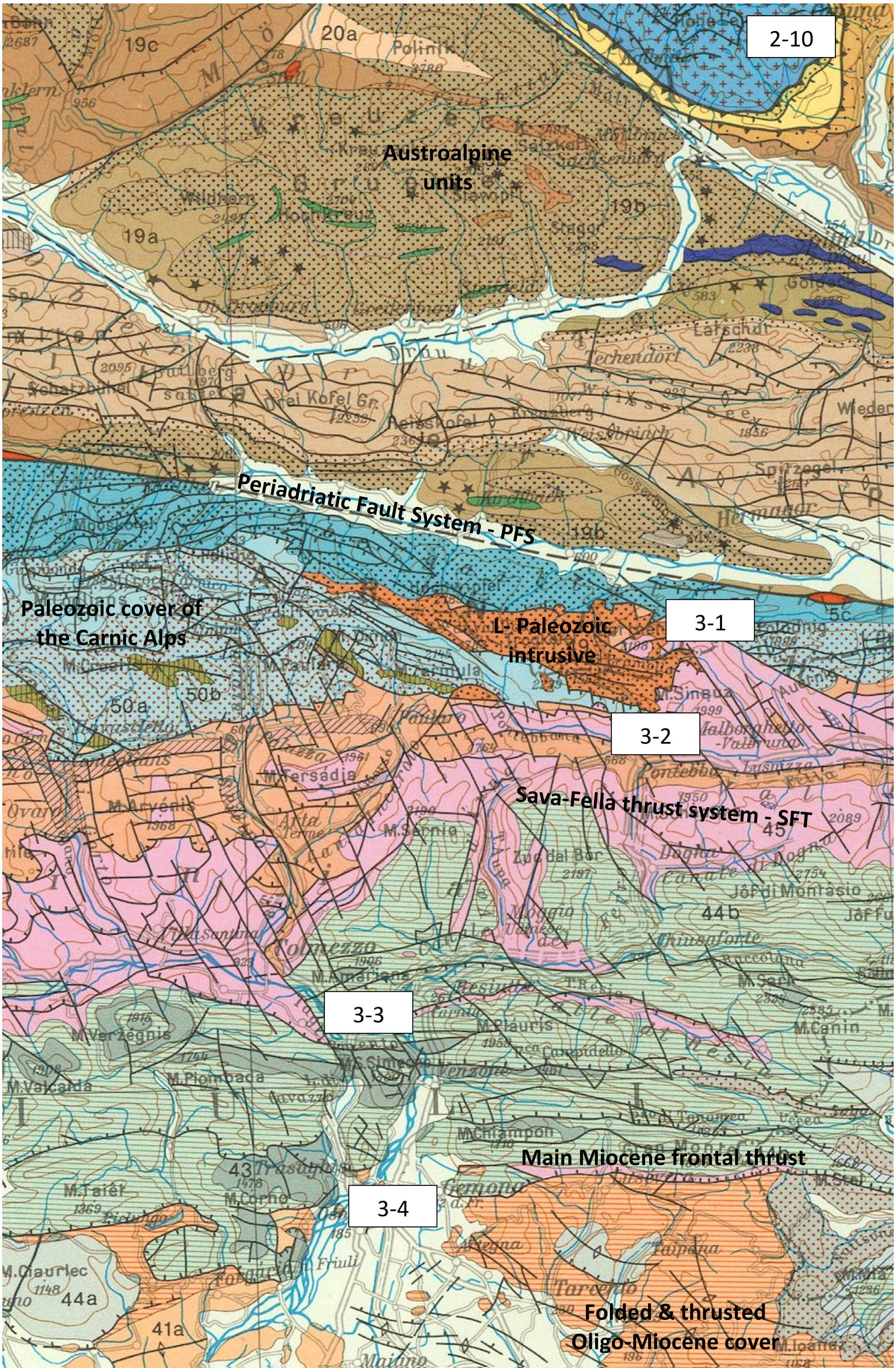


***Figure 3-2**: Structural Map of Italy (BIGI ET AL. 1981) showing the Periadriatic Fault System (PFS) and subsidiary faults thereof, the Sava-Fella thrust (SFT), and folds and thrusts of the Southern Alps affecting the Oligo-Miocene and Plio-Pleistocene cover of the Veneto Plain. Numbers indicate stops.*

<u>Stop 3.1b</u>: Overview of the Southern Alps at Nassfeld (46°36’32.04°N, 13°17’37.50°E elevation: 647m)

The Southern Alps are defined as all tectonic units located S of the Periadriatic Fault System (**Figs. 1-1, 3-2**). However, they comprise sediments, and in some cases also basement units, whose ages and facies are similar if not identical to those of the Austroalpine nappes (**Fig. 3-3**). The main difference between Southern and Eastern (Austroalpine) Alps is that the former are only slightly affected, if at all, by Alpine (i.e. Late Cretaceous-Paleogene) metamorphism, whereas the latter have experienced both subduction- and thermal, Barrow-type) Alpine metamorphism.

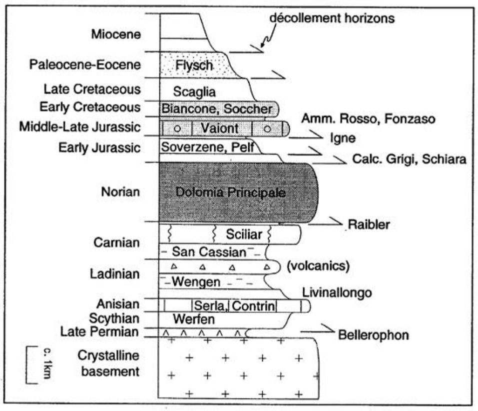


Figure 3-3*: Generalized stratigraphy of the Southern Alps (from Fig. 6 of SCHÖNBORN 1999). Detachment layers indicated with arrows. Note that thickness and facies of l.-m. Jurassic layers vary significantly.*

The tectonics of the Southern Alps involve predominantly S-vergent Neogene thrusting and folding, which is opposite to the N-vergence of folds in the Eastern and Central Alps. Locally, however, N-vergent thrusts occur (**Fig. 3-4**). These Neogene structures overprint older SE-verging thrusts and folds that formed during Paleogene tectonics related to Adria-Europe collision in the Dinarides (DOGLIONI 1987, DOGLIONI & BOSELLINI 1987). Note that both Neogene thrusting and “Dinaric” thrusting are prevalent only in the Southern Alps E of the Giudicarie Belt (itself a Neogene structure, **Fig. 1-1**). W of the Giudicarie Belt, most S-vergent thrusts and folds are older (Late Cretaceous-Oligocene, SCHÖNBORN 1987).

Tectonics is active today, with an Adria-Europe convergence rate of about 2 mm/a accommodated by seismogenic thrusts in the Southern Alps and dextral strike-slip faults in the northern Dinarides (**Fig. 3-4**). Many of these thrusts are reactivated Paleogene- and even Miocene structures (**Fig. 3-5**).

The onset of S-vergent thrusting coincides broadly with the end of N-vergent thrusting along the Northern Alpine front (Stop 1-1). This switch in thrust polarity is consistent with a change in subduction polarity from S- to N-directed after breakoff of the European slab in Oligocene time (HANDY ET AL. 2015).

Outcrop: This is the starting point for a hiking tour that allows one to study Upper Carboniferous successions and provides an overview of the structure of Southern Alps, including the Pliocene Sava-Fella strike-slip fault.

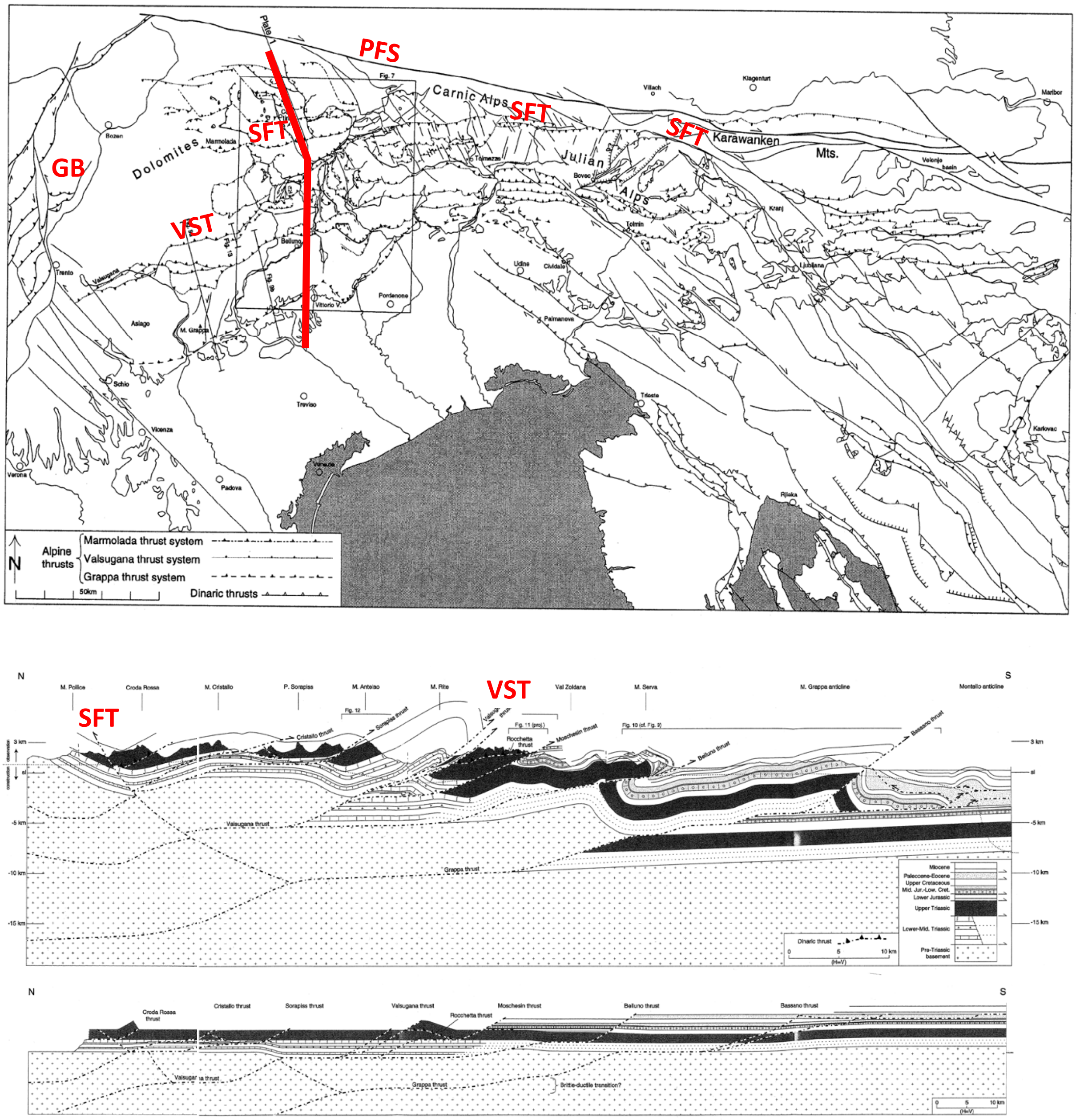


Figure 3-4*: Map (top) and cross section (middle) of the Southern Alps along red trace marked in map. Modified from Fig. 2 and Plate 1 in SCHÖNBORN (1999). Minimum shortening based on line-length balancing of sedimentary layers is 50 km (bottom). PFS – Periadriatic Fault System, SFT – Sava-Fella thrust system (active), VST – Val Sugana thrust (Miocene).*

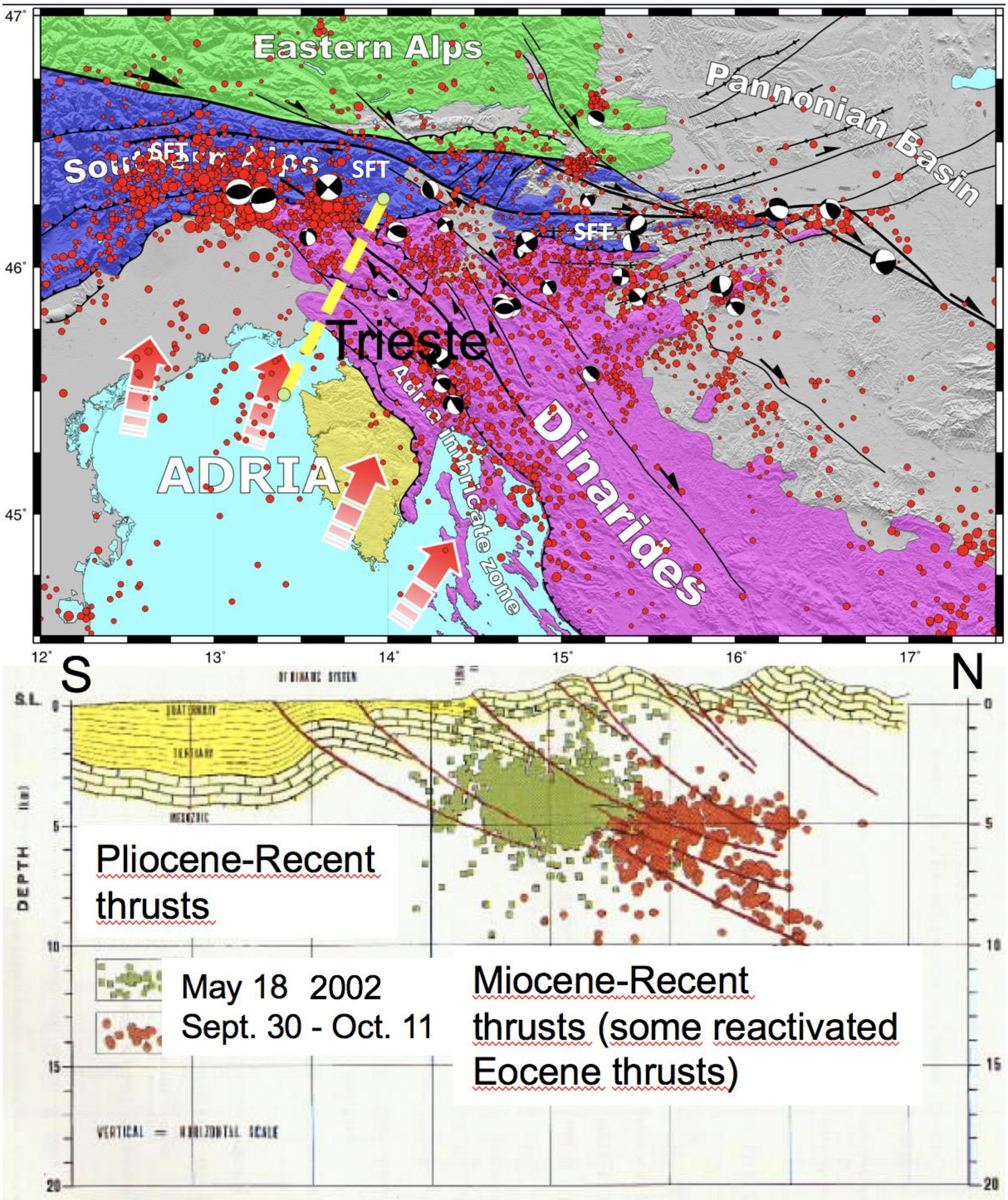


Figure 3-5*: Seismo-tectonic map of the Southern and Eastern Alps, and the northern Dinarides from VRABEC ET AL. 2005, 2006; Cross section of seismically active part of Southern Alps from MERLINI ET AL. 2002 (section along yellow dashes in map). SFT – Sava-Fella Thrust*

Stop 3-2: Sava-Fella Fault

The **Sava-Fella Fault or Thrust** (SFT) is the main seismogenic structure actively accommodating Adria-Europe shortening; focal mechanisms indicate almost pure thrusting in this central segment, with motion becoming more oblique and dextral along strike of the fault to the E (**Fig. 3-5**).

Directions/Outcrop: Drive from Nassfeld in the Pustertal to Pontebba, then drive N onto Strada Provinciale, Rt. 112, stopping for the view to the E **(**N46° 30' 32.39'', E13° 18' 09.96") OR take the main road from Villach to Tarvisio and Pontebba, then exit at Ugovizza and drive S into the Val Saisera.

View from Pontebba (Fig. 3-6): Looking E along the Val Tarvisio, one can see the E-W trace of the Sava-Fella fault running along the middle to S side of the valley as a S-dipping, N-vergent thrust that emplaces clastic, alluvial and shallow marine, middle Permian-lower Anisian rocks of the hangingwall (S side) onto mainly carbonate, lower-middle Triassic (Carnian-Anisian) rocks (N side). This thrust is inferred to continue at depth, offsetting a major S-vergent Miocene thrust, the Val Sugana thrust (VST) that is exposed in the W (**Fig. 3-4**).

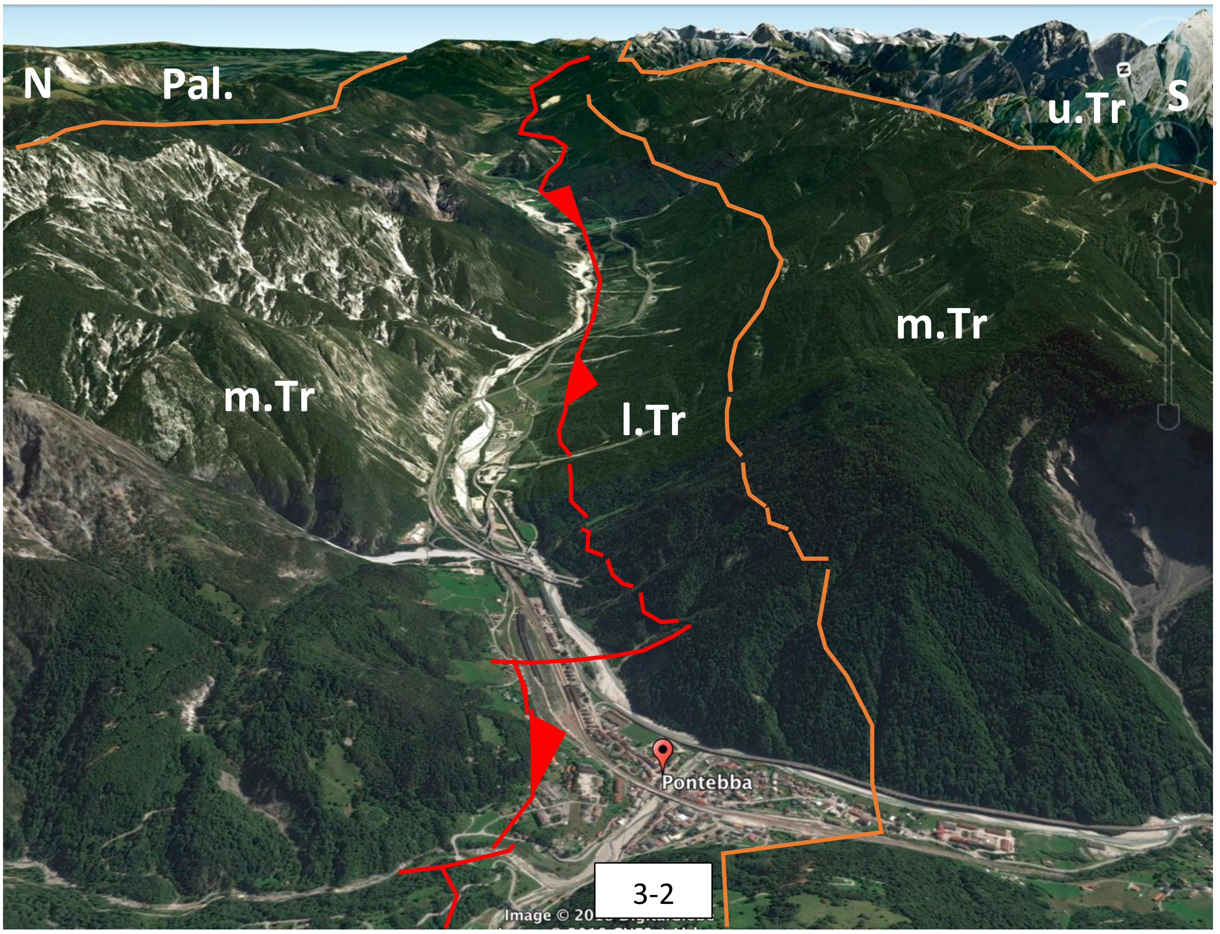


Figure 3-6*: View to ESE along the Sava-Fella Fault in the upper Val Tarvisio (Tagliamento River valley) of the Southern Alps.*

Stop 3-3: Cross section of S. Alpine nappes in the Tagliamento Valley

Directions/Location: Turn off of main road near Velzone, cross bridge to the west side of the Tagliamento River and park next to the bridge (N46° 20’ 10.18’’, 13° 07’ 58.38”, alt. 250m),

View: Miocene S- and N-vergent thrusts and folds in Jurassic and late Triassic carbonates (**Fig. 3-7**)

Stop 3-4: Main frontal thrust of the Southern Alps

Directions/Location: Turn off of main road at Trasaghis, Osoppo, drive across the bridge over the Tagliamento River, then north onto road along river to the parking lot near Braulins (N46° 17’ 6.97’’, E13° 05’ 38.42’’, alt. 203m)

View: frontal thrust of u. Triassic “Hauptdolomit/Dolomia Principale” onto Paleocene-Eocene-Oligocene flysch (**Fig. 3-7**)

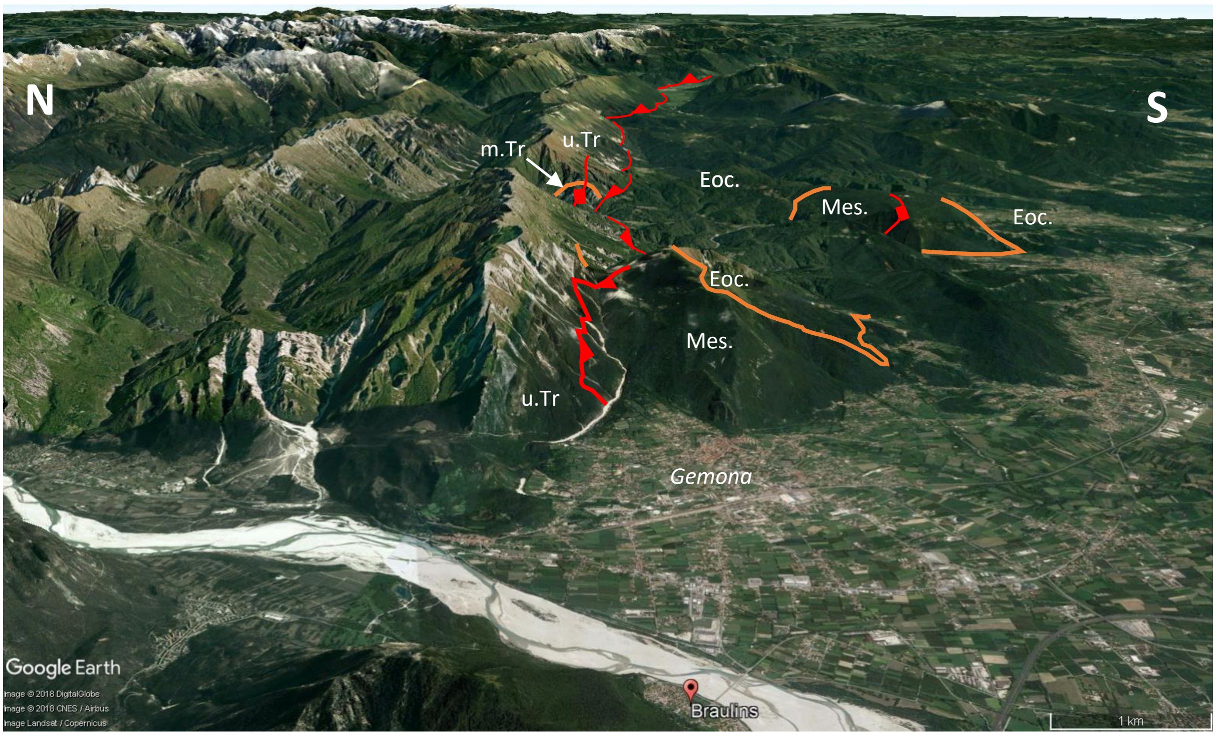


***Figure 3-7**: View to E of Southern Alps along the upper Tagliamento River with stops at* Tolmezzo and/or M. Simeone *to see folds (left) and at Gemona for frontal thrust of Mesozoic strata onto Tertiary flysch (right).*

<u>Stop 3-5</u>: Pleistocene faulting and displacement

Directions/Location: bridge across Tagliamento River between Pinzano and San Pietro (N46° 11’ 04.17’’, E12° 57’ 20.49’’, alt. 157m)

Outcrop: The Tagliamento River is spectacularly diverted by a N-directed thrust in Pleistocene-Recent river deposits. The older river channel to the E has dried up and is now host to rich farmland. This outcrop is near the epicentre of the 1976 Friaul earthquake.

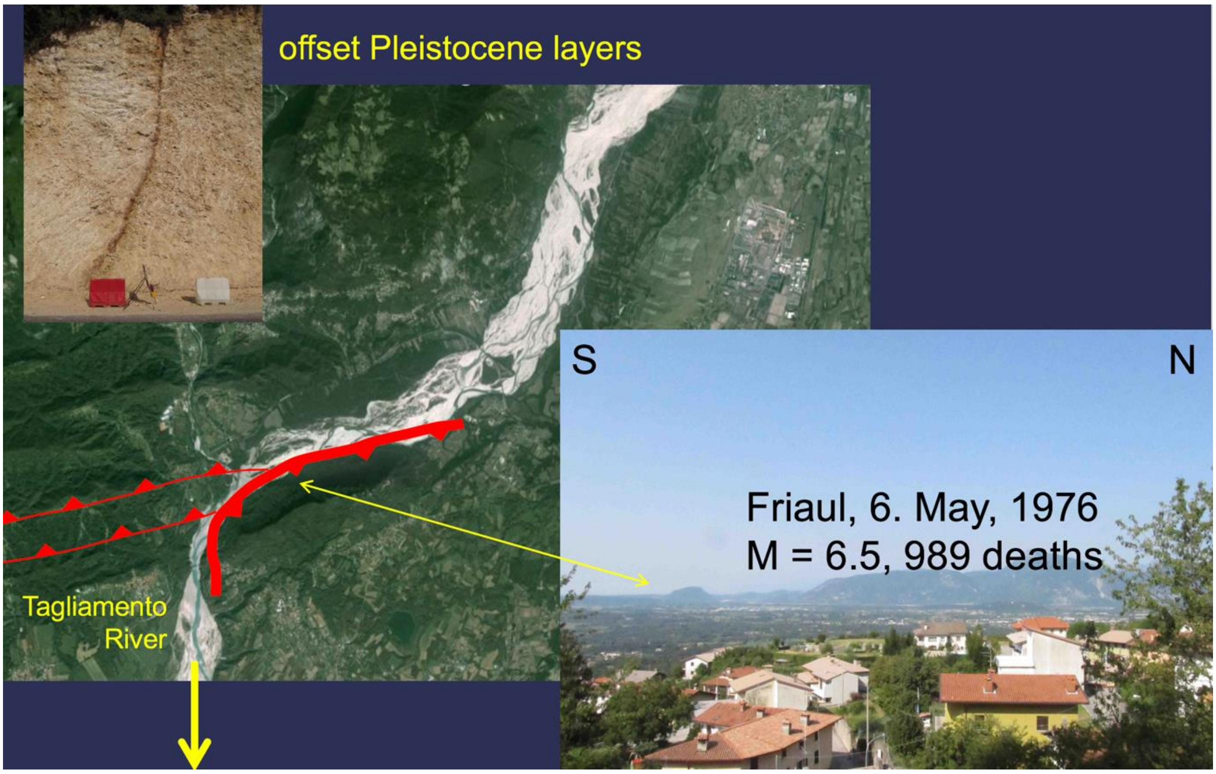


***Figure 3-8**: Map view of tectonically induced bend in the Tagliamento River between Pinzano and San Pietro (top) and site of the Friaul May 6, 1976 event with uplift at Pinzano in background.*

Overnight in Maniago (see important addresses below)

Important addresses

To obtain permission for access to the Groppenstein Gorge:

Incoming Co. (Groppenstein Gorge)
Director – Bernhard Huber
Tel +43-(0)4782-2027-11
Fax: +43-(0)4782-3038-14
Email – huberpapier@skribo.at

Town Hall, Obervellach, Tel +43-(0)4782-2111

Nationalpark Hohe Tauern - Kärnten
A-9843 Großkirchheim
Döllach 14
Tel: ++43-(0)4825-6161, E-Mail: nationalpark@ktn.gv.at

Nationalpark Hohe Tauern - Salzburg
A-5730 Mittersill
Gerlosstraße 18
Tel: ++43 (0) 6562 40849, E-Mail: nationalpark@salzburg.at

Overnight addresses

1st night:
Boutique-Gasthof UEBERFUHR
Ignaz-Rieder-Kai 43, A-5026 Salzburg
Tel. +43 662 23 10 94, Email:

2nd night:
Panoramahotel Lärchenhof
Hof 70, A-9844 Hof
Tel. +43 4824 2262

3rd night:
Locus Malontina Hotel
Fischertratten 3, A-9853 Gmünd in Kärnten
Tel. +43 4732 20304

4th night:
Eurohotel Palace
Viale della Vittoria 3, I- 33085 Maniago PN
Tel. +39 0427 71432

5th night:
Hotel zur Post
Bodenseestraße 4a, D-81241 München
Tel. +49 89 896950

References

Agard, P. & Lemoine, M. (2005). Face of the Alps: structure & geodynamic evolution. Paris (Commission for the Geological map of the World).

Bernroider, M., & Hock, V. (1983). Metamorphose der Serpentin-Randgesteine im obersten Mölltal (Kärnten, Österreich). *Der Karinthin*, *89*, 51-71.

BIGI ET AL. 1981

Bijwaard, H., & Spakman, W. (2000). Non-linear global P-wave tomography by iterated linearized inversion. *Geophysical Journal International*, *141*(1), 71-82.

BLANCKENBURG & DAVIES 1995, ROSENBERG 2004

Borowicka, H. (1966). Versuch einer stratigraphischen Gliederung des Dolomitmarmorzuges zwischen Dietersbach-und Mühlbachtal (Oberpinzgau, Salzburg). *Unpublished report, Univ. Wien*.

Braunstingl, R., Hejl, E. & Pestal, G. in collaboration with von Egger, H., Husen v., D., Linner, M., Mandel, G.W., Moser, M., Reitner, J., Rupp, Ch. und Schuster, R. (2005). Geologische Karte von Salzburg 1:200 000. Wien (Geologische Bundesanstalt).

Christensen, J. N., Selverstone, J., Rosenfeld, J. L., & DePaolo, D. J. (1994). Correlation by Rb-Sr geochronology of garnet growth histories from different structural levels within the Tauern Window, Eastern Alps. *Contributions to Mineralogy and Petrology*, *118*(1), 1-12.

Cliff, R. A., Oberli, F., Meier, M., & Droop, G. T. R. (1998). Achieving geological precision in metamorphic geochronology: a Th–Pb age for the syn-metamorphic formation of the Mallnitzermulde synform, Tauern Window, from individual allanite porphyroblasts. *Mineralogical Magazine A*, *62*, 337-338.

CSONTOS ET AL. 1992, FODOR ET AL. 1998

Dachs, E., & Proyer, A. (2001). Relics of high-pressure metamorphism from the Grossglockner region, Hohe Tauern, Austria. *European Journal of Mineralogy*, *13*(1), 67-86.

Drescher-Schneider, R. & Kellerer-Pirklbauer, A. (2008). Gletscherschwund einst und heute - Neue Ergebnisse zur holozänen Vegetations- und Gletschergeschichte der Pasterze (Hohe Tauern, Österreich). *Abhandlungen der Geologischen Bundesanstalt*, *62*, 45-51. Wien.

DOGLIONI 1987, DOGLIONI & BOSELLINI 1987

Ebbing, J., Braitenberg, C., & Götze, H. J. (2006). The lithospheric density structure of the Eastern Alps. *Tectonophysics*, *414*(1), 145-155.

Favaro, S., Handy, M. R., Scharf, A., & Schuster, R., (2016, in press). Changing patterns of exhumation and denudation in front of an advancing crustal indenter, Tauern Window (Eastern Alps). *Tectonics*, *in press*.

Favaro, S., Schuster, R., Handy, M. R., Scharf, A., & Pestal, G. (2015). Transition from orogen-perpendicular to orogen-parallel exhumation and cooling during crustal indentation—Key constraints from 147 Sm/144 Nd and 87 Rb/87 Sr geochronology (Tauern Window, Alps). *Tectonophysics*, *665*, 1-16.

Frank, W. (1969). Geologie der Glocknergruppe. *Neue Forschungen im Umkreis der Glocknergruppe. Wissenschaftliche Alpenvereinshefte des Deutschen Alpenvereins*, *21*, 95-111.

Frank, W., Höck, V., & Miller, C. (1987). Metamorphic and tectonic history of the central Tauern Window. In Flügel, H. W., & Faupl, P. (Eds.). (1987). *Geodynamics of the Eastern Alps*, *34-54*.

Frasl, G. (1958). Zur Seriengliederung der Schieferhülle in den mittleren Hohen Tauern. *Jahrbuch der Geologischen Bundesanstalt*, *101*, 323-472, Wien.

Frasl, G., & Frank, W. (1964). Exkursion I/2: Mittlere Hohe Tauern. *Mitteilungen der Geologischen Gesellschaft in Wien*, *57*(1), 17-31.

Frasl, G., & Frank, W. (1966). Einführung in die Geologie des Penninikums im Tauernfenster mit besonderer Berücksichtigung des Mittelabschnittes im Oberpinzgau. *Der Aufschluß, Sonderheft*, *15*, 30-58, Heidelberg.

Frasl, G., & Frank, W. (1969). Bemerkungen zum zweiteiligen geologischen Panorama von Edelweissspitze (Grossglockner Hochalpenstrasse). *Wissenschaftliche. Alpenvereinshefte*, *21*, 112-114.

Froitzheim, N., Schmid, S. M., & Conti, P. (1994). Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. *Eclogae Geologicae Helvetiae*, *87*(2), 559-612.

Genser, J., & Neubauer, F. (1989). Low angle normal faults at the eastern margin of the Tauern window (Eastern Alps). *Mitteilungen der Österreichischen Geologischen Gesellschaft*, *81*, 233-243.

Glodny, J., Ring, U., Kühn, A., Gleissner, P., & Franz, G. (2005). Crystallization and very rapid exhumation of the youngest Alpine eclogites (Tauern Window, Eastern Alps) from Rb/Sr mineral assemblage analysis. *Contributions to Mineralogy and Petrology*, *149*(6), 699-712.

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E., & Bernoulli, D. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews*, *102*(3), 121-158.

Handy, M. R., Ustaszewski, K., & Kissling, E. (2015). Reconstructing the Alps–Carpathians–Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion. *International Journal of Earth Sciences*, *104*(1), 1-26.

Hetenyi et al. 2018a

Hetenyi et al. 2018b

Höck, V. & Marschallinger, R. (1988). Exkursion Hohe Tauern, Jahrestagung ÖGG. *Österreichische Geologische Gesellschaft Exkursionsführer, 7*, Salzburg.

Höck, V., & Miller, C. (1987). Mesozoic ophiolitic sequences and non-ophiolitic metabasites in the Hohe Tauern. In Flügel, H. W., & Faupl, P. (Eds.). (1987). *Geodynamics of the Eastern Alps*, *16-33*.

Höck, V. & Pestal, G. (1994). Geologische Karte der Republik Österreich 1 : 50.000, Blatt 153 Großglockner. *Geologische Bundesanstalt*, *Wien*.

Hoinkes, G., Koller, F., Rantitsch, G., Dachs, E., Hock, V., Neubauer, F., & Schuster, R. (1999). Alpine metamorphism of the Eastern Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen*, *79*(1), 155-181.

Inger, S., & Cliff, R. A. (1994). Timing of metamorphism in the Tauern Window, Eastern Alps: Rb-Sr ages and fabric formation. *Journal of Metamorphic Geology*, *12*(5), 695-707.

Krainer, K. (2005). Nationalpark Hohe Tauern, Geologie. – 2. Auflage, 199 p., Klagenfurt (Carinthia Verlag)

Kurz, W., Handler, R., & Bertoldi, C. (2008). Tracing the exhumation of the Eclogite Zone (Tauern Window, Eastern Alps) by 40Ar/39Ar dating of white mica in eclogites. *Swiss Journal of Geosciences*, *101*(1), 191-206.

Kurz, W., & Neubauer, F. (1996). Deformation partitioning during updoming of the Sonnblick area in the Tauern Window (Eastern Alps, Austria). *Journal of Structural Geology*, 18, 11, 1327-1343.

Lammerer, B., & Weger, M. (1998). Footwall uplift in an orogenic wedge: the Tauern Window in the Eastern Alps of Europe. *Tectonophysics*, *285*(3), 213-230.

Lemoine, M. (2003). Schistes lustrés from Corsica to Hungary: back to the original sediments and tentative dating of partly azoic metasediments. *Bulletin de la Société géologique de France*, *174*(3), 197-209.

Lippitsch, R., Kissling, E., & Ansorge, J. (2003). Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. *Journal of Geophysical Research: Solid Earth*, *108*(B8).

MERLINI ET AL. 2002

Milnes, A. G. (1974). Structure of the Pennine Zone (Central Alps): a new working hypothesis. *Geological Society of America bulletin*, *85*(11), 1727-1732.

Mitterbauer, U., Behm, M., Brückl, E., Lippitsch, R., Guterch, A., Keller, G. R., Koslowskaya, E., Rumpfhuber, E. & Šumanovac, F. (2011). Shape and origin of the East-Alpine slab constrained by the ALPASS teleseismic model. *Tectonophysics*, *510*(1), 195-206.

Nagel, T. J., Herwartz, D., Rexroth, S., Münker, C., Froitzheim, N., & Kurz, W. (2013). Lu–Hf dating, petrography, and tectonic implications of the youngest Alpine eclogites (Tauern Window, Austria). *Lithos*, *170*, 179-190.

Patzelt, G. (1969). Zur Geschichte der Pasterzenschwankungen. *Wiss. Alpenvereinshefte*, *21*, 171-179.

Pestal, G. & Hejl, E. (2009). Erläuterungen zur Legende (Subpenninikum). - In: Pestal, G., Hejl, E., Braunstingl, R., & Schuster, R. (2009). Erläuterungen Geologische Karte von Salzburg 1: 200000. *Geologische Bundesanstalt, Wien*, *162*.

Pestal, G., Hejl, E., Braunstingl, R., & Schuster, R. (2009). Erläuterungen Geologische Karte von Salzburg 1: 200000. *Geologische Bundesanstalt, Wien*, *162*.

Plomerová, J., Bianchi, I., Hetényi, G., Munzarová, H., Bokelmann, G., Kissling, E., AlpArray-EASI Field Team & AlpArray-EASI Working Group. (2015). The Eastern Alpine Seismic Investigation (EASI) project. *EGU General Assembly Conference Abstracts* (Vol. 17, p. 5560).

Proyer, A., Dachs, E., & Kurz, W. (1999). Relics of high-pressure metamorphism in the Glockner region, Hohe Tauern, Austria: Textures and mineral chemistry of retrogressed eclogites. *Mitteilungen der Österreichischen Geologischen Gesellschaft*, *90*, 43-55.

Ratschbacher, L., Dingeldey, C., Miller, C., Hacker, B. R., & McWilliams, M. O. (2004). Formation, subduction, and exhumation of Penninic oceanic crust in the Eastern Alps: time constraints from 40 Ar/39 Ar geochronology. *Tectonophysics*, *394*(3), 155-170.

Sander, B. (1914). Geologische Studien am Westende der Hohen Tauern. *Denkschriften der Kaiserlichen Akademie der Wissenschaften*, *82*, 257-320.

Scharf, A., Handy, M. R., Favaro, S., Schmid, S. M., & Bertrand, A. (2013). Modes of orogen-parallel stretching and extensional exhumation in response to microplate indentation and roll-back subduction (Tauern Window, Eastern Alps). *International Journal of Earth Sciences*, *102*(6), 1627-1654.

Scharf, A., Handy, M. R., Schmid, S., & Sudo, M. (2013a). Contemporaneous versus diachronous rapid exhumation in the Tauern Window-new perspectives from in-situ 40Ar/39Ar laser-probe ages of white mica (Eastern Alps). In *EGU General Assembly Conference Abstracts* (Vol. 15, p. 8399).

Scharf, A., Handy, M. R., Ziemann, M. A., & Schmid, S. M. (2013b). Peak-temperature patterns of polyphase metamorphism resulting from accretion, subduction and collision (eastern Tauern Window, European Alps)–a study with Raman microspectroscopy on carbonaceous material (RSCM). *Journal of Metamorphic Geology*, *31*(8), 863-880.

SCHMID ET AL: 1989

Schmid, S. M., Fügenschuh, B., Kissling, E., & Schuster, R. (2004). Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae*, *97*(1), 93-117.

Schmid, S. M., Scharf, A., Handy, M. R., & Rosenberg, C. L. (2013). The Tauern Window (Eastern Alps, Austria): a new tectonic map, with cross-sections and a tectonometamorphic synthesis. *Swiss Journal of Geosciences*, *106*(1), 1-32.

Schmidt, K. (2015). Microstructural and thermobarometric investigations of high-pressure mineral assemblages in metapelites of the Modereck Nappe Complex (Tauern Window, Austria). *Unpublished Master's thesis*. Berlin.

Schmidt, K., Handy, M. R., Scharf, A., Milke, R., John, T., & Oberhänsli, R. (2014). First evidence of subduction-related metamorphism in the most distal European continental margin unit of the Eastern Alps (Modereck Nappe, Tauern Window). In *TSK15 Potsdam 2014 Abstract Volume* (p. 44).

(SCHMIDT ET AL., 1991).

SCHÖNBORN 1987

SCHÖNBORN (1999)

Schuster, R. (2003). Das eo-Alpidische Ereignis in den Ostalpen: Plattentektonische Situation und interne Struktur des Ostalpinen Kristallins. In Rockenschaub, M. (ed.), *Arbeitstagung 2003 der Geologischen Bundesanstalt Trins im Gschnitztal* (pp. 41-159). Wien: Geologische Bundesanstalt.

Schuster, R., Pestal, G., & Reitner, J. (2006). Erläuterungen zu Blatt 182 Spittal an der Drau, Geologische Karte der Republik Österreich 1: 50 000. *Geologische Bundesanstalt, Wien*.

Selverstone, J. (1988). Evidence for east-west crustal extension in the Eastern Alps: Implications for the unroofing history of the Tauern window. *Tectonics*, *7*(1), 87-105.

Spada, M., Bianchi, I., Kissling, E., Agostinetti, N. P., & Wiemer, S. (2013). Combining controlled-source seismology and receiver function information to derive 3-D Moho topography for Italy. *Geophysical Journal International*, *194*(2), 1050-1068.

Steinmann, M. C. (1994) Die nordpenninischen Bündnerschiefer der Zentralalpen Graubündens, Tektonik, Stratigraphie und Beckenentwicklung. Diss. Naturwiss. ETH Zürich, Nr. 10668, 1994.

Tollmann, A. (1977). *Geologie von Österreich: Die Zentralalpen* (Vol. 1). Deuticke.

Van Husen, D. (1987). *Die Ostalpen in den Eiszeiten*. Geologische Bundesantalt, Wien, 24 p.

Villa, I. M., Hermann, J., Müntener, O., & Trommsdorff, V. (2000). 39Ar− 40Ar dating of multiply zoned amphibole generations (Malenco, Italian Alps). *Contributions to Mineralogy and Petrology*, *140*(3), 363-381.

von Blanckenburg, F., Villa, I. M., Baur, H., Morteani, G., & Steiger, R. H. (1989). Time calibration of a PT-path from the Western Tauern Window, Eastern Alps: the problem of closure temperatures. *Contributions to Mineralogy and Petrology*, *101*(1), 1-11.

VRABEC ET AL. 2005, 2006