Field guide

A Transect of the Eastern and Southern Alps

August 11th – 16th, 2022
SPP 2017 "Mountain Building in 4-Dimensions" (4D-MB)

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INTRODUCTION

The transect from Salzburg to the Veneto area exposes all main components of the Alpine collisional belt (**Fig. 1-1**), from the northern and southern peripheral basins (Molasse, Po-Veneto), to nappes derived from the upper (Adriatic) and lower (European) plates and the Adria-Europe suture (Alpine Tethys), to recent thrusts in the Southern Alps where active seismicity reflects ongoing Adria-Europe convergence. During the course of this trip, we will attempt to link these crustal features with first-order geophysical structures in the orogenic crust and mantle, including new ones imaged in AlpArray.

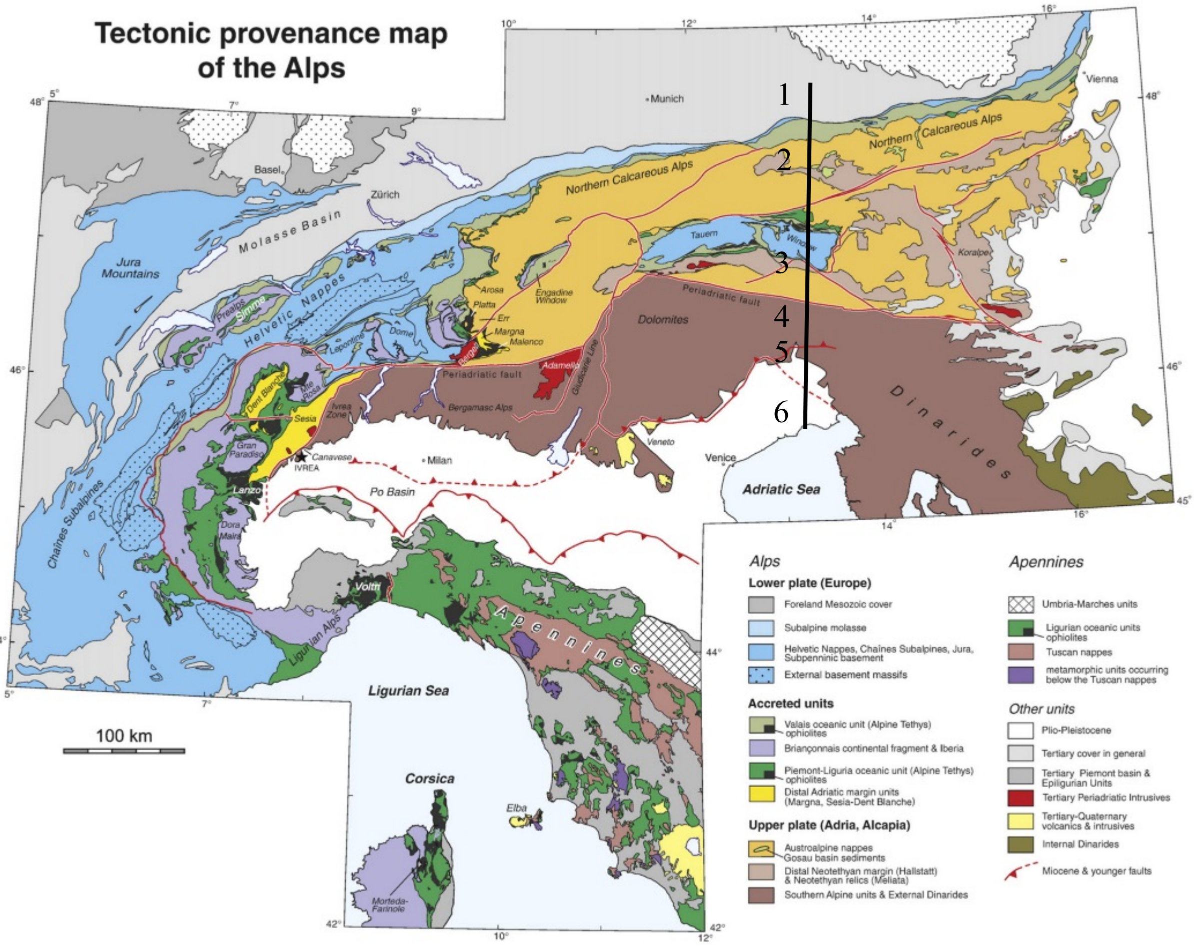


Figure 1-1: *Tectonic map of the Alps (M.R. Handy, simplified from HANDY ET AL. 2010 & SCHMID ET AL. 2004) with colours indicating upper & lower plate affinities and Jurassic paleogeographic origin of nappes. Numbers correspond to units numbered in text.*

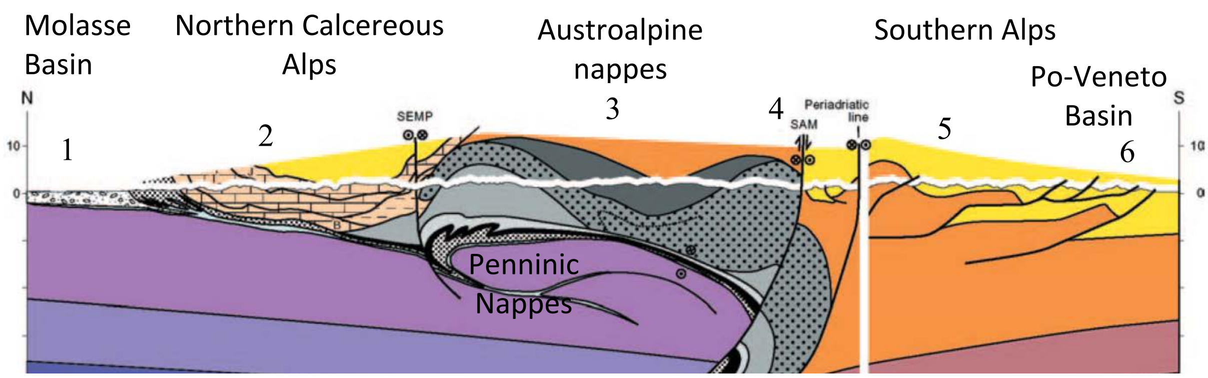


Figure 1-2: *Cross section of the Eastern & Southern Alps (trace shown in Fig. 1-1), modified from SCHMID ET AL. (2004)*

<u>Tectonic units</u> <u>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 (**Penninic Nappes**) 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

<u>Deep Structure (</u>Figs. 1-3 to 1-8)<u>:</u>

The transect in our field trip crosses three main geophysical features:

(1) **a +Vp slab anomaly** (**Fig. 1.3c**) that dips vertically to steeply NE-ward (BABUŠKA ET AL. 1990, LIPPITSCH ET AL. 2003, PLOMEROVA ET AL. 2015, ZHAO ET AL. 2016, PAFFRATH ET AL, 2021) and has been variously interpreted as subducted Adriatic (SCHMID ET AL. 2004, KISSLING ET AL. 2006, HANDY ET AL. 2015, HETÉNYI ET AL. 2018, PLOMEROVÀ ET AL. 2021), European (MITTERBAUER ET AL. 2011, ROSENBERG ET AL. 2018, HANDY ET AL. 2021), or combined Adriatic and European lithospheres (HANDY ET AL. 2015, KÄSTLE ET AL. 2020, JI ET AL. 2019, SUN ET AL. 2019, MALUSÀ ET AL. 2021). This slab anomaly is detached from the orogenic lithosphere beneath the central and eastern parts of the Tauern Window (**Fig. 1-5**). Beneath the western Tauern Window and under the Central and Western Alps, the +Vp anomaly dips SE-ward (**Fig. 1-3b**). The consensus view is that this anomaly is subducted European lithosphere;

(2) an **orogenic Moho** that shallows dramatically from W (55-60 km) to E (≤ 20 km) parallel to the orogen and towards the Pannonian Basin (**Figs. 1-6, 1-7;** KIND ET AL. 2021, ZAHOREC ET AL. 2021) and that is weakly defined between 12-15°E (white area in **Fig. 1-4**);

(3) A lower crustal bulge located below and S of the Tauern Window (**Figs. 1-7, 1-8**). Unlike the Western and Central Alps where exhumed high-grade metamorphic rocks of the lower plate overlie a lower crustal wedge derived from Adria (e.g., ROSENBERG & KISSLING 2013), the same exhumed units in the Tauern Window coincide with large positive gravity anomaly (EBBING ET AL. 2006) and occur above and to the north of a large lower crustal bulge (**Fig. 1-8**). Another anomalous feature is a large gap in the +Vp slab anomaly beneath the Dinarides, indicating possible loss of the Adriatic slab preserved further S beneath the Hellenides (**Fig. 1-3d**).

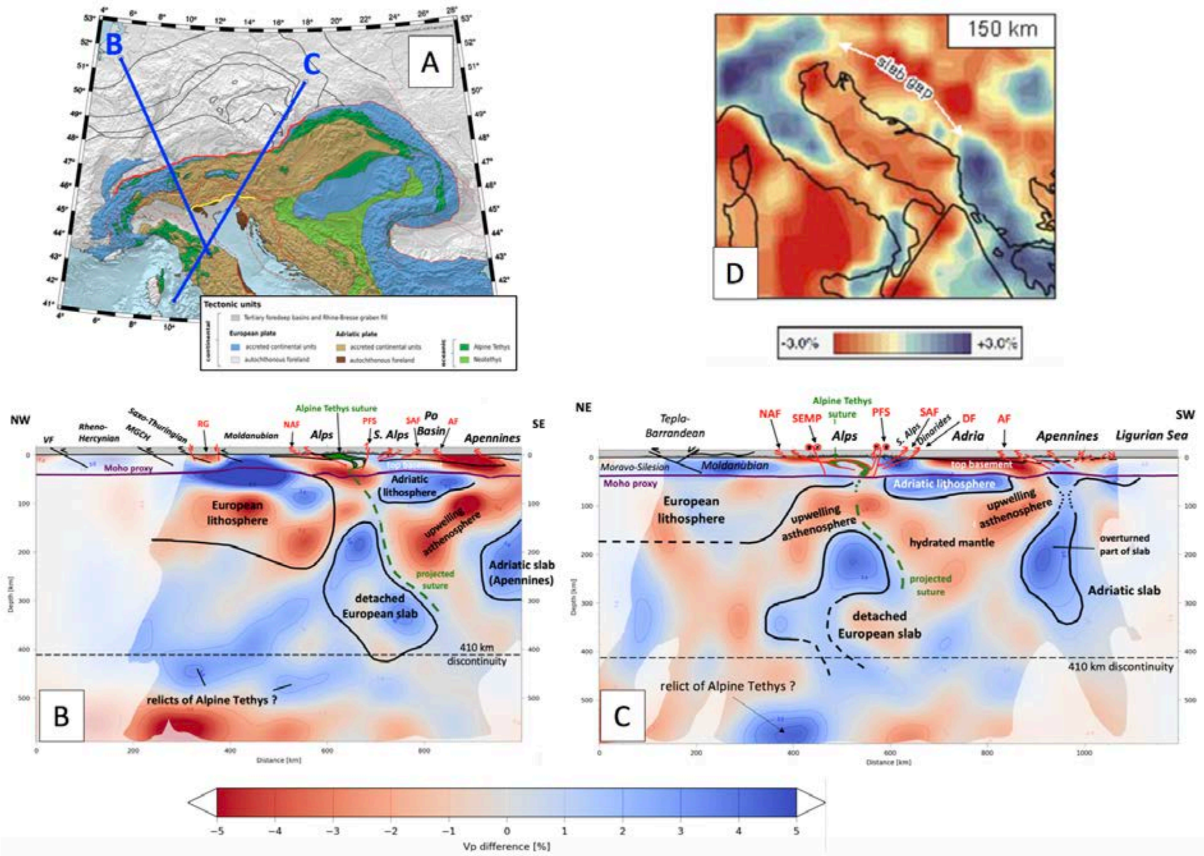


Figure 1-3: *Tectonic map (A) with northern Alpine front (red) and active southern Alpine front (yellow). P-wave tomographic cross sections (B) and (C) of the Central and Eastern Alps modified from PAFFRATH ET AL. (2021) and HANDY ET AL. (2021). P-wave tomographic map of the Adriatic region (D) from BIJWAARD & SPAKMAN (2000) showing slab gap beneath the northern Dinarides. AF – Alpine thrust front, PF – Periadriatic Fault System*

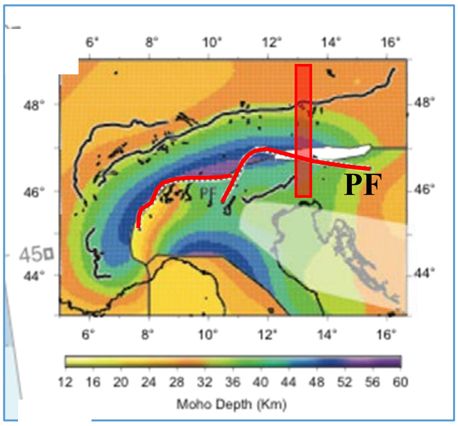


Figure 1-4: *Moho map of SPADA ET AL. (2013) with Periadriatic Fault (PF), Alpine thrust fronts (black lines) and box outlining EASI swath (red).*

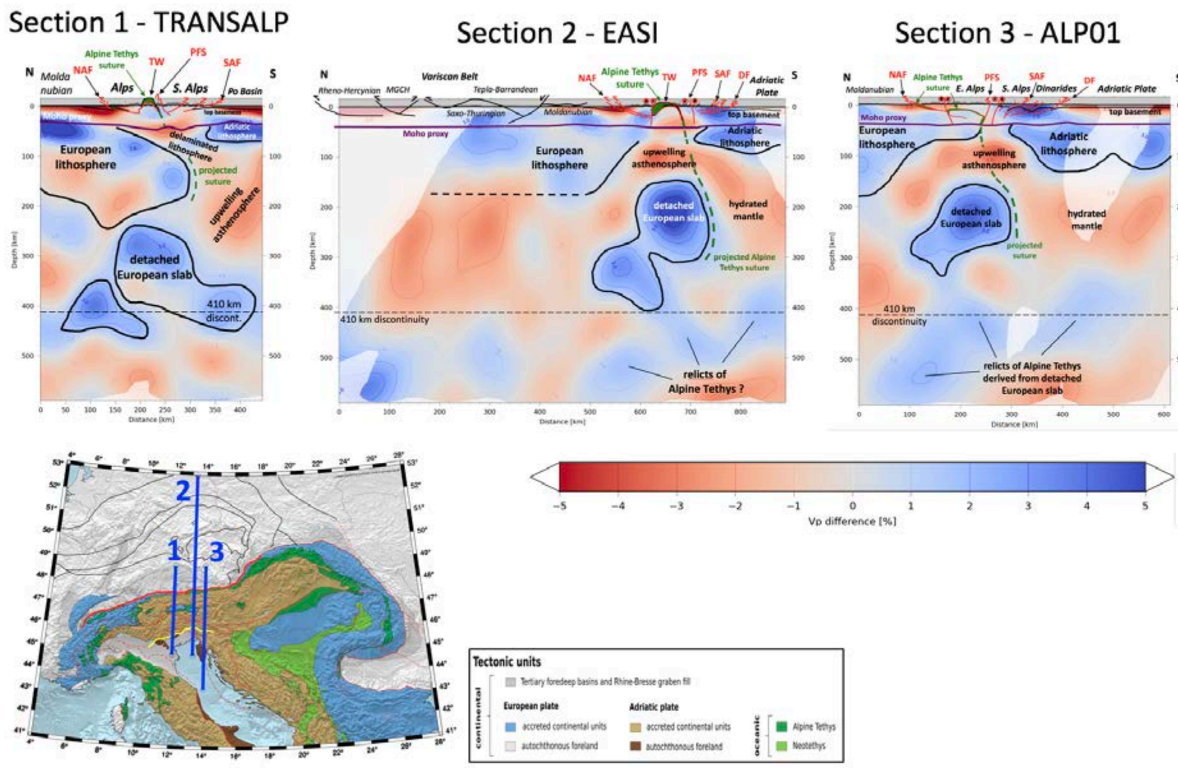


Figure 1-5: *Moho and upper mantle structure along three transects of the Eastern Alps. P-wave tomography of PAFFRATH ET AL: 2021 as interpreted by HANDY ET AL. 2021.*

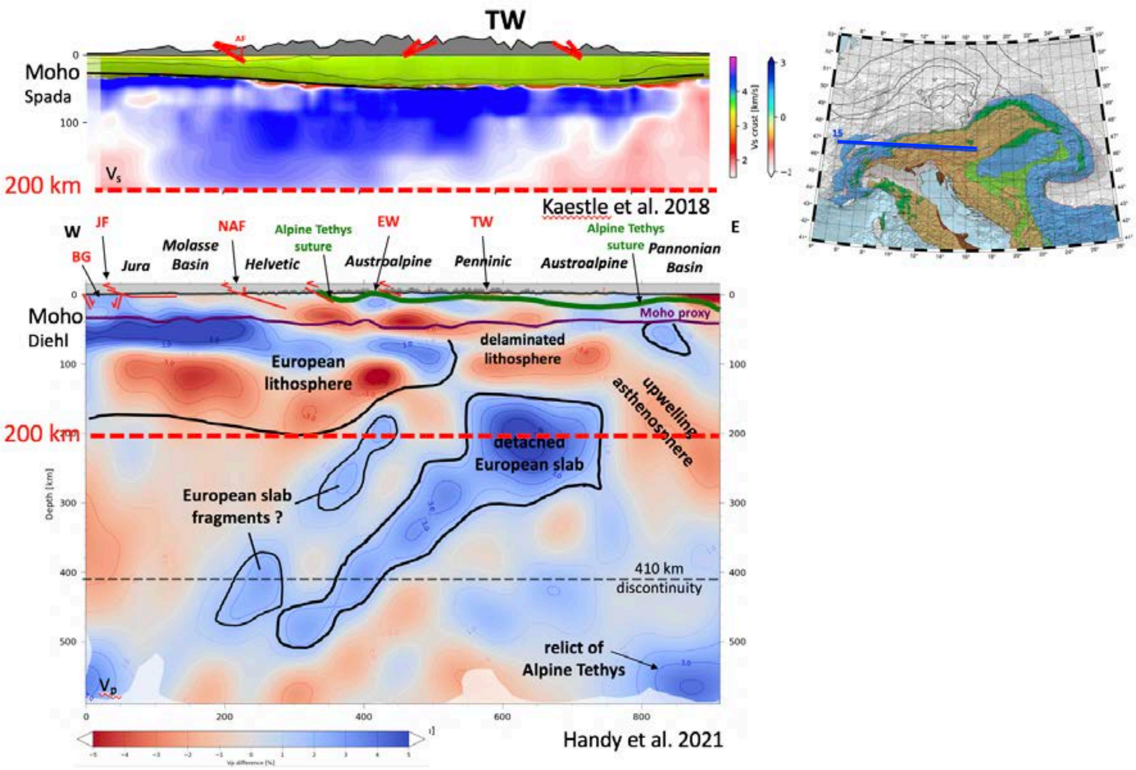


Figure 1-6: Orogen-parallel transects showing lithospheric structure in surface wave tomography (top) and V_p tomography (bottom), respectively, from HANDY ET AL. 2021, KAESTLE ET AL. 2018 and KIND ET AL. 2021. The bottom section includes a higly oblique slice through a detached part of the European slab.

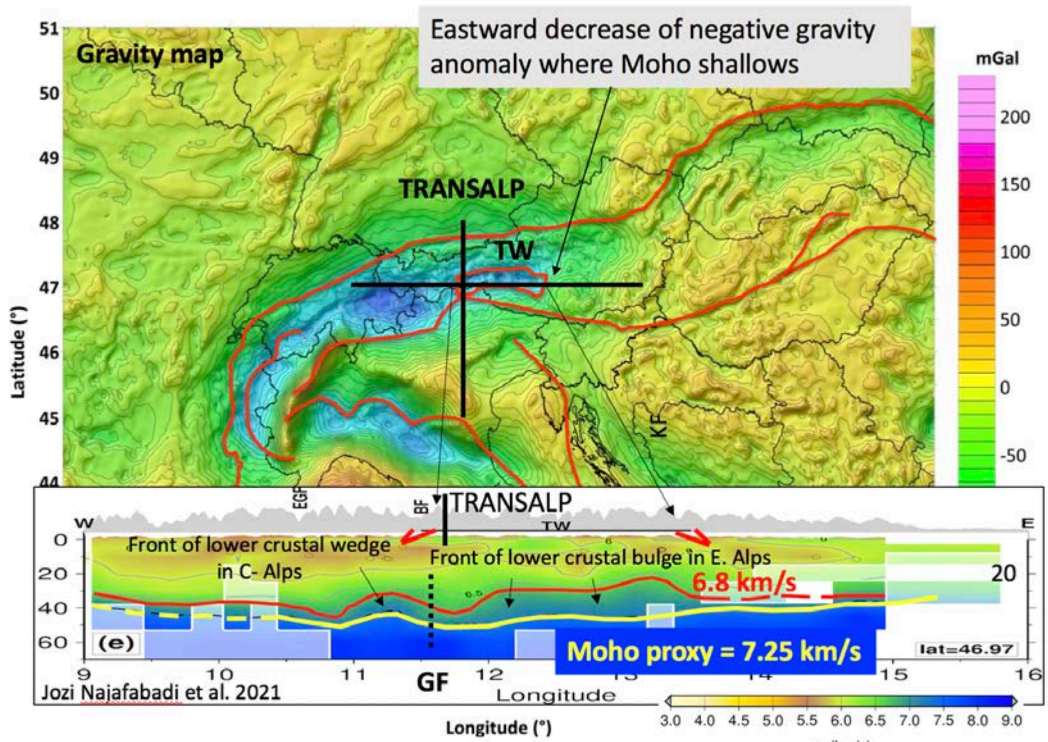


Figure 1-7: Gravity map of ZAHORIC ET AL. 2021 (top) and LET vertical orogen-parallel section showing eastward shallowing Moho and lower crustal bulge beneath the Eastern Alps towards the Pannonian Basin. GF = trace of Giudicarie Fault

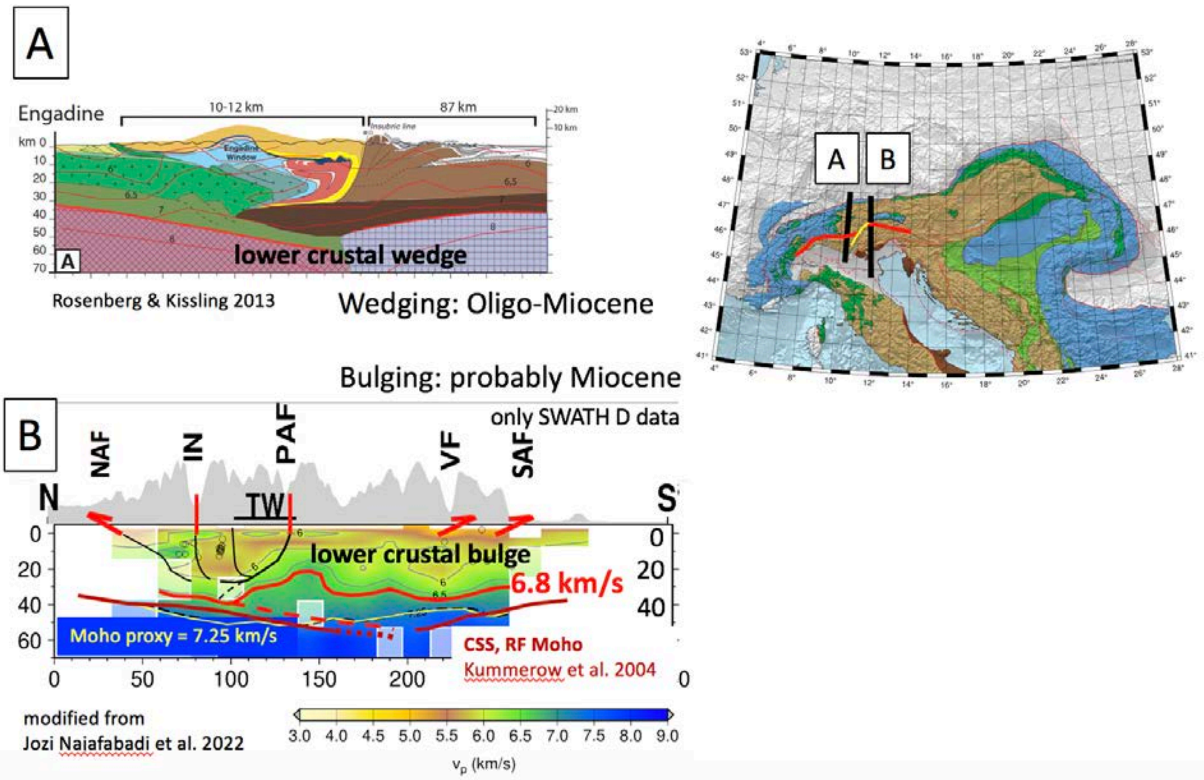


Figure 1-8: Cross sections from Local Earthquake Tomography (LET) showing deep crustal structure of the Alpine orogen west (A) and of the east (B) of the Giudiccarie Fault (from ROSENBERG & KISSLING 2013; JOZI NAJAFABADI ET AL. 2021, LÜSCHEN ET AL. 2004 and KUMMEROW ET AL. 2004.

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. 1-9**).

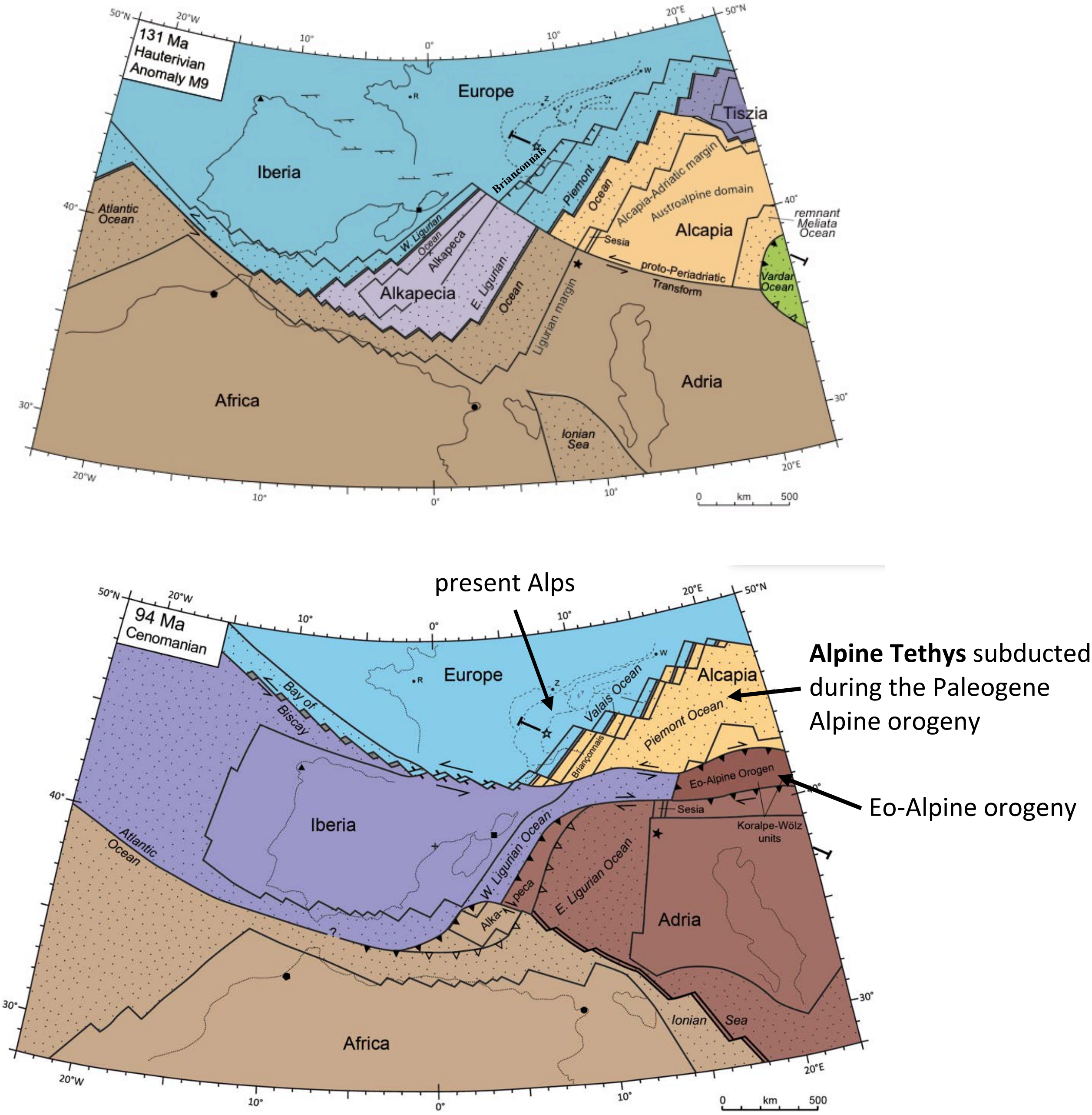


Figure 1-9*: Plate tectonic reconstruction of the central and western Mediterranean at the end of spreading of the Piemont-Liguria part of Alpine Tethys (top) and near the end of spreading of the Valais part of Alpine Tethys during the Eo-Alpine orogeny (bottom) after HANDY ET AL. 2010, their Fig. 10. The present Alps are outlined by fine dashed lines.*

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

Route: Salzburg-Rossfeld-Großglockner
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 Bohemian Massif) 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. 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. The thrust front migrated north until c. 19 Ma while the basin continued to subside. Thrusting stagnated or even retreated into the orogen as the basin rapidly filled from 18-16 Ma (**Fig. 1-10**, HINSCH 2013, ORTNER ET AL. 2014)

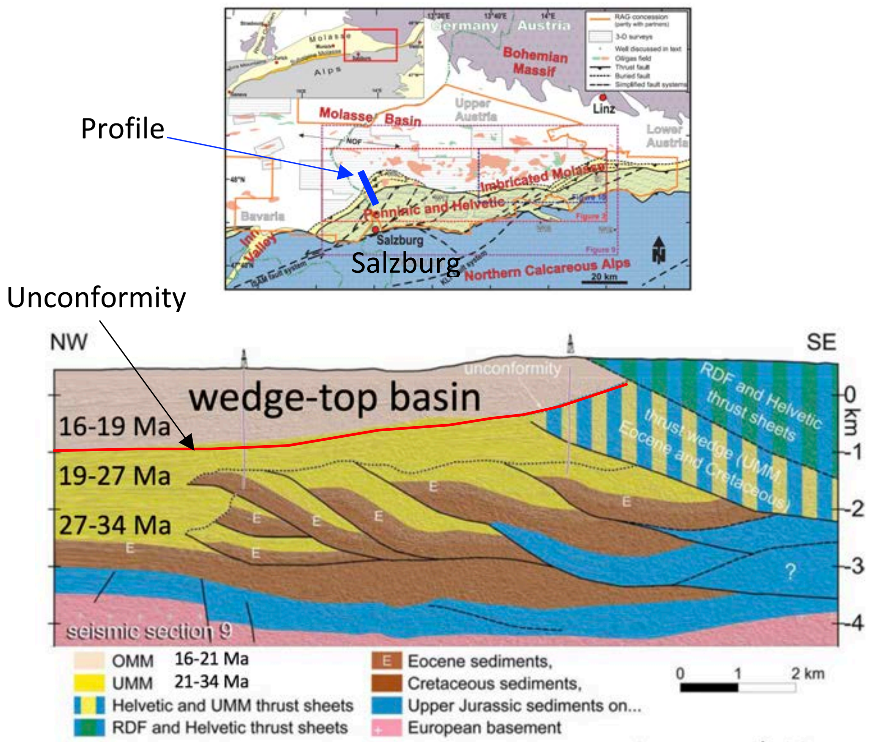


Fig. 1-10: Map and cross section of the Northern Alpine Front (HINSCH 2013, ORTNER ET AL. 2014). Note the unconformity at the base of the OMM (19 Ma) sealing the thrust wedge and pre-dating out-of-sequence thrusts.

Panorama at Gaisberg: The Gaisberg panorama (**Fig. 1-11**) 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 thrust wedge in **Fig. 1-10** is buried beneath this plain. The hilly area contains 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 margin of the Gaisberg and extends W through Salzburg. (**Fig. 1-10**), 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.

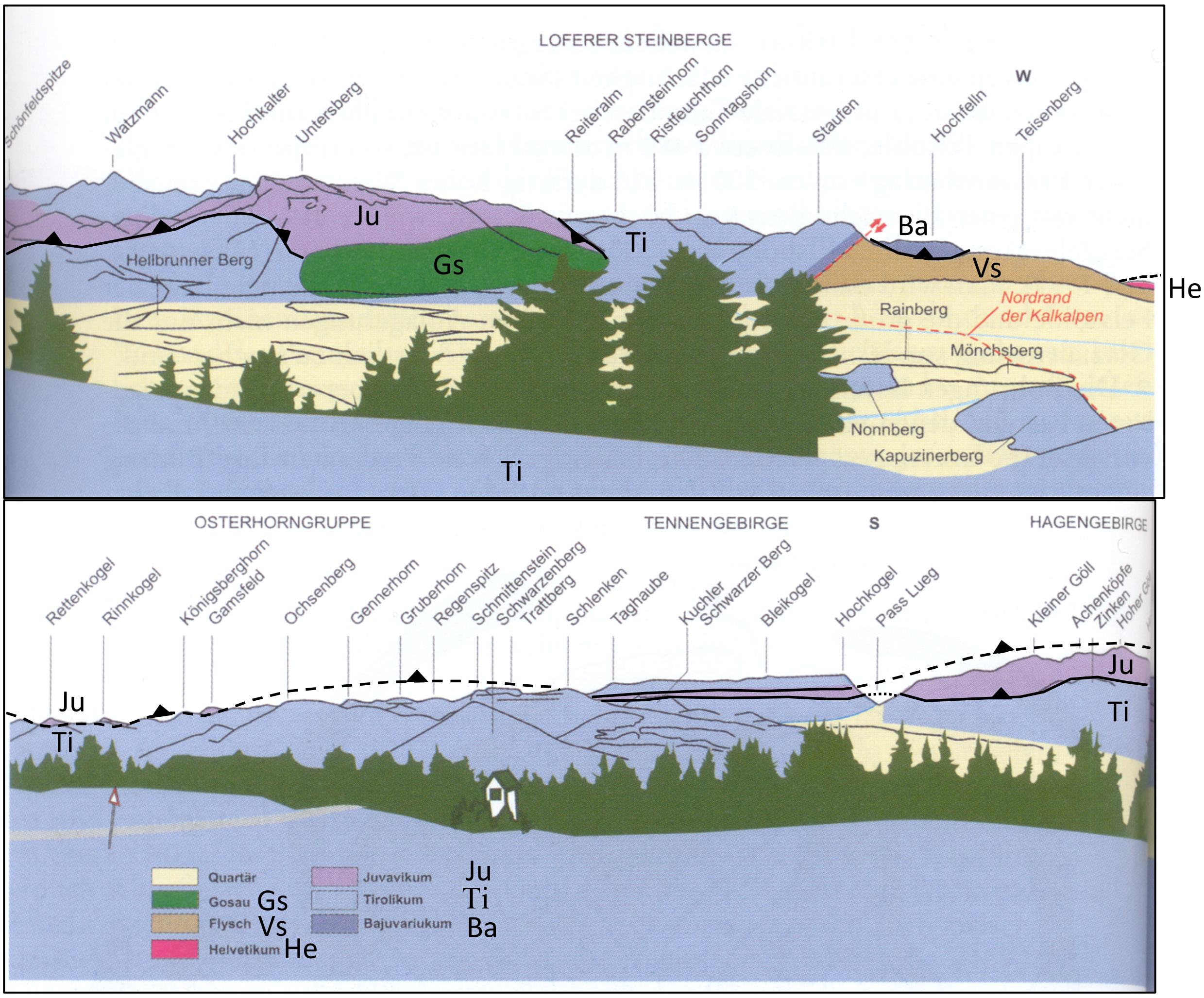


__Figure 1-11__: Geological units viewed from the Gaisberg to the W (top) and S (bottom). From GENSER, NEUBAUER & TICHY, courtesy of H.-P. STEYRER 2009

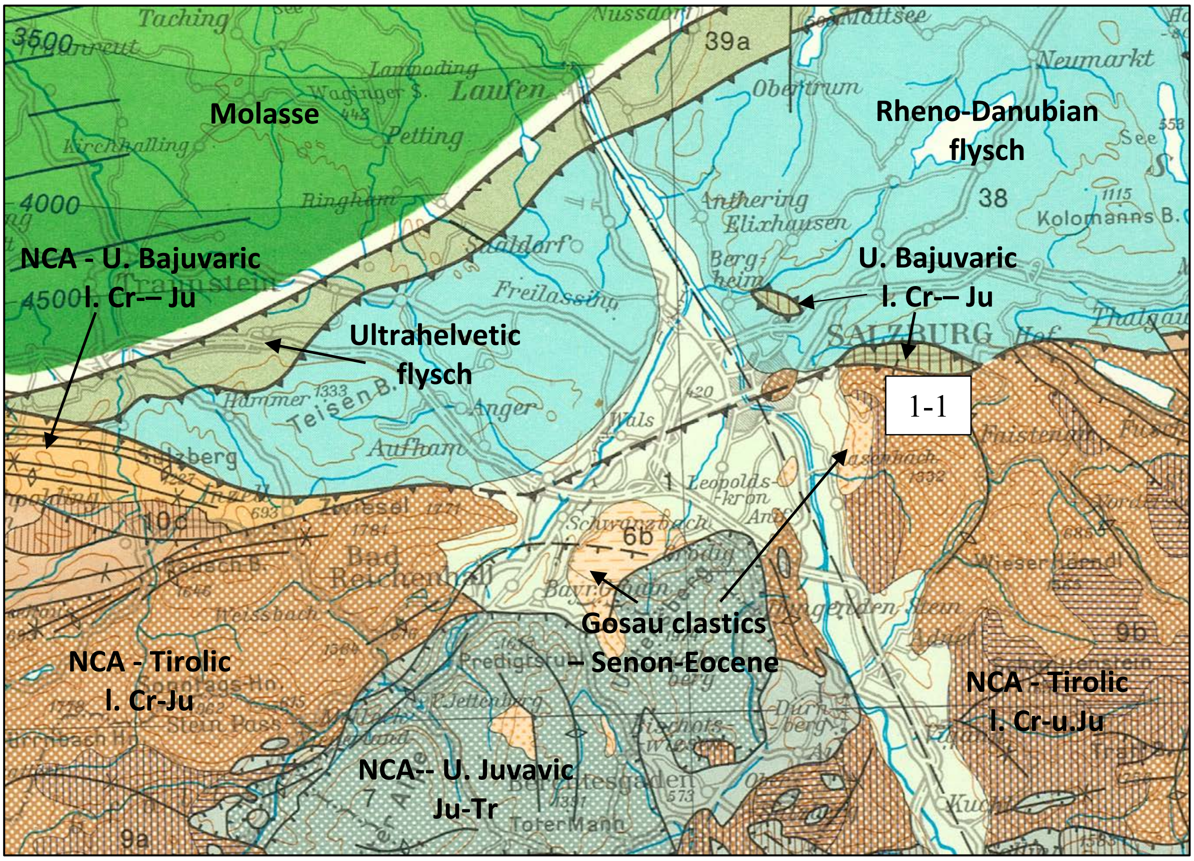


***Figure 1-12**: Tectonic units along the Alpine front near Salzburg in Structural Map of Italy, Bigi et al. 1981; Note that a post-orogenic Gosau-type basin is included in the hangingwall of the NCA thrust (NEUBAUER, 2002; UHLIR and VETTERS, 2009).*

Stop 1-2: 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. 1-9**). The NCA is subdivided from top to bottom into the *Juvavic, Tirolic, and Bajuvavic* 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. 1-13, 1-14**). 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).

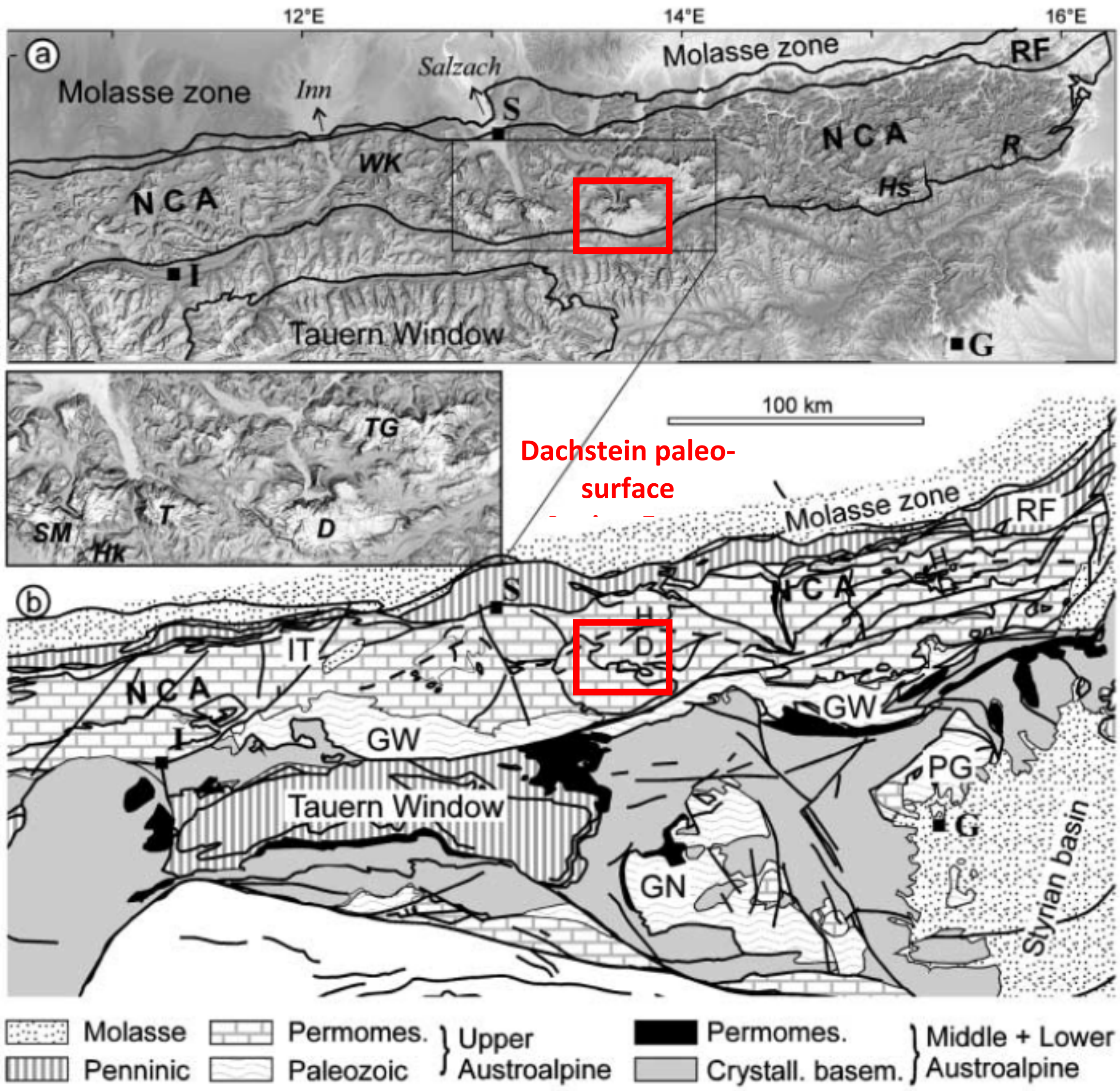


***Figure 1-13**: Satellite view (a) and geological overview (b) of Eastern Alps with location of elevated paleosurfaces and Augenstein sediments in the Northern Calcereous Alps, NCA (modified from FRISCH ET AL. 2001). D - "Dachstein" paleosurface within red box.*

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 Salzach-Ennstal-Mariazell-Puchberg Lineament (SEMP, **Fig. 1-14**) 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. 1-14**).

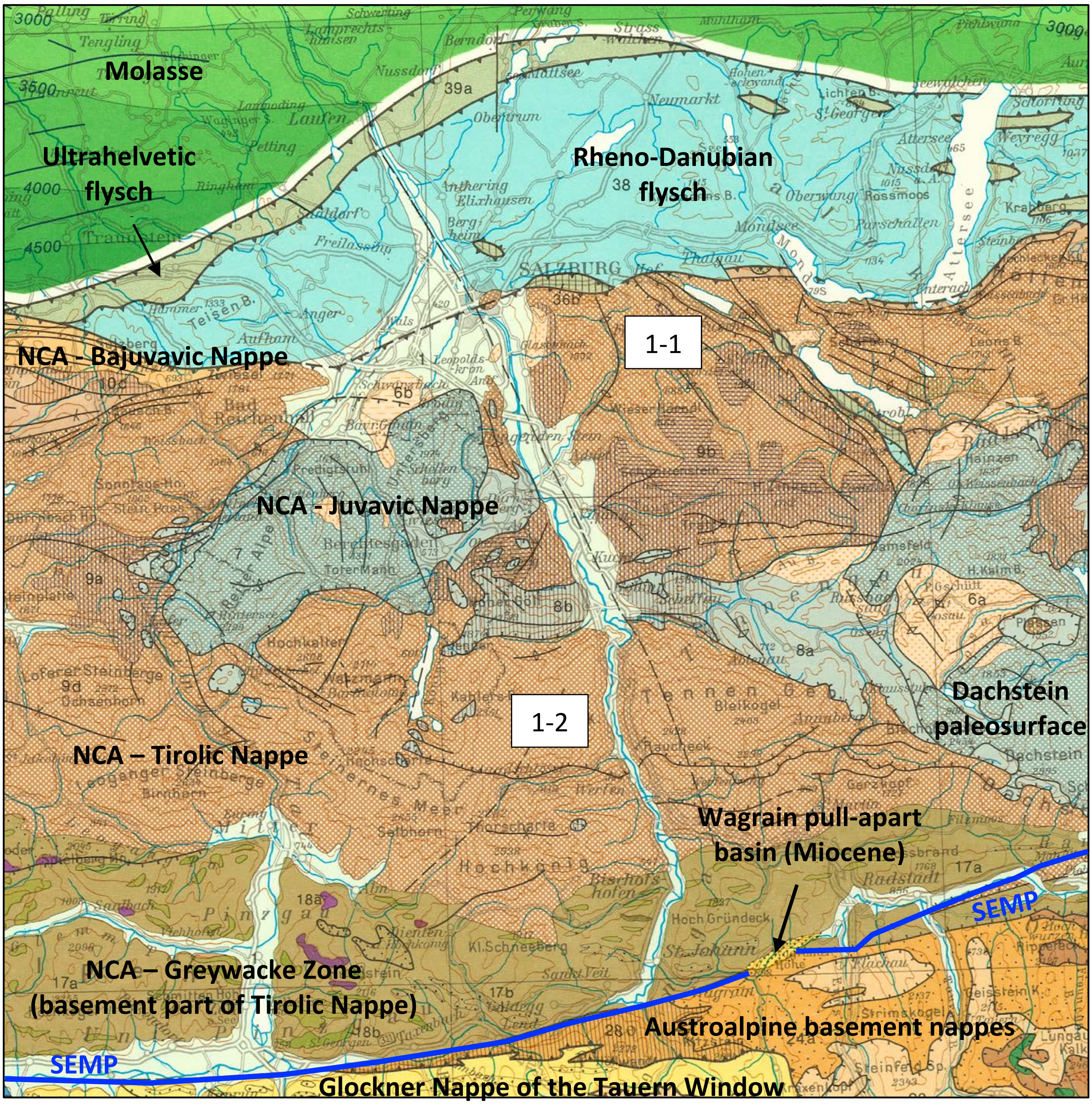


***Figure 1-14**: Nappes of the NCA shown in Structural Map of Italy, BIGI ET AL. (1981); SEMP – sjnistral Salzack-Ennstal-Mariazell-Puchberg Fault. European units – Rhenodanubian, Ultrahelvetic & Helvetic flysch, Adriatic units - NCA*

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. 1-15**). 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. 1-15**):

- **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 1-16**: 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 exhumed 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. 1-15**). 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.

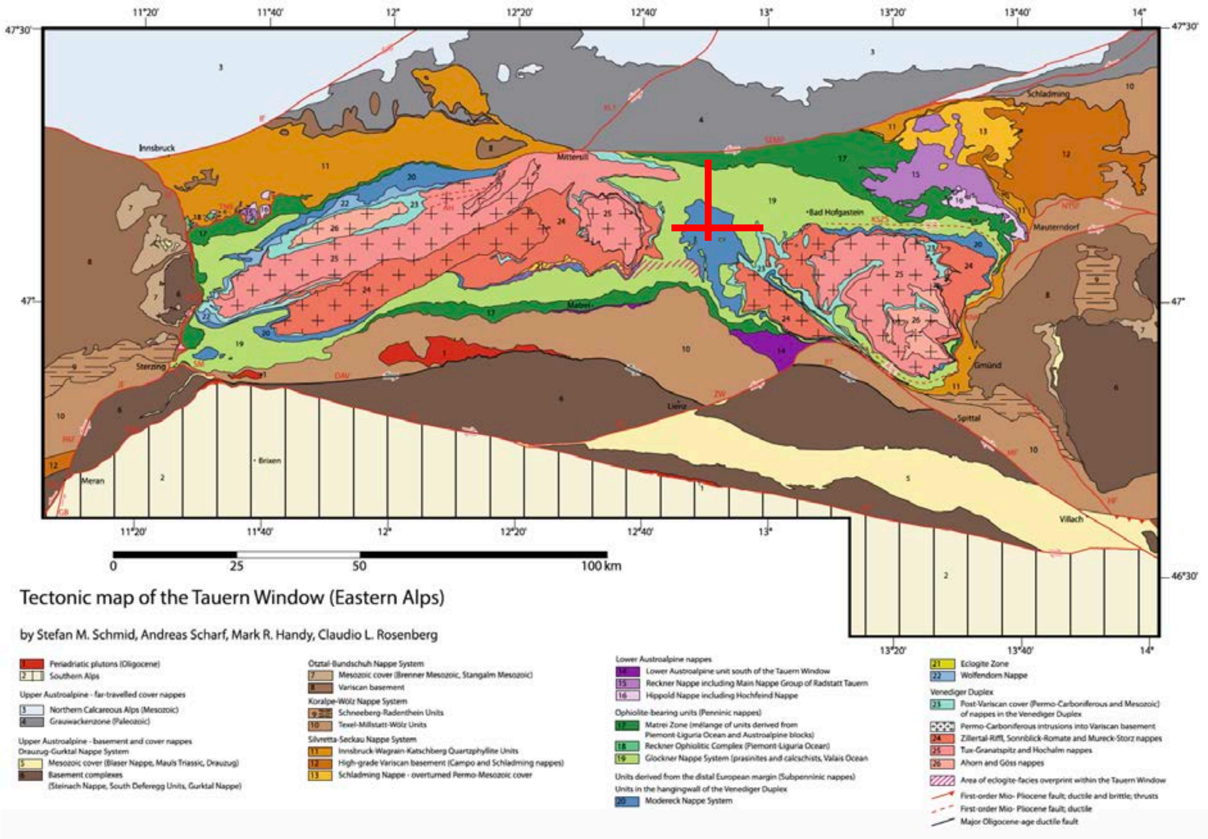


Figure 1-15: *Tectonic Map of the Tauern Window (SCHMID ET AL. 2013). Red lines across the Seidwinkl sheath fold (blue) show traces of cross sections in Fig. 1-17.*

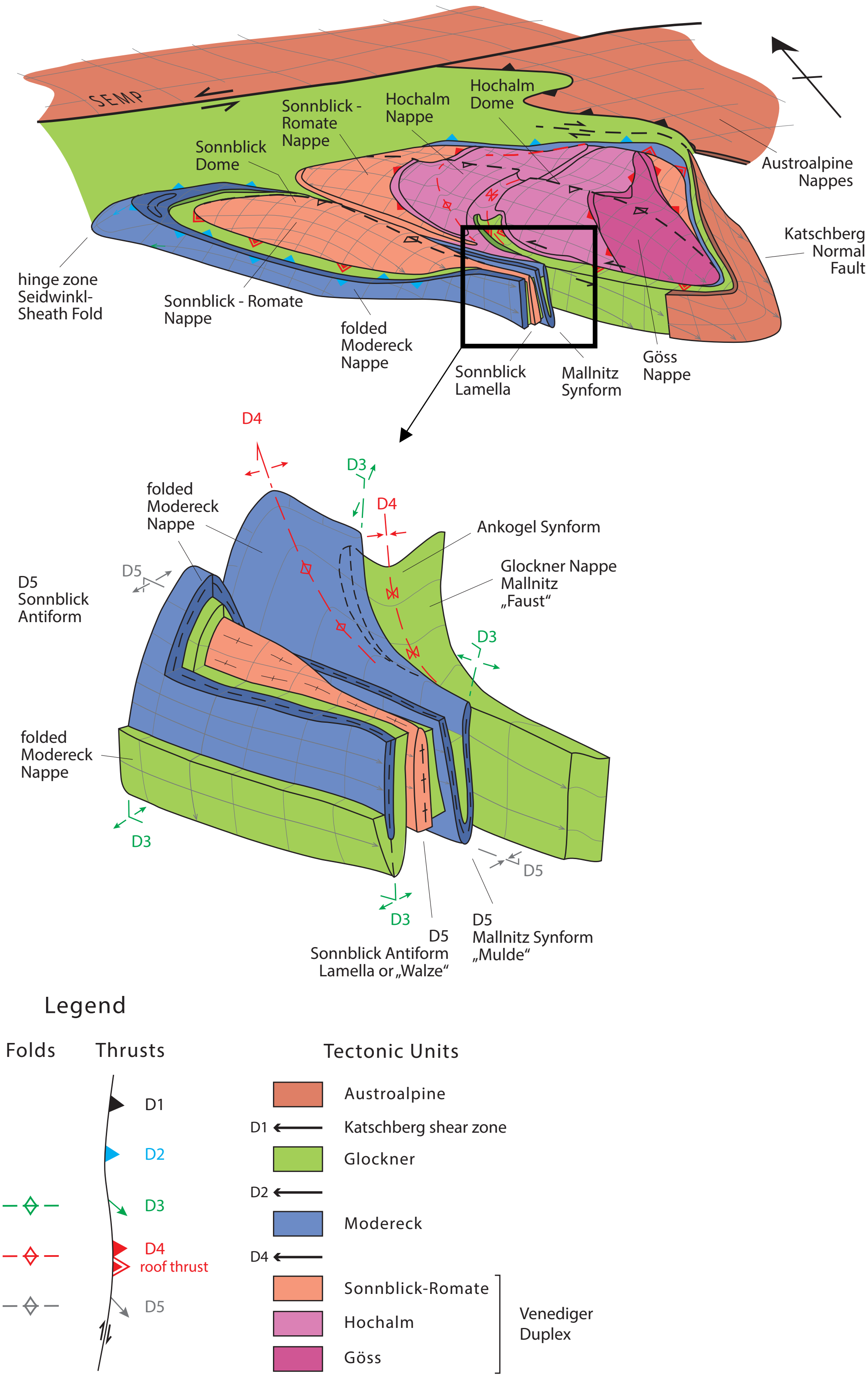


Figure 1-16: *Block diagram of the eastern Tauern Window with main nappes and thrusts (top). Detailed diagram (middle) of nappe structure in the Obervellach area (Stop 2-5). Legend (bottom) shows structural position, from highest to lowest in the nappe pile. HANDY, unpubl.*

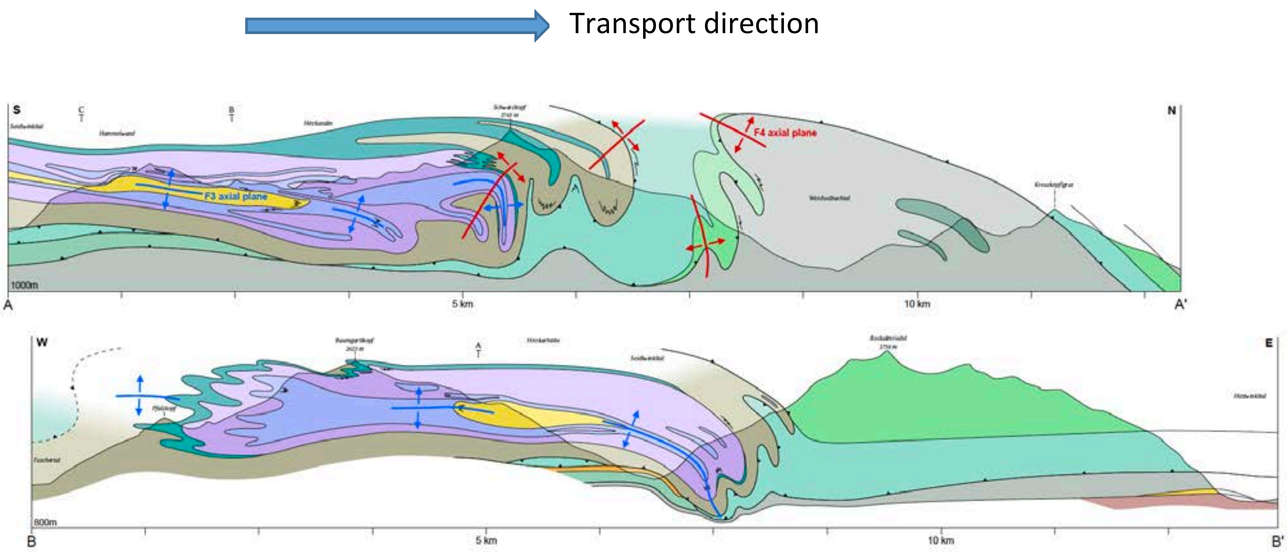


Figure 1-17: *Cross sections parallel (top) and perpendicular (bottom) to the N-S transport direction of the Modereck Nappe and the Seidlwinkel sheath fold formed during subduction and exhumation prior to collision. Blue – axial trace of the F3 Seidlwinkl sheath fold; Red – axial traces of the F4 folds. Cross sections from GROSS ET AL. 2020a.*

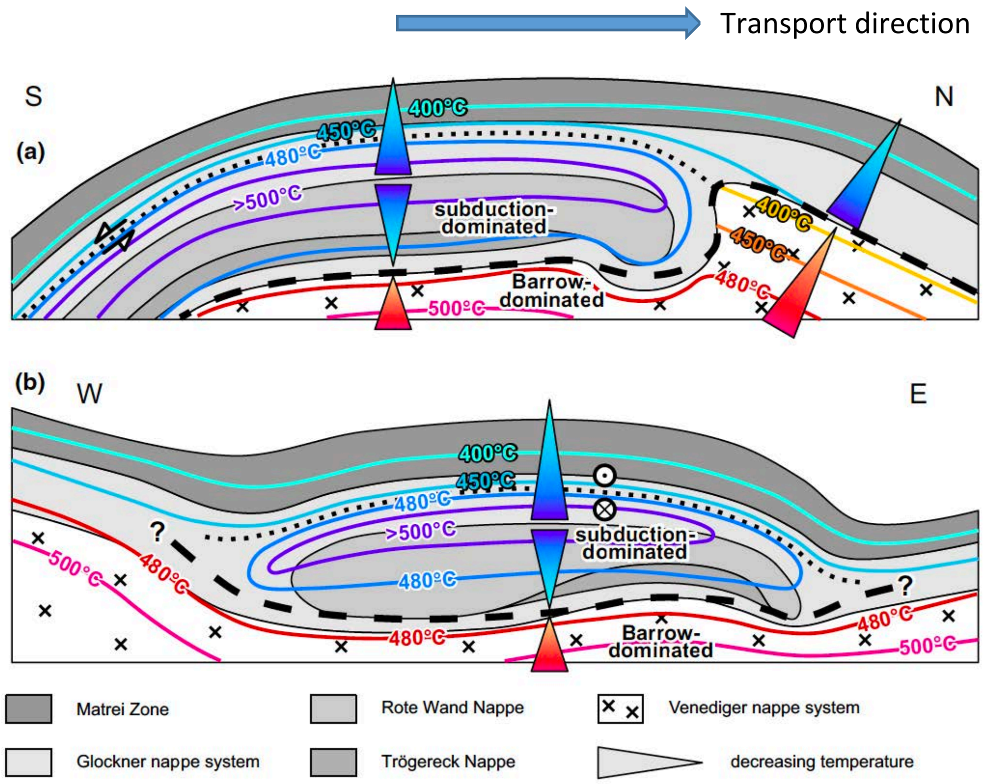
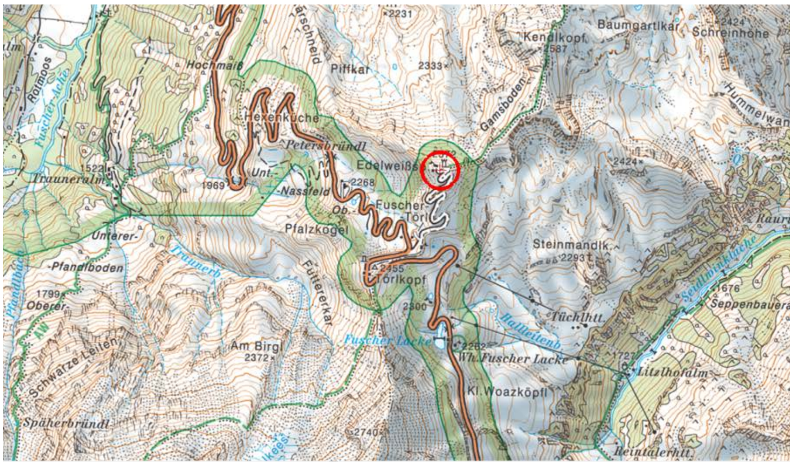


Figure 1-18: *Sketch of the peak-T pattern in the Seidlwinkl sheath fold. The sections are parallel (a) and perpendicular (b) to the nappe transport direction. The boundary between subduction- and Barrow-related peak-T domains (dashed black line) is marked by inversion of the peak-T gradient. In the Barrovian domain, peak-T decreases away from the core of the basement domes (below the sections). In the subduction domain, peak-T contours form a sheath-like pattern similar to the lithological layering. (GROSS ET AL. 2020b).*

Route:



Stop 1-3: Edelweissspitze (circle)

Panorama: The Edelweißspitze affords a 360° panorama from the central part of the Tauern Window (**Figs. 1-19 to 1-21**). 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 Triassic 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. 1-18**). The mountain to the S (Brennkogel, 3018 m, **Fig. 1-21**) comprises lower Cretaceous metasediments of the Modereck Nappe system (see Stop 1-2). Also visible to the S on a cloud-free day is Austria´s highest mountain, the Großglockner (3798m, **Fig. 1-21**), comprising ophiolite and calc-schist “Bündnerschiefer” of the Glockner Nappe. To the W we have the Große Wießbachhorn (**Fig. 1-20**) 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 sheath fold nappe (see Stop 1-4). The outrop occupies the western limb of the recumbent Seidwinkl sheath fold (see **Fig. 1-17**, bottom).

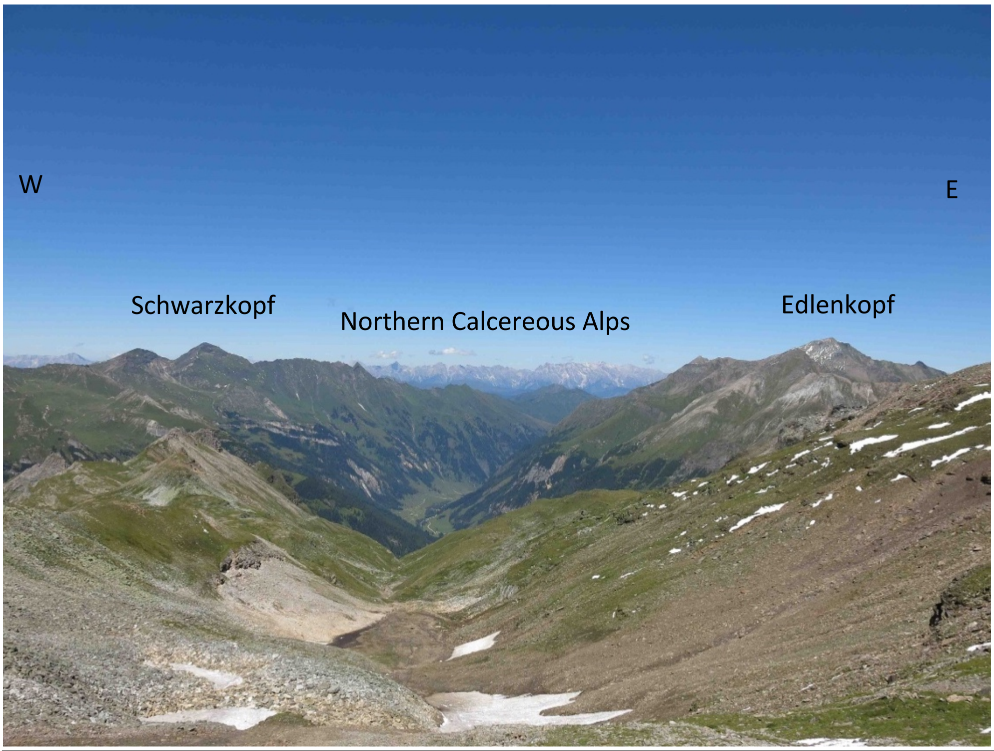


***Figure 1-19**: View to the N of the Tauern Window seen from the Weissenbachscharte. Lower left: late Permian "Wustkogel" strata forming core of the isoclinal Seidlwinkl sheath fold (originally distal European margin); Pyramidal peak on left: Schwarzkopf, with lower Jurassic shales; Right: Edlenkopf with contact of early Cretaceous Brennkogel schist with light calc-schist of Glockner Nappe. Middle: Seidwinkl Valley and Northern Calcereous Alps (originally SE Adriatic margin) in the distance.*

***Figure 1-20**: 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.*

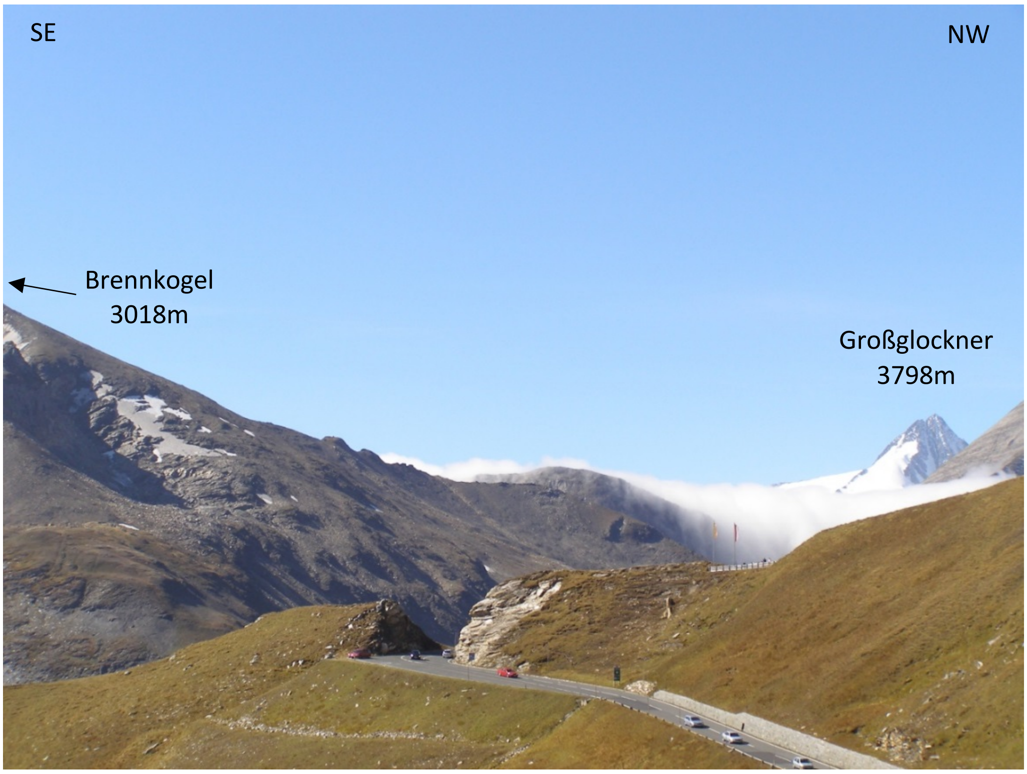
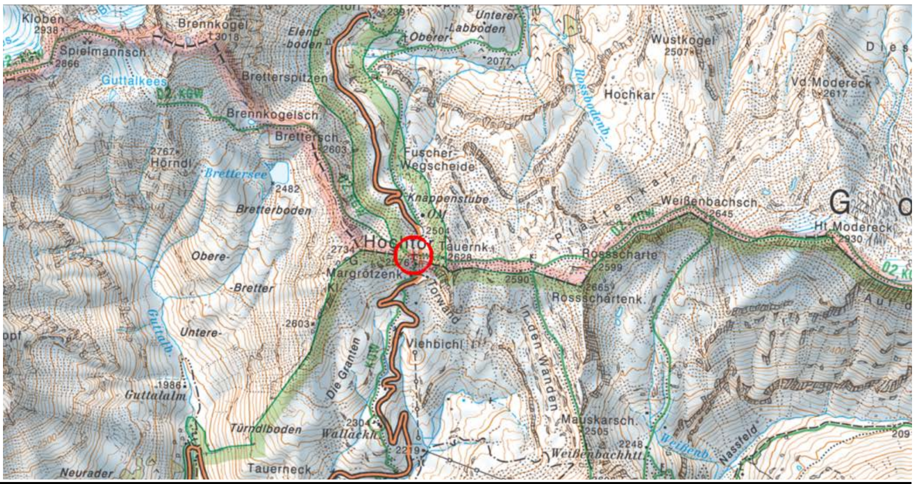


***Figure 1-21**: View to the SW of Austria's highest mountain, the Großglockner (3798 m) comprising ophiolite and calc-schist (Bündnerschiefer) of the Glockner Nappe. Mountain flank on left belongs to the Brennkogel.*

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. 1-15, 1-16**), 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. 1-16**). This large-scale fold is interpreted as a sheath fold (**Fig. 1-17**) 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 eastwards from the Hochtor traverses an almost complete, though deformed stratigraphic section of the distal European continental margin, preserved in the upright limb of the Seidlwinkel Fold nappe (**Fig. 1-23**). 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. 1-22**, 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 1-22 *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.

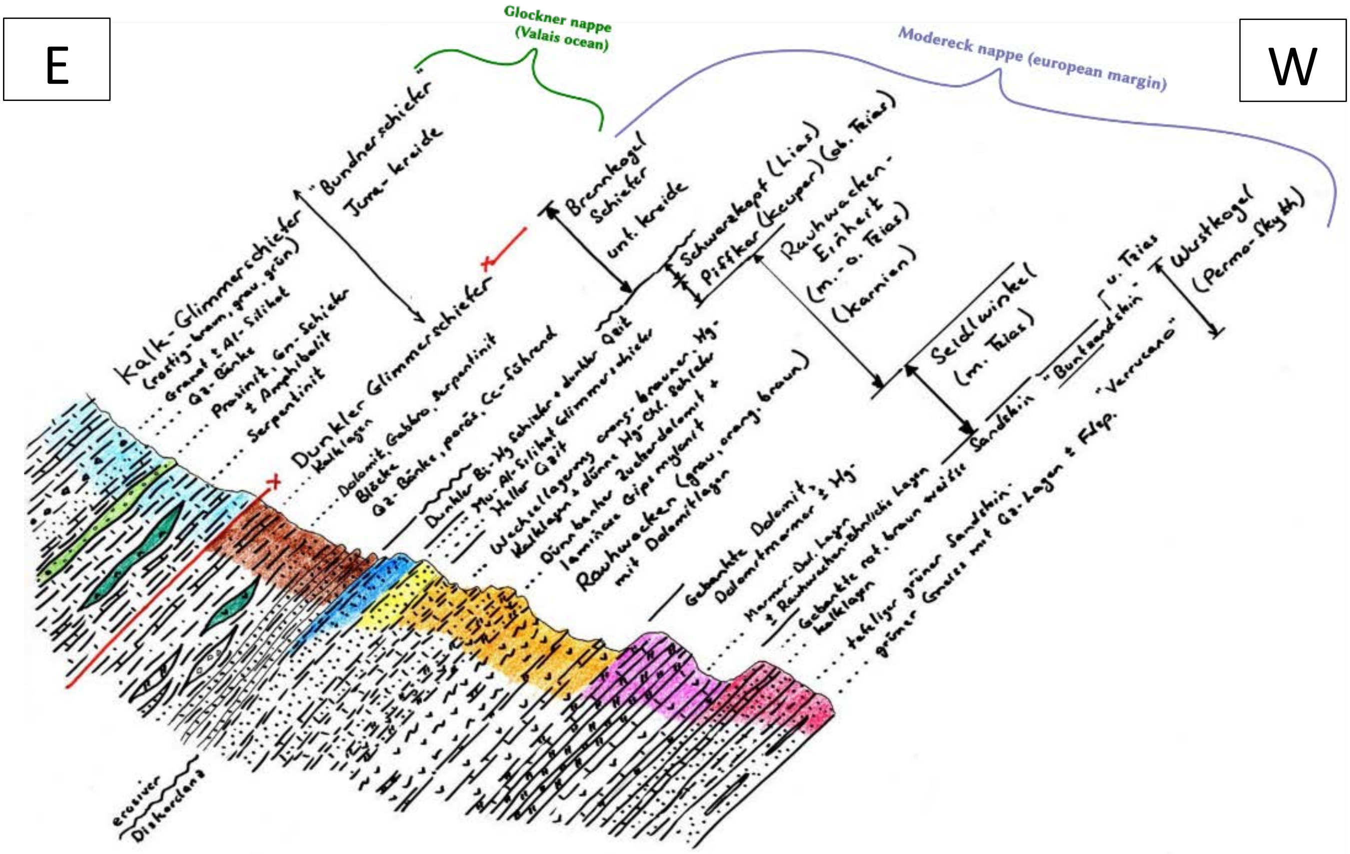


Figure 1-23a: *Composite stratigraphic section of the Mesozoic cover of the Modereck Nappe near Hochtorland*

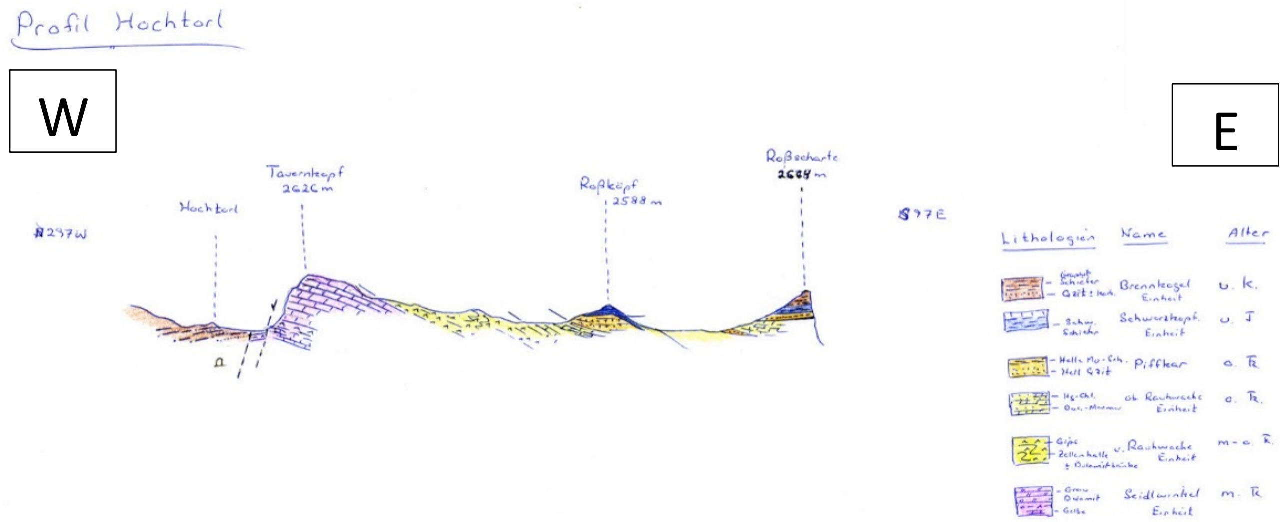


Figure 1-23b: *Schematic W-to-E cross section from the Hochtor to the Roßscharte (bottom). Fieldbook sketch*

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 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. 1-24**). By combining thermodynamic modelling of zoned garnets with Raman microspectroscopy of quartz inclusions in garnet and Si-in-phengite geobarometry, we obtain a steep decompression path during D3 shearing (**Fig. 1-25**). The Tertiary exhumation history of the various subducted units in the Tauern Window is shown in **Figure 1-25** (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.

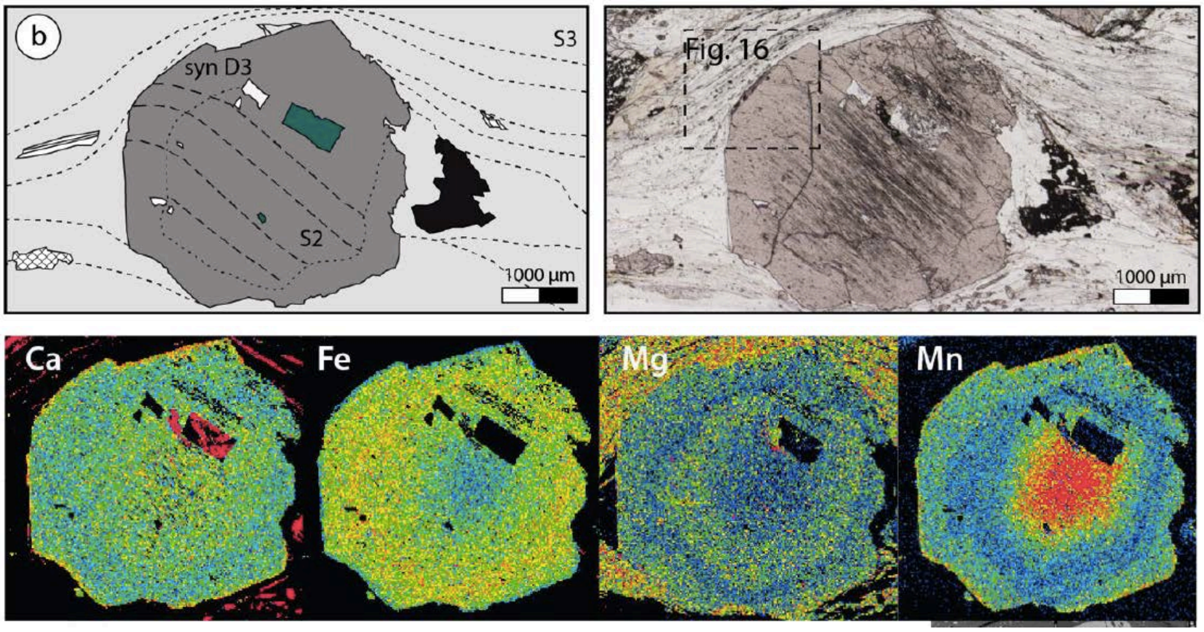


Figure 1-24: *Garnet from Brennkogel schist of the Seidlwinkl fold nappe: (top row) microstructure with curved inclusions documents post-D2 (core) and pre- to syn-D3 growth (rims); (bottom row) compositional zonation with lawsonite pseudomorphs (K. SCHMIDT, 2015, MSc thesis).*

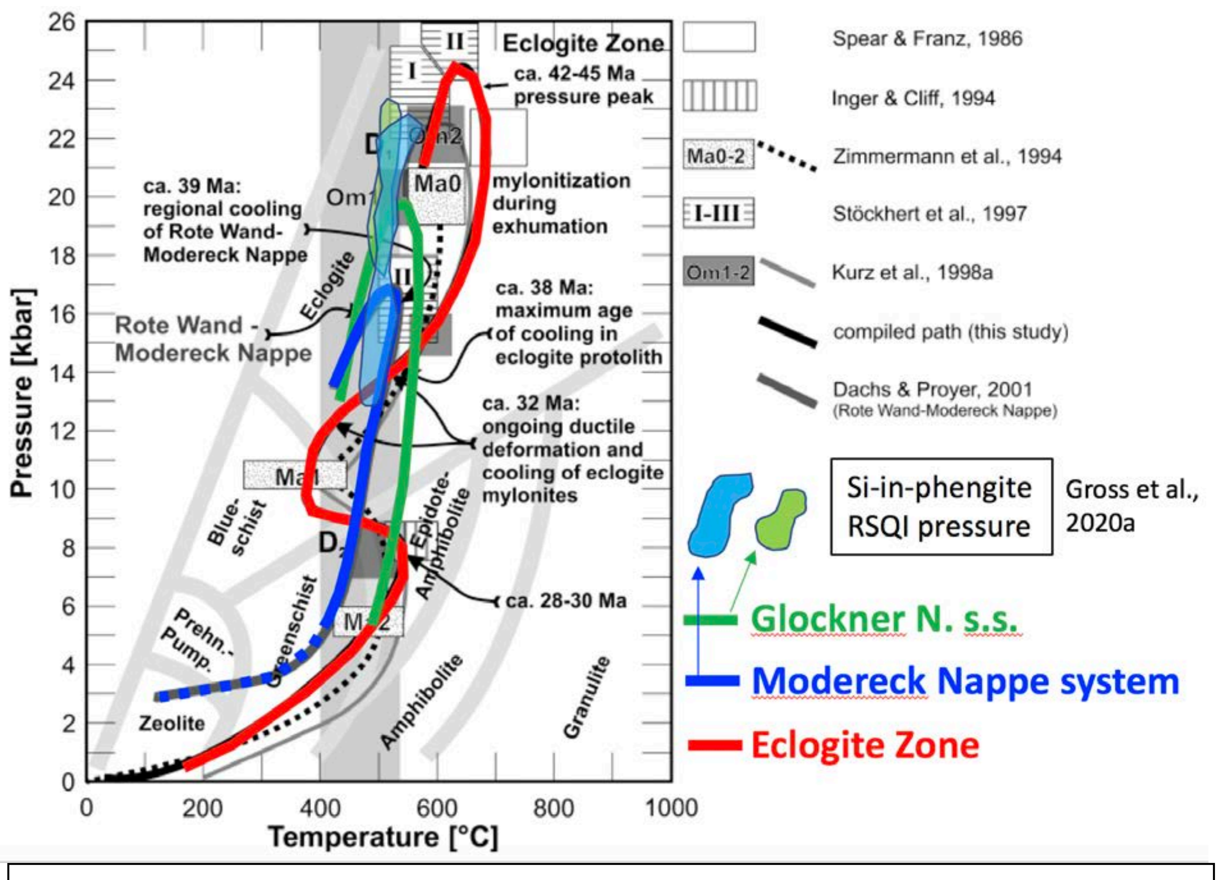


Figure 1-25*: P-T curves showing subduction and exhumation of continentally derived nappes in the Tauern Window (modified from Fig. 4 of KURZ ET AL. 2008): the Eclogite Zone of the W Tauern Window (**Fig. 1-15**) the Glockner Nappe s.s. and the Modereck Nappe System (GROSS ET AL. 2020b).*

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 Wallachhaus (see Important Addresses)

Day 2: Adriatic 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).

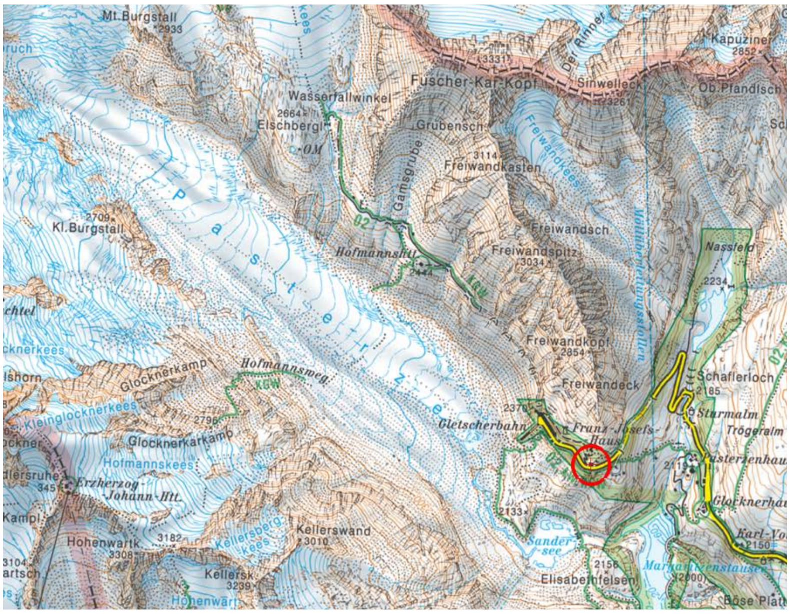
***Stop 2-1 (circle)**: Pockhorner Wiesen*

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 2-2 (circle)__: Franz-Josefs-Haus_

_Figure 2-1__: View to NNW of the Großglockner (3798 m), Austria´s highest mountain, and the Pasterze glacier from the Gamsgrubenweg in June of 2013._

General geology: The parking terrasse at the Franz-Josefs-Höhe affords an excellent view of the Großglockner (3798 m), Austria's highest mountain, and the Pasterze Glacier (**Fig. 2-1**). The exposures reveal a record of subduction and exhumation of Penninic units in the Tauern Window, while also providing evidence for the advance and retreat of one of the largest glaciers in the eastern part of the Alps. The

Großglockner is made up entirely of metabasalt (greenish color towards the peak) and its late Cretaceous cover (brown calc-schist at its base) derived from the Valaisan part of the Alpine Tethyan Ocean.

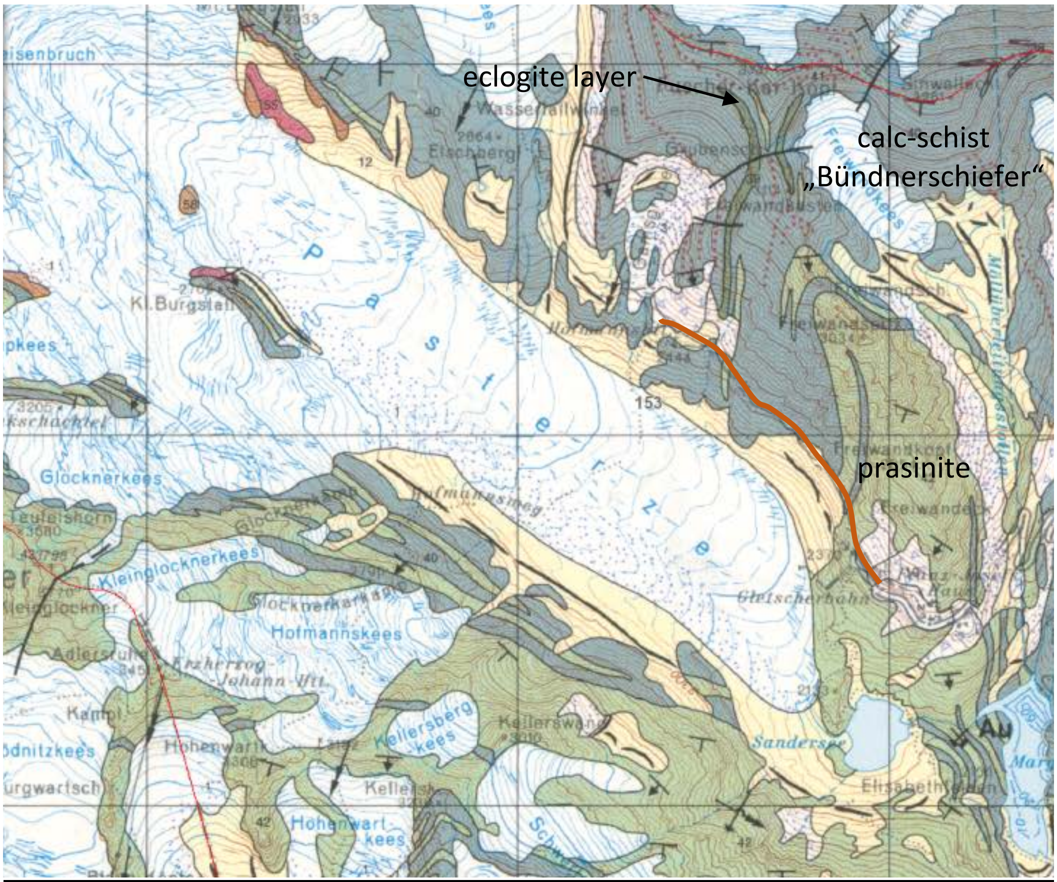


***Figure 2-2**:_Geology around the Pasterze Glacier (HÖCK & PESTAL 1994). Path from Franz-Josefs-Höhe to Hofmannshütte is marked with a red line.*

Bedrock geology: The surrounding peaks comprise metabasites and calc-schists derived from oceanic units (Glockner Nappe system). On the map scale, these units are exposed in a saddle between the two basement subdomes of the Tauern Window (**Fig. 1-11**). The rocks of the Glockner Nappe experienced penetrative deformation under upper greenschist facies conditions (Miocene) that overprints an older high-pressure (eclogite, blueschist-facies) metamorphism of probable Eocene age. Two lithologies predominate here: (1) prasinite*; (2) calc-micaschist (so-called Bündnerschiefer) with marly, occasionally pelitic chlorite-sericite-rich layers alternating with variably thick quartzose to calc-arenetic layers.

***Nomenclature and its paleogeographical significance**: *Prasinite* is a field term derived from the Greek for “leek green” and refers to a fine-grained, usually greenish rock comprising albite-chlorite-epidote-clinozoisite +- amphibole. It is characterized by MORB-type geochemistry (HÖCK & MILLER, 1987). The yellow-green colour of prasinite reflects the high epidote content, especially as micro-inclusions in albite. The amphibole is often zoned (actinolitic cores to Al- und Fe-rich, tschermakitic rims (Fig. 3c of FRANK , ET AL., 1987; HÖCK & MARSCHALLINGER, 1988), whereas albite has oligoclase rims (Fig. 4 of FRANK ET AL, 1987). Accessory minerals are biotite, calcite, phengite, quartz, titanite, apatite and oxides. Occasionally (in the Glockner Nappe s.s), prasinite contains light-coloured rhombohedral pseudomorphs of clinozoisite and chlorite after lawsonite, indicative of high-pressure (blueschist-facies) subduction metamorphism (HÖCK et al., 1994).

Bündnerschiefer, also a widespread Alpine term, is used for flaggy, brown-grey calc-schists with marly, occasionally pelitic chlorite-sericite-rich layers alternating with variably thick quartzose to calc-arenetic layers (HEJL & PESTAL, 2009). The protolith was Early Cretaceous arenite, occasionally interbedded with weakly bituminous marl and mud that was deposited in distal parts of the European continental shelf, before being redeposited by cyclical debris and turbidity flows onto the abyssal plain of Alpine Tethys. This lithology is widespread in the Tauern Window (light green in **Figs. 1-15, 1-16**). The term *Bündnerschiefer* originates from the Graubünden area (Bündnerland) of eastern Switzerland where this rock suite shows low-grade metamorphism (anchizone) and occurs in the nappe pile below continental units (Brianconnais) of the rifted European margin. For this reason, Bündnerschiefer and its mafic substratum, the prasinites of the Graubünden have always been attributed to the Valais part of Alpine Tethys (STEINMANN 1994). In the Tauern Window, however, Brianconnais units are missing and Bündnerschiefer calc-schist (referred to as *obere Schieferhülle* in the older Tauern literature) overlies the European units, represented by basement slices of the Venediger Nappe complex, described above. Thus, for many years, there was a controversy about the paleogeographic origin of the Bündnerschiefer, with some geologists favouring a provenance in the Piemont-Liguria domain of Alpine Tethys (originally located south of Brianconnais) and others favouring an origin in the Valais part of Alpine Tethys (N and E of the Brianconnais units, but S of the European margin). The debate was finally resolved in favour of a Valais origin due to the strong similarity of Triassic and early Jurassic rocks in the cover of the Venediger basement with the cover of the Bohemian Massif, north of the European Alpine foreland (FRISCH, 1979; see discussion and references in SCHMID ET AL., 2013).

Note that Bündnerschiefer calc-schist strongly resembles (indeed, is locally identical to) the lower-Cretaceous *Brennkogel schist* (see above, Day 1, **Fig. 1-20**) which overlie Late Jurassic marble of the Hochalm Nappe of the European margin. For this reason, the Bündnerschiefer and Brennkogel schists are regarded as temporal equivalents that were deposited on either side of the ocean-continent transition. The Brennkogel Fm contains dark to black, organic-rich layers intercalated with quartzite beds and carbonatic breccias which are typical for ‘‘Gault-type’’ black shales found elsewhere in Mid-Cretaceous deposits of the Alps (LEMOINE 2003). This led SCHMID ET AL. (2013) to speculate that the Brennkogel Fm was deposited in an oxygen-starved environment during one of several Cretaceous global anoxic events.

Directions: There are two attractive trips to consider from the Franz-Josefs-Höhe, depending on the time available:

1) Short trip (1.5 hrs): Take the funicular from the Franz-Josefs-Höhe to an area 200m lower, exposing prasinites and glacial features (polished bedrock, etched boulders and Toteislöcher).
2) Long trip (3 hrs, described below and marked in **Fig. 2-2**): Hike to the north from the Franz-Josefs-Höhe along the scenic path on the eastern side of the Pasterze Valley (Gamsgrubenweg) to the Hofmannshütte; the path is for visitors to the Hohe Tauern National Park and passes through tunnels containing motifs of the local cultural history. The excellent outcrops along this path include calc-schist (Bündnerschiefer) of the Glockner Nappe s.s. and prasinite with boudins of eclogite.
3) **Description of trip 2 (includes stop 2-3)**: Die Gamsgrubenweg has two tunnels, the first of which crosses the prasinite described above, the second of which crosses a thick sequence of calc-schists striking from the Freiwandkasten

and Fuscher-Kar-Kopf into the Pasterze Valley. Also occasionally present are layers of quartz-rich garnet-muscovite schist und dark, calcareous phyllite. The calc-schist has grey to grey-blue fresh surfaces and contains variable relative amounts of calcite, white micas (phengite, paragonite, margarite) intergrown with chlorite, and quartz, as well as minor amounts of feldspar, biotite, zoisite, clinozoisite, chloritoid, garnet, iron oxides and graphite.

4) The outcrops at the end of the tunnels in the north comprise graphitic, carbonaceous and quartzose garnet-bearing schists (calc-schists of the Bündnerschiefer) with occasional prasinite bands. With a bit of luck, one finds pieces of eclogitic prasinite, particularly in the numerous gorges crossing the path on the way to the Hofmannshütte. These pieces come from a band of eclogitic prasinite above the path that strikes from the Gamsgruben gully to the Pasterze valley. These relicts of Tertiary (Eocene?) high-pressure metamorphism were overprinted by Oligocene high-temperature, Barrow-type metamorphism (Tauernkristallisation).

Stop 2-3: Hofmannshütte (N47.0863°, E12.7391°)

Themes: High-pressure metamorphism of subducted oceanic crust, glacial retreat

Directions: Follow the Gamsgrubenweg* as far as a fork in the path; the lower path descends a few meters to the Hofmannshütte and exposes outcrops of eclogitic prasinite (as described above).

*The Gamsgrube is a gully north of the Hofmannshütte and at the foot of the Fuscherkarkopf, opposite the Großglockner. As recently as 20 years ago, field trips to the Gamsgrube visited nice samples of eclogitic prasinite and provided views of drift-sand dunes (Flugsanddünen) up to 3 meters high. Today, the Gamsgrube Kar is a protected area of the National Park and leaving the path to traverse it requires the permission of the park authorities. This is to protect unique animals and plants which thrive in arctic climates and are otherwise only found on Iceland, Spitzbergen, Greenland and parts of Asia Minor.

Outcrop: The outcrop is part of a ca. 20m wide band of dark green, fine-grained retrogressed eclogite surrounded by garnet-bearing micaschist and calcareous micaschist (**Fig.2-2**, PROYER ET AL. 1999 and DACHS & PROYER 2001). The eclogitic paragenesis at this locality is garnet + omphacite + zoisite/clinozoisite + paragonite + glaucophane + quartz + rutile ± dolomite ± phengite (17 kbar and 570°C). The garnets are zoned and contain inclusions (amphibole, omphacite, chlorite, dolomite, ilmenite). This paragenesis underwent symplectic breakdown to mainly calcic amphibole + plagioclase + chlorite + biotite + calcite + titanite ± hematite ± magnetite, characteristic of the amphibolite-facies “Tauernkristallisation” (5-6 kbar and 500-530°C).

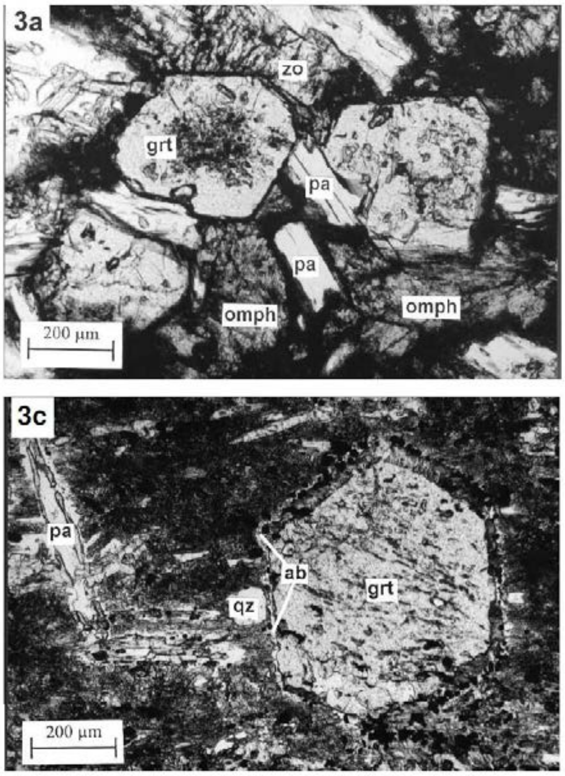


Figure 2-3: *Eclogitic parageneses and retrogression features at Gamsgrube (DACHS & PREUER (2001): Top – Garnet (grt), omphacite (omph), paragonite (pa) and zoisite (zo). Not shown are dolomite, glaucophane, quartz and phengite. Dark areas show incipient breakdown to extremely fine-grained symplectite. Bottom - Replacement of idiomorphic garnet by polycrystalline rims of pargasitic amphibole + epidote (inner rim) and albite (ab) + magnetite (outer rim). Note the lack of corrosion of garnet along grain boundaries with matrix quartz (qz). Paragonite (pa) is rimmed by epidote and albite.*

Figure 2-4*: Eclogite near the Hofmannshütte, upper Pasterze Valley*

***Figure 2-5**: Garnet (small blebs) of the Tauernkristallisation overgrowing the main foliation in an aluminous layer of calc-schist (Bündnerschiefer), along the Gamsgrubenweg, upper Pasterze Valley.*

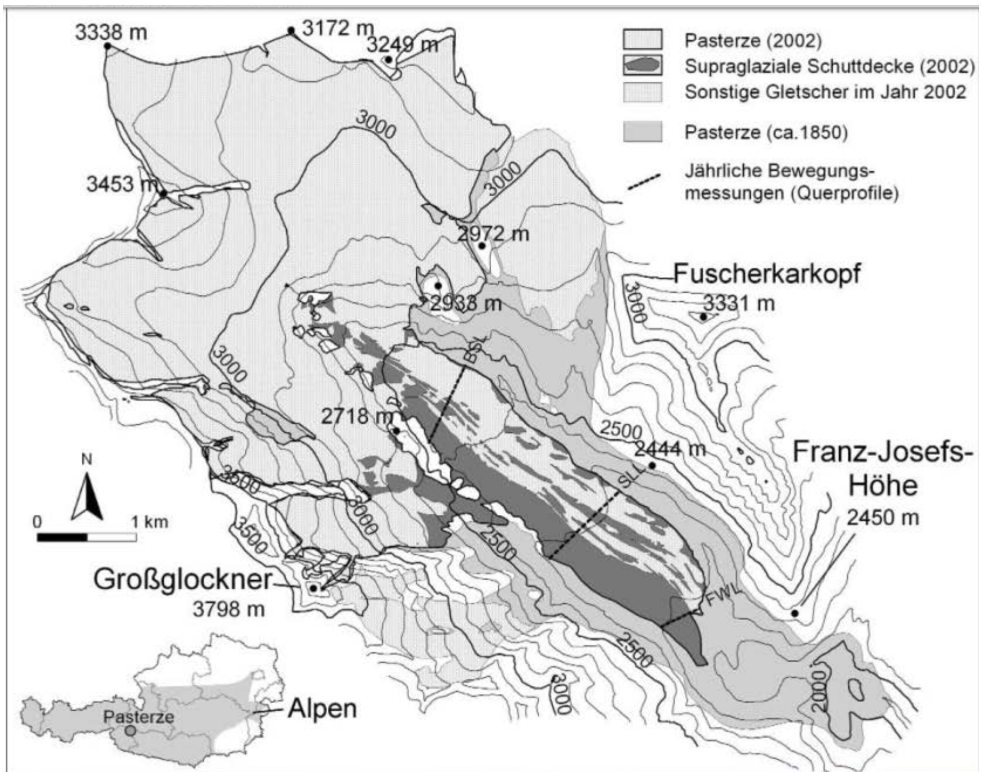


***Figure 2-6**: Pasterze Glacier and extent of its debris cover around 1850 (Little Ice Age maximum) and in 2002 (based on the "Alpenvereinskarte Glocknergruppe", DAV, 2006). Lines indicate 3 cross sections where annual ice measurements are made (FWL = Freiwandlinie, SLL = Seelandlinie, BSL = Burgstalllinie). Map from DRESCHER-SCHNEIDER & KELLERER-PIRKLBAUER, 2008)*

Outwash Plains (Sanderflächen) and melting of the Pasterze Glacier: The lateral moraine from the most recent glacial maximum in 1856 is visible on the southwest side of the valley, high above the current glacier. The glacier ended near the Elisabethfelsen*. Today, the Pasterze glacier ends far up the valley from the Elisabethfelsen* and the area of retreat is filled with an outwash plain. This plain and the murky waters of the lake at the foot of the glacier give an impression of the impressive volume of debris that is deposited (mostly in the summer) by meltwater. Measurements of the Tauern Power Company (Tauernkraftwerke AG) indicate that about 40.000 m^3 of sediment are deposited annually in the outwash plain alone.

In past decades there have been sensational discoveries of glacially overprinted peat, wood, and various plant relics in the outwash plain (**Fig. 2-7**). These indicate that the Pasterze glacier retreated in Holocene time, most recently in the late Middle Ages (PATZELT, 1969). Pollen analysis and radiometric dating of this peat suggest that it grew over a long time, from c. 3370–2200 cal BC to 1940–1430 cal BC. Spruce (Picea) dominated the flora, which are typical for a middle to late Holocene plant assemblage at this altitude (DRESCHER-SCHNEIDER & KELLERER-PIRKLBAUER, 2008). The retreat of the Pasterze glacier since 1856 is well documented on National Park posters near the Pasterzenhaus (Stop 2-3) as well as in the photos of KRAINER (2005, pages 128- 131). *As recently as 1930 to 1960, the Pasterze glacier reached down to the Elisabethfelsen (see map of CORNELIUS & CLAR, 1935). The map of PATZELT (1969) documents the retreat of the glacier to a position northwest of the Elisabethfelsen, as well as the development of the outwash plains and a terminal melt-water lake (Pasterzensee).

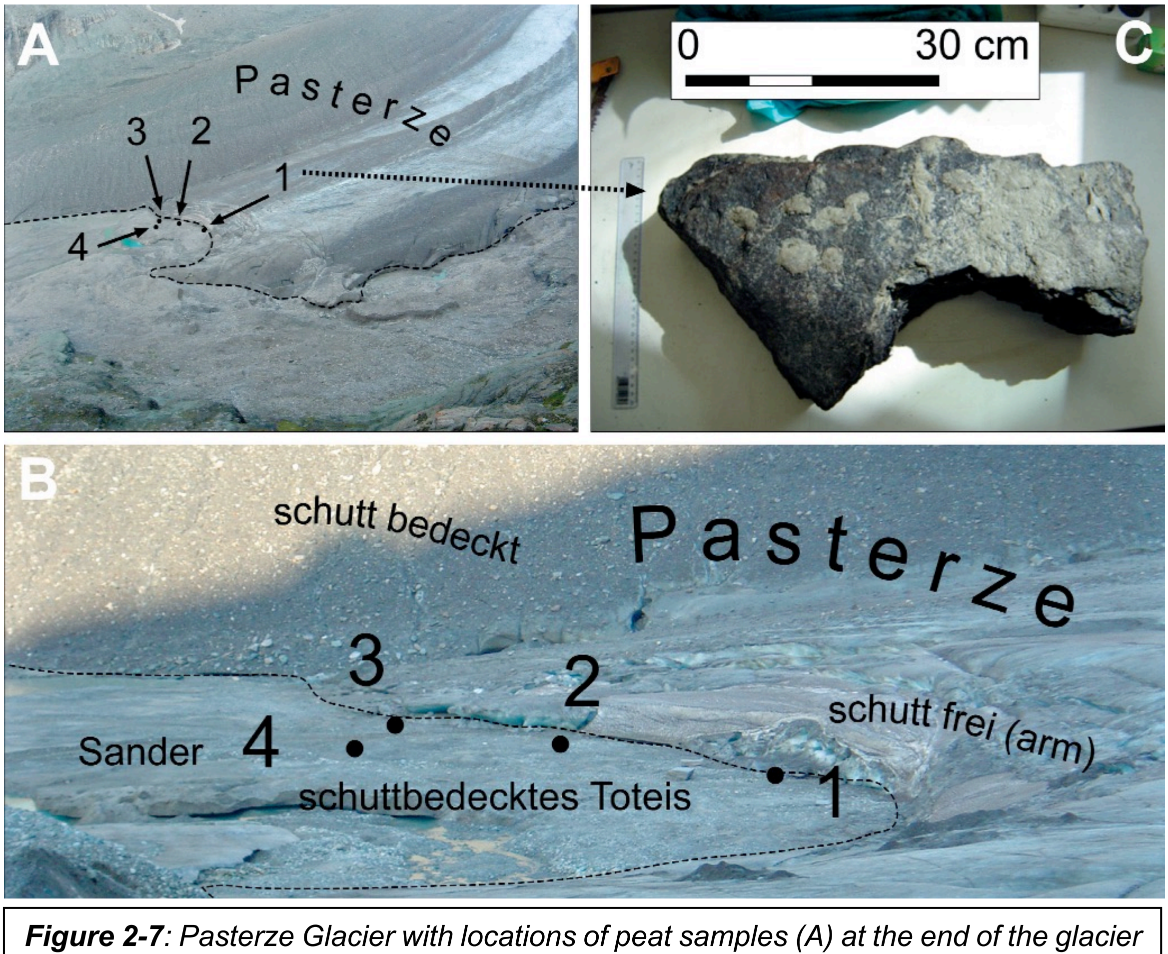
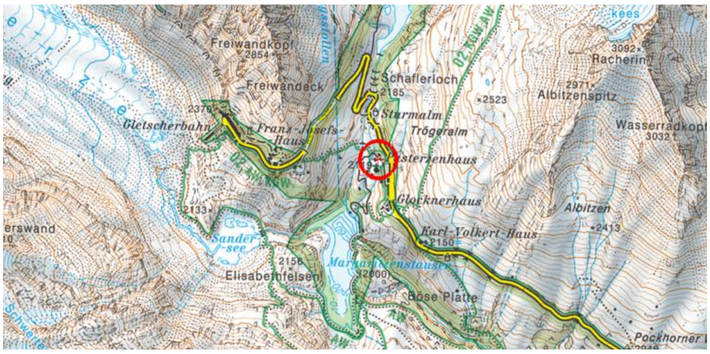


***Figure 2-7**: Pasterze Glacier with locations of peat samples (A) at the end of the glacier (B). Samples are pre-glacial and come from below the glacier (C). Photo by A. KELLERER-PIRKLBAUER, taken on the 25th of June, 2007 when 4 samples (labelled) were collected).*

Themes: Cover of the Valais oceanic crust (Bündnerschiefer), retreat of the Pasterze Glacier

Directions: House is located along the road from Heiligenblut to the end of the road at Franz-Josefs-Höhe



Stop 2-3 (circle) - *Pasterzenhaus*

Bedrock Geology: Outcrops of Bündnerschiefer calc-schist from a sequence some several hundred meters thick occur in the vicinity of the Pasterzehaus (map with circle). This aspect of the stop can be skipped if already seen at Stop 2-2.

Pleistocene Geology: The view from the Jungfernsprung or Kasereck includes a part of the Möll Valley that was carved during and just after the last ice age some 20,000 – 11,700 years ago (Würm). Among the many glacial features, the most prominent is undoubtedly the U-shape of the valley itself, as well as the stepped hanging valleys that have been incised by streams and waterfalls**.** The outdoor posters of the National Park Service on the terasse of the Pasterzenhaus have impressive historical pictures of the glacier at its most recent maximum (1856), as well as its ensuring retreat.

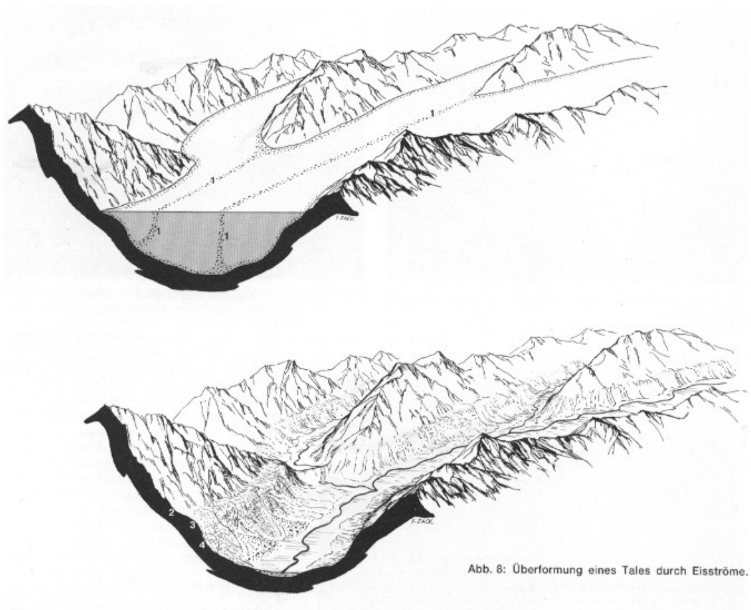


Abb. 8: Überformung eines Tales durch Eisströme.

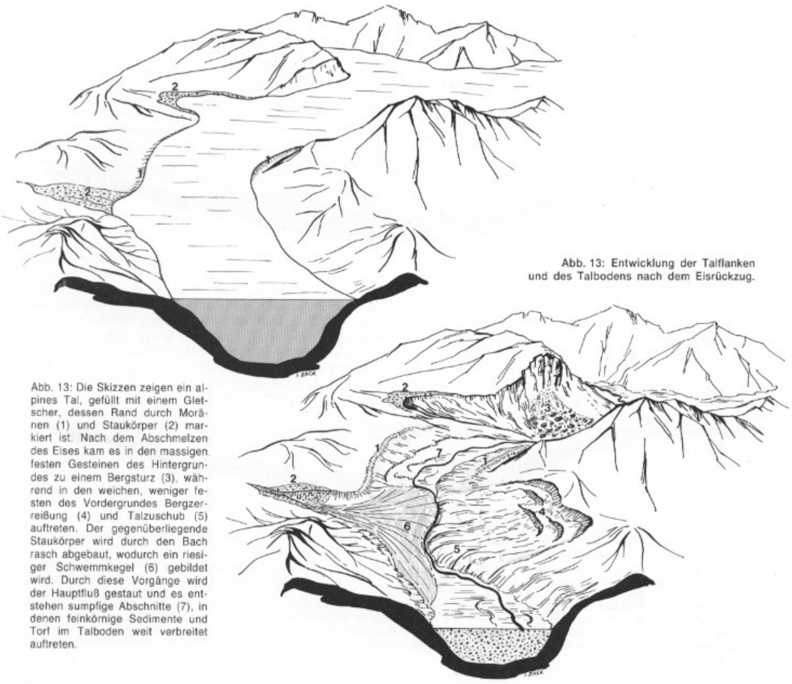


Abb. 13: Entwicklung der Talflanken und des Talbodens nach dem Eisrückzug.

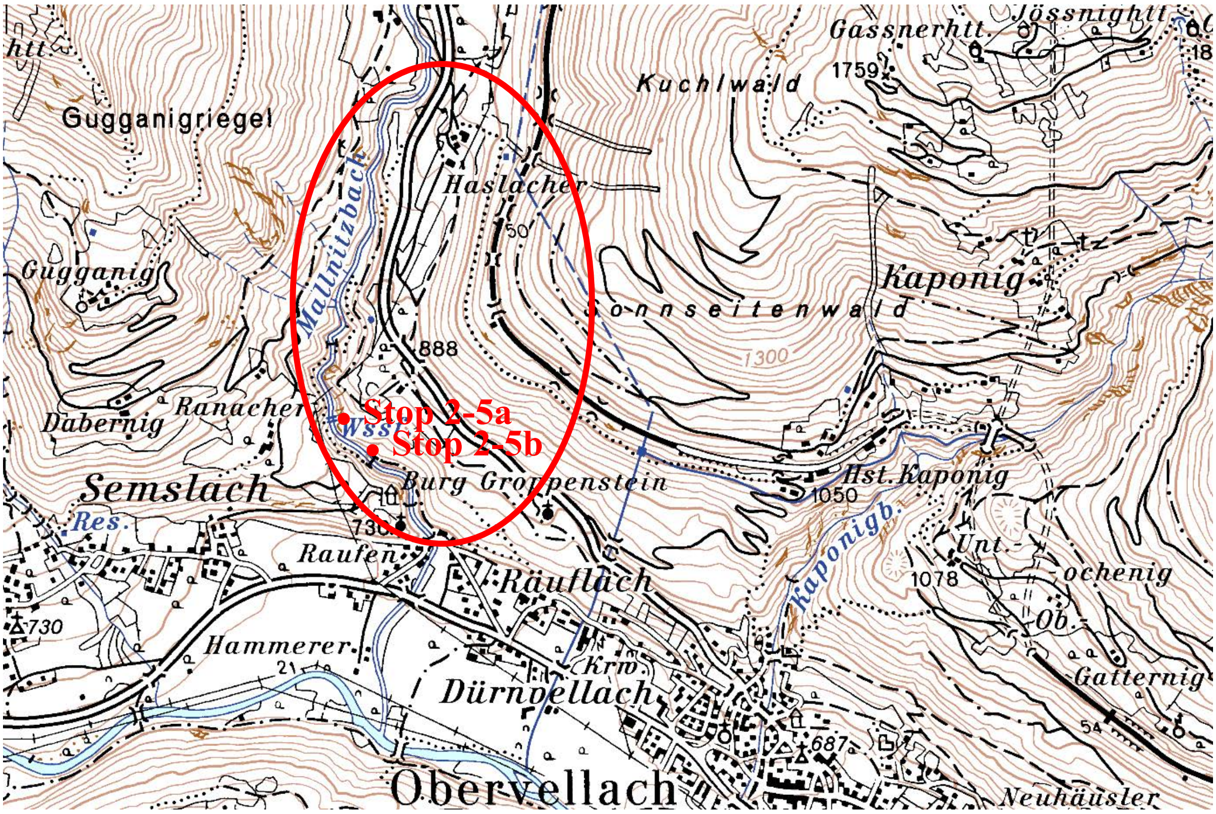
Abb. 13: Die Skizzen zeigen ein alpines Tal, gefüllt mit einem Gletscher, dessen Rand durch Moränen (1) und Staukörper (2) markiert ist. Nach dem Abschmelzen des Eises kam es in den massigen festen Gesteinen des Hintergrundes zu einem Bergsturz (3), während in den weichen, weniger festen des Vordergrundes Bergzerreißung (4) und Talzuschub (5) auftreten. Der gegenüberliegende Staukörper wird durch den Bach rasch abgebaut, wodurch ein riesiger Schwemmkegel (6) gebildet wird. Durch diese Vorgänge wird der Hauptfluß gestaut und es entstehen sumpfige Abschnitte (7), in denen feinkörnige Sedimente und Torf im Talboden weit verbreitet auftreten.

Fig. above After the glacier retreated, the valley experienced several big landslides and rockfalls, especially on its eastern side where the glacier gouged deeply, destabilizing the rock with its SW dipping main foliation. The alternation of metabasic rocks with permeable calc-schist further enhanced the erodability of the area. Landslides filled up a significant part of the formerly U-shaped valley, especially below the western flank of the Goldberg Group between the towns of Heiligenblut and Döllach.

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. 1-15**). A similar system of shear zones at the Brenner Normal Fault delimits the western end of the Tauern Window (**Fig. 1-15**). 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 the Figure to Stop 2-1.

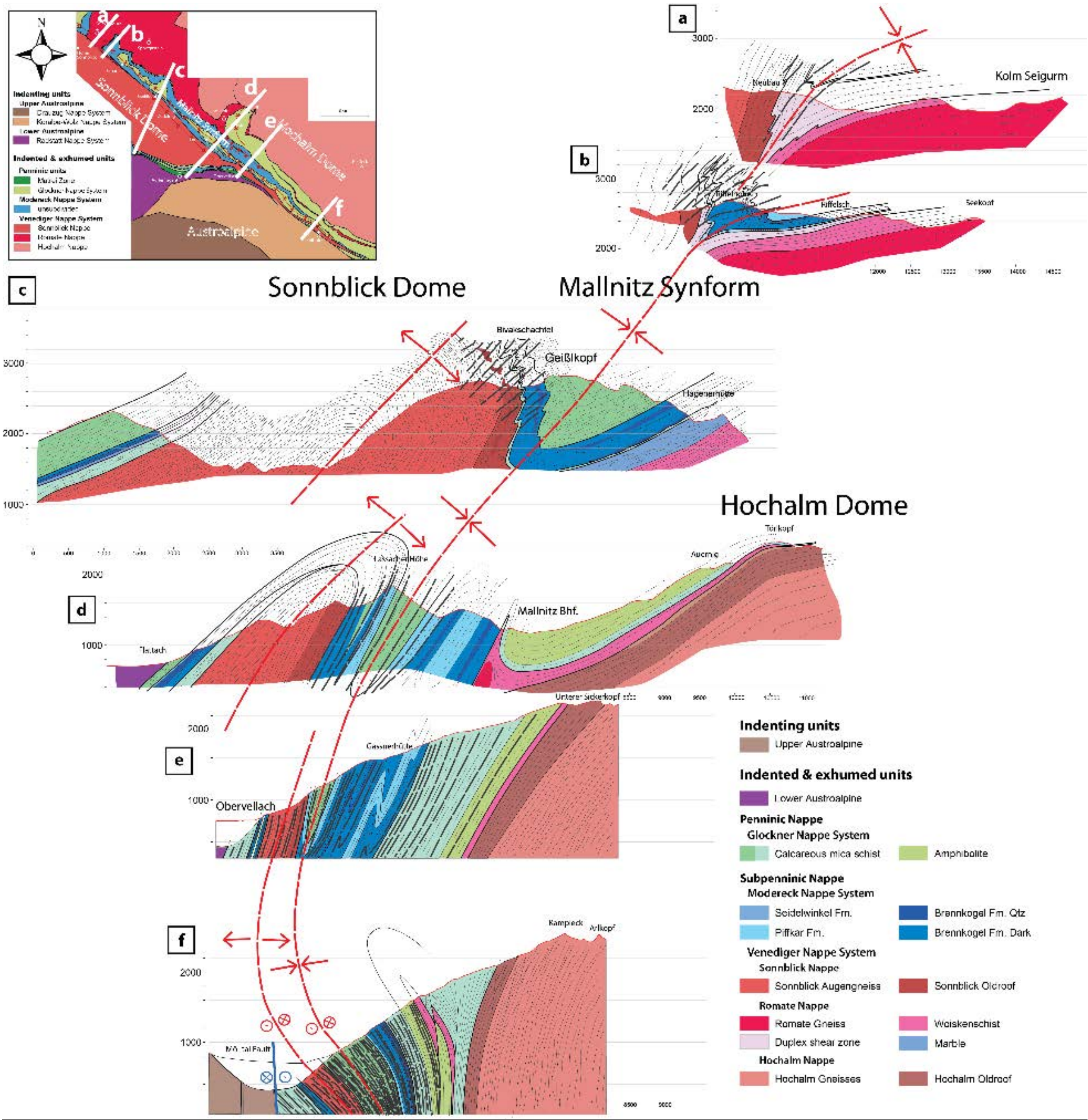


Figure 2-9*: Cross sections of Mallnitz Synform, Sonnblick and Hochalm Domes (inset map): Red dashed lines - traces of the F5 axial planes; black dashed lines - main S5 foliation. Older foliations indicated with grey lines. Note in (f) the opposite shear senses of indenting Austroalpine crust along the 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 1-16**. 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. 1-15, 1-16**). We relate this thinning to northward indentation of the rigid Austroalpine Drau-Möll Block exposed on the southwestern side of the Möll Valley (**Fig. 1-15**).

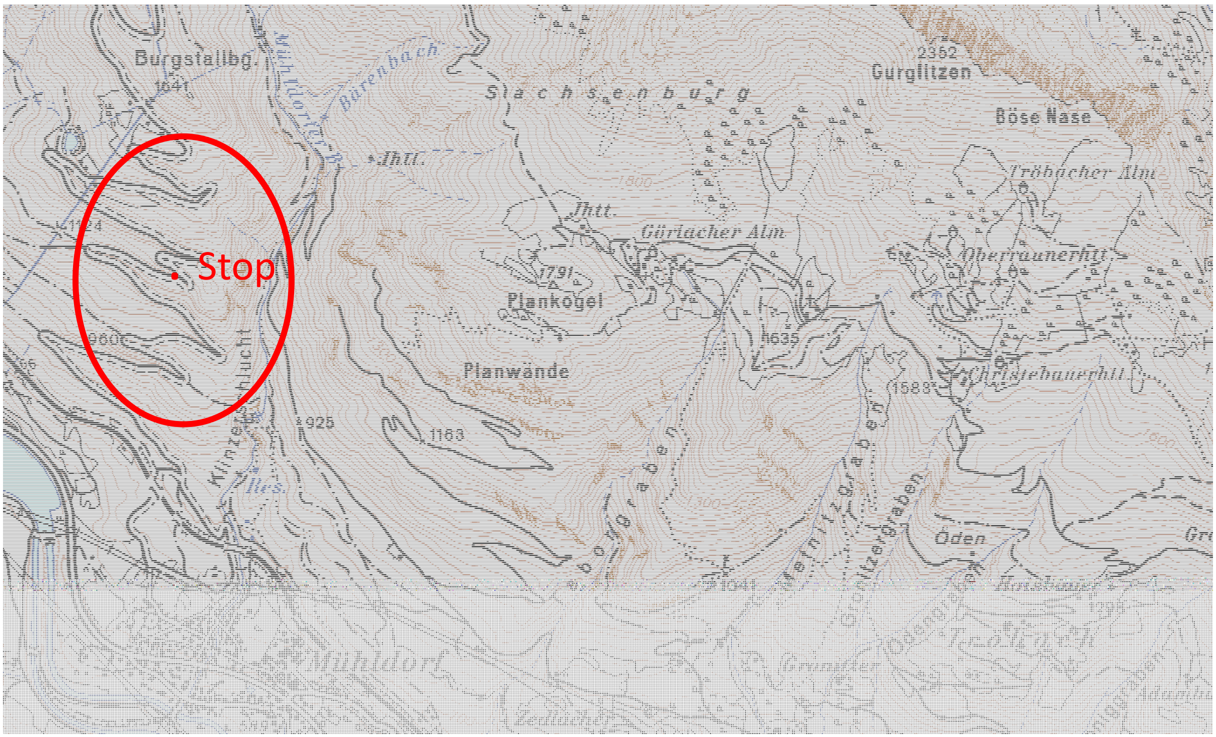
Cross the bridge and continue up the steep, winding path along the southern bank of the Mallnitz stream. Where the path steepens, one crosses the subvertical contact of schists of the Brennkogel Fm with the gneisses and schists of the Sonnblick basement. This contact is the roof thrust of the D4 Venediger 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?).

Stop 2-6: 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).

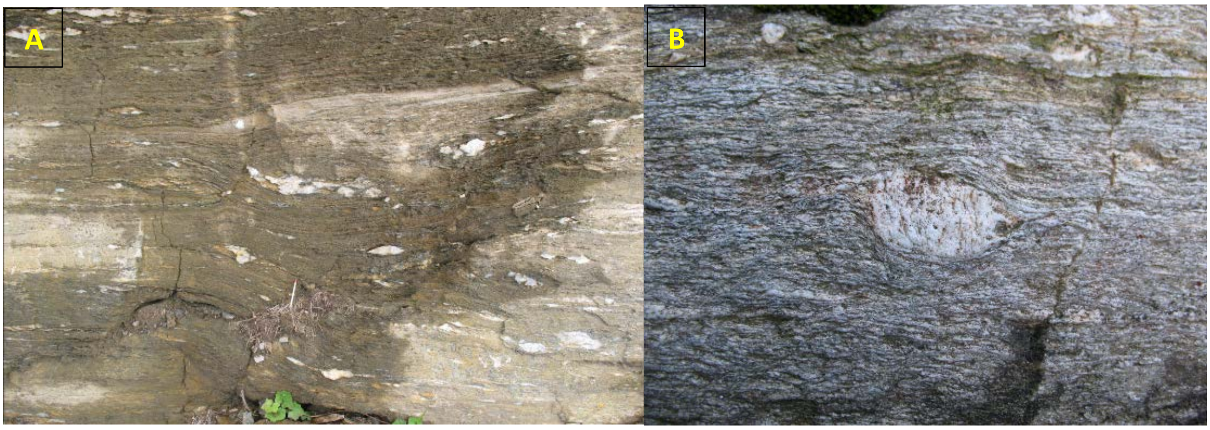
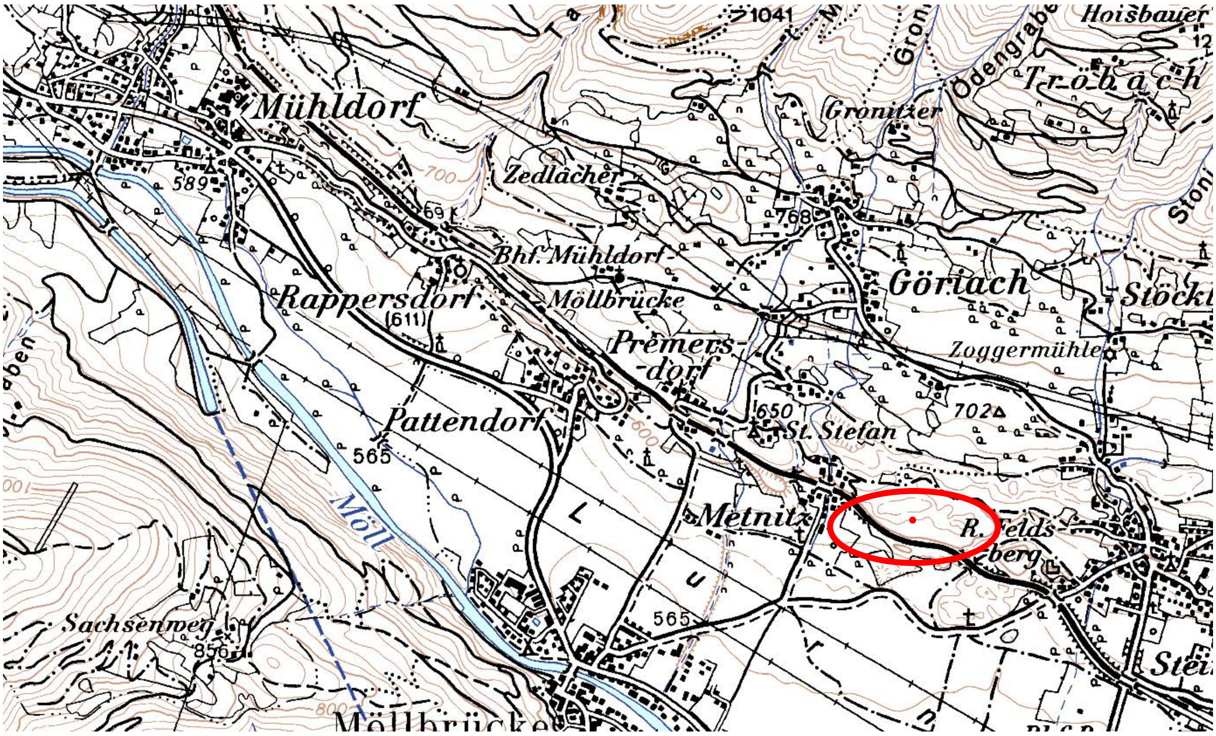


***Figure 2-10**: (A) Intrafoliational boundins with asymmetry and rotation indicating sinistral shear sense in calc-schist (Bündnerschiefer) of the Glockner Nappe system; Outcrop along road to Burgstallberg on NE side of the Möll Valley; (B) Rotated feldspar clast in granitoid of the Sonnblick Lamellae;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

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.

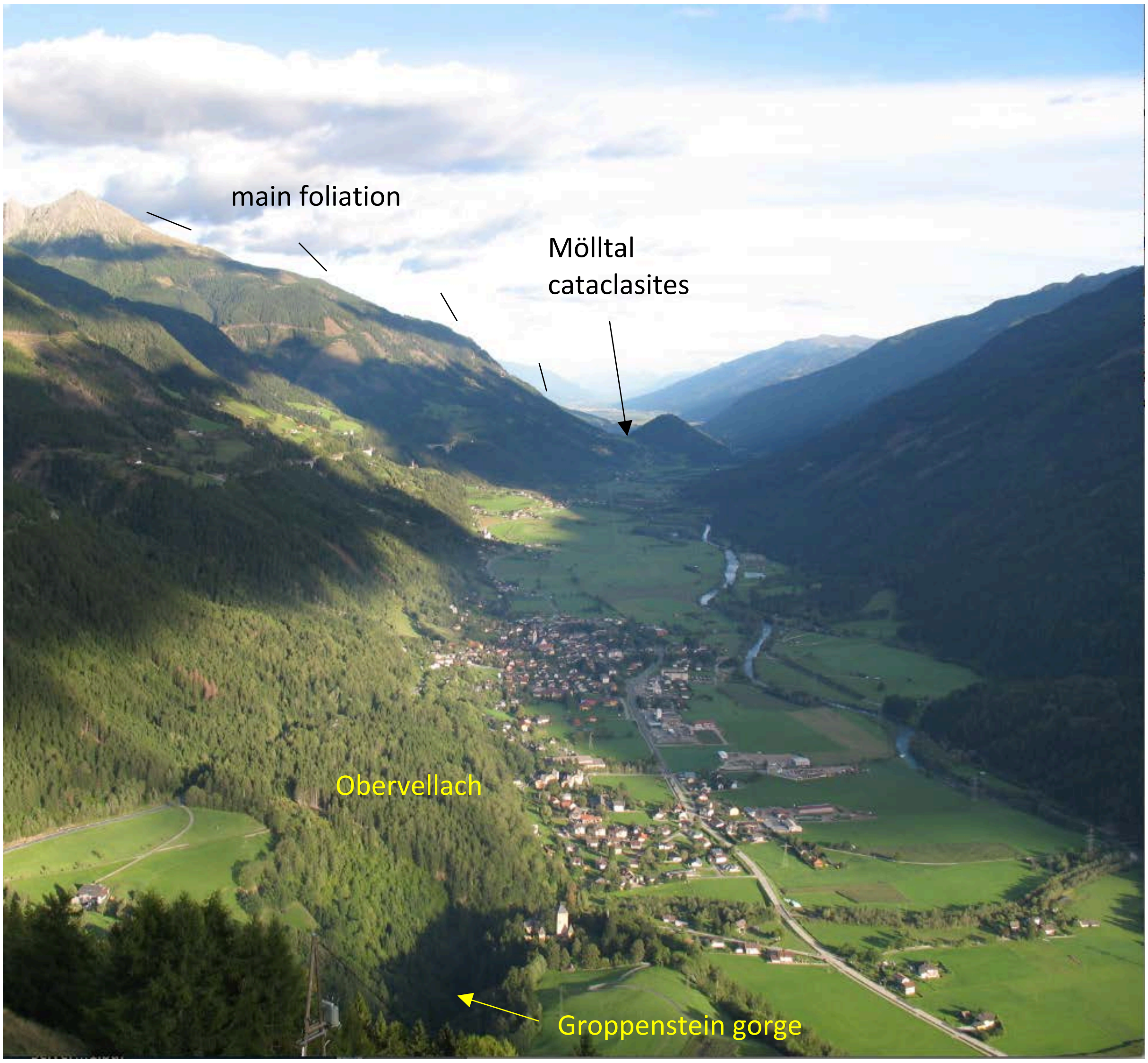


***Figure 2-11**: View to SE along the Möll Valley, a glacial valley running parallel to the dextral Mölltal strike-slip fault separating the Austroalpine crust (right) from the exhumed Penninic Sonnblick Lamella and Venediger Nappe complex (left). Note landslides reaching the valley floor.*

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.

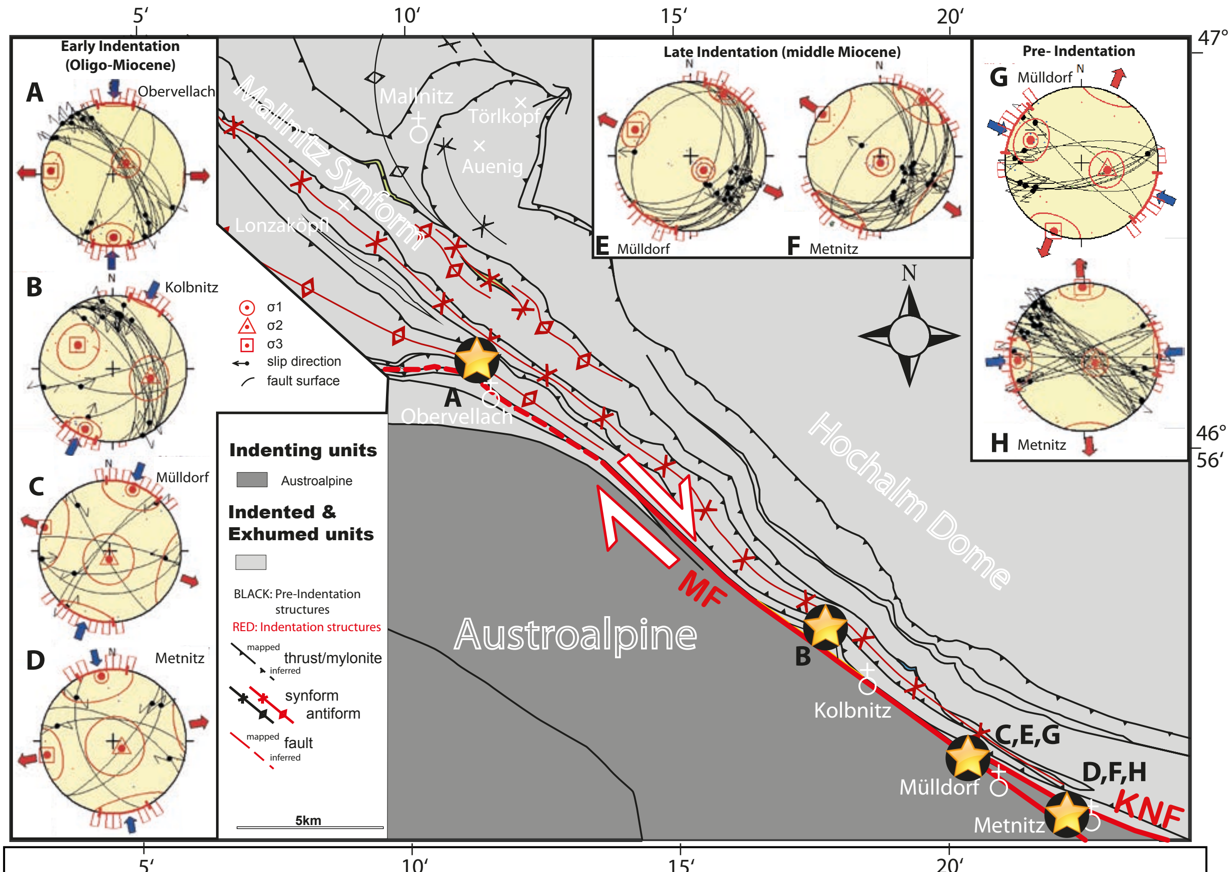
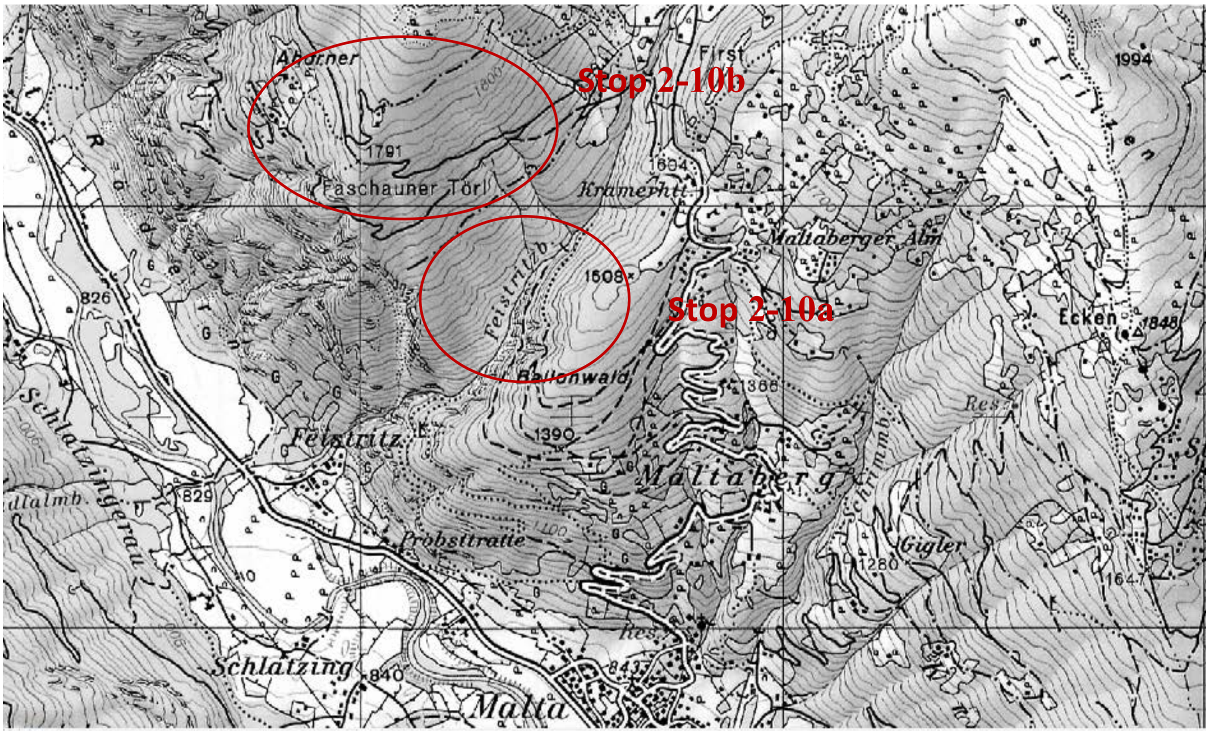


Figure 2-12: P-T-B analysis of brittle fault planes along the Mölltal Fault that overprint mylonite of the southern branch of the KNF. (A) Brittle deformation of Sonnblick Lamella near Obervellach; (B) brittle deformation in the Glockner Nappe System near Kolbnitz: (C, E, G) cataclasites in lower Australpine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

<u>Stop 2-10</u>: Katschberg Normal Fault in the Malta Valley

Themes: low-angle normal faulting, crustal thinning and exhumation

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).



***Stop 2-10**: Topographic map and stop location (circled)*

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 its footwall: 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.

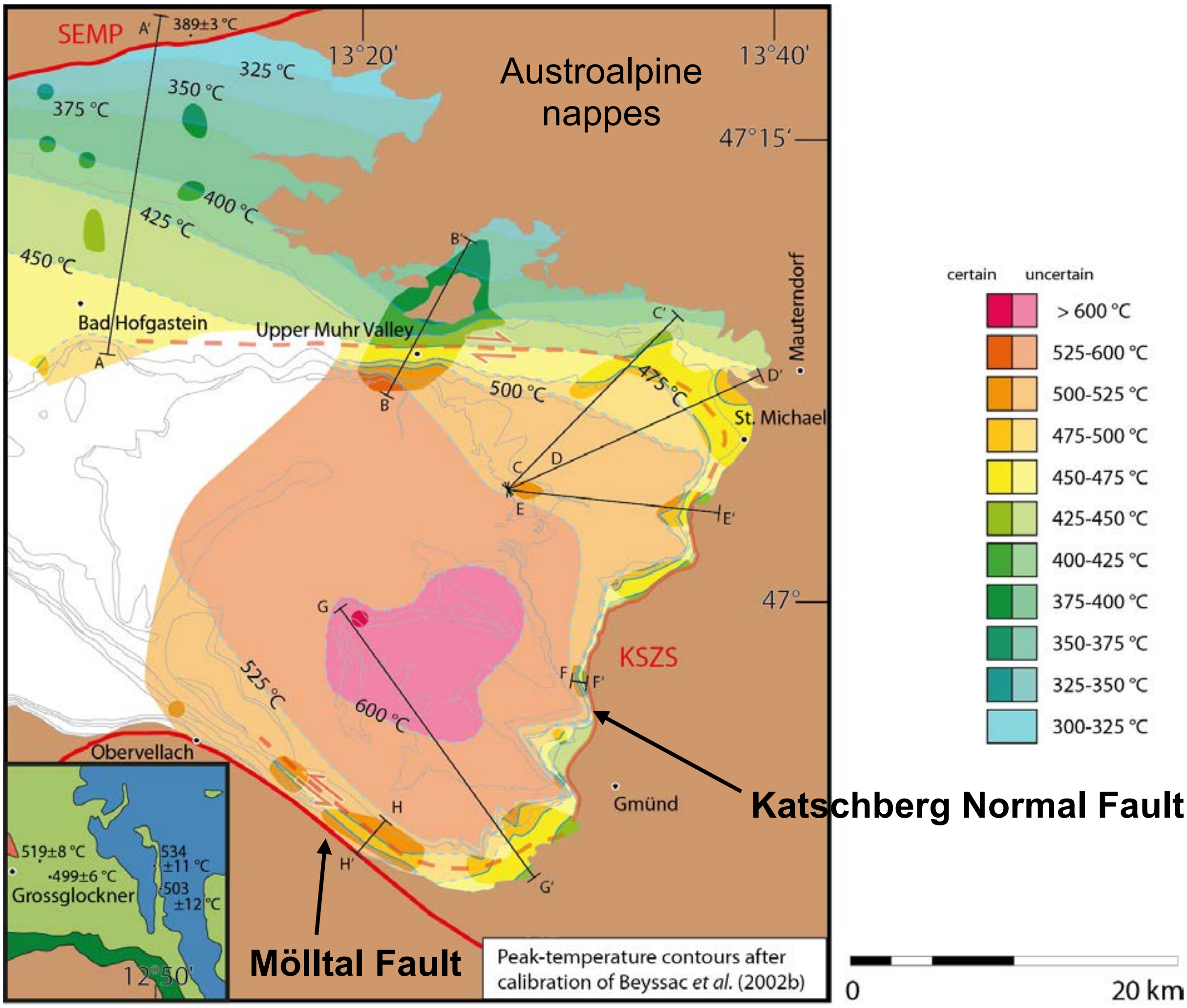


Figure 2-14*: Peak-temperature contours of the Eastern Tauern Dome (SCHARF ET AL. 2013b) based on the calibration of BEYSSAC ET AL. (2002b) for CM. Transparent colours and dashed lines indicate areas and contours where the sample density is low, solid colours where sample density is high. Brown = Austroalpine 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. 1-15, 1-16**). 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.

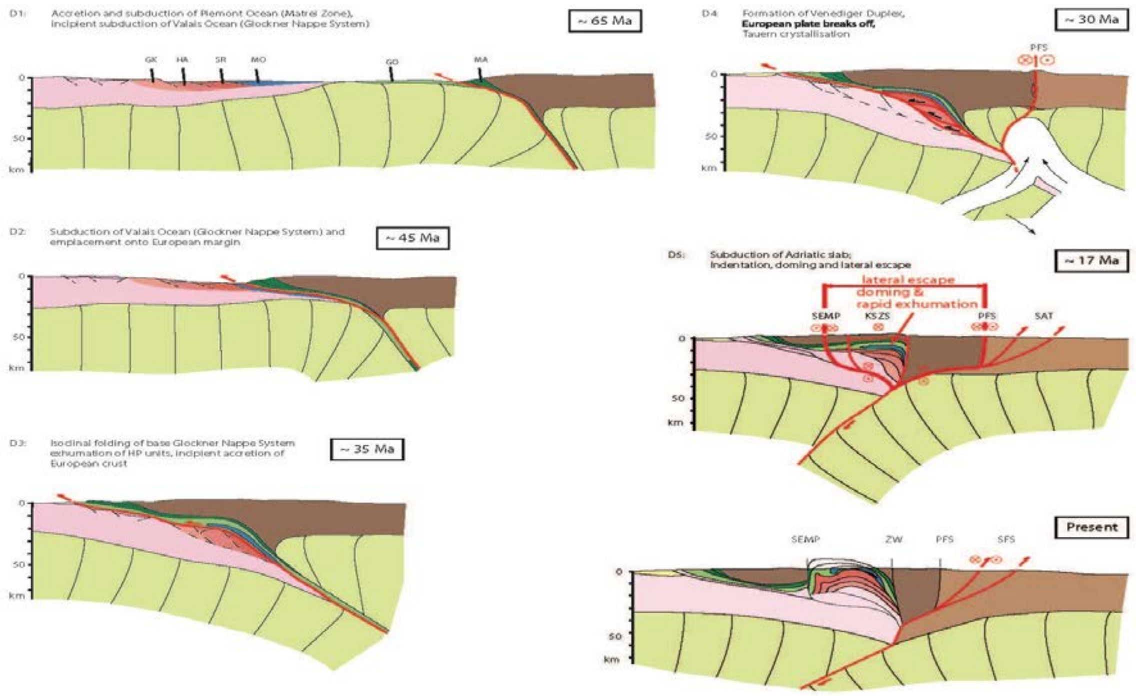
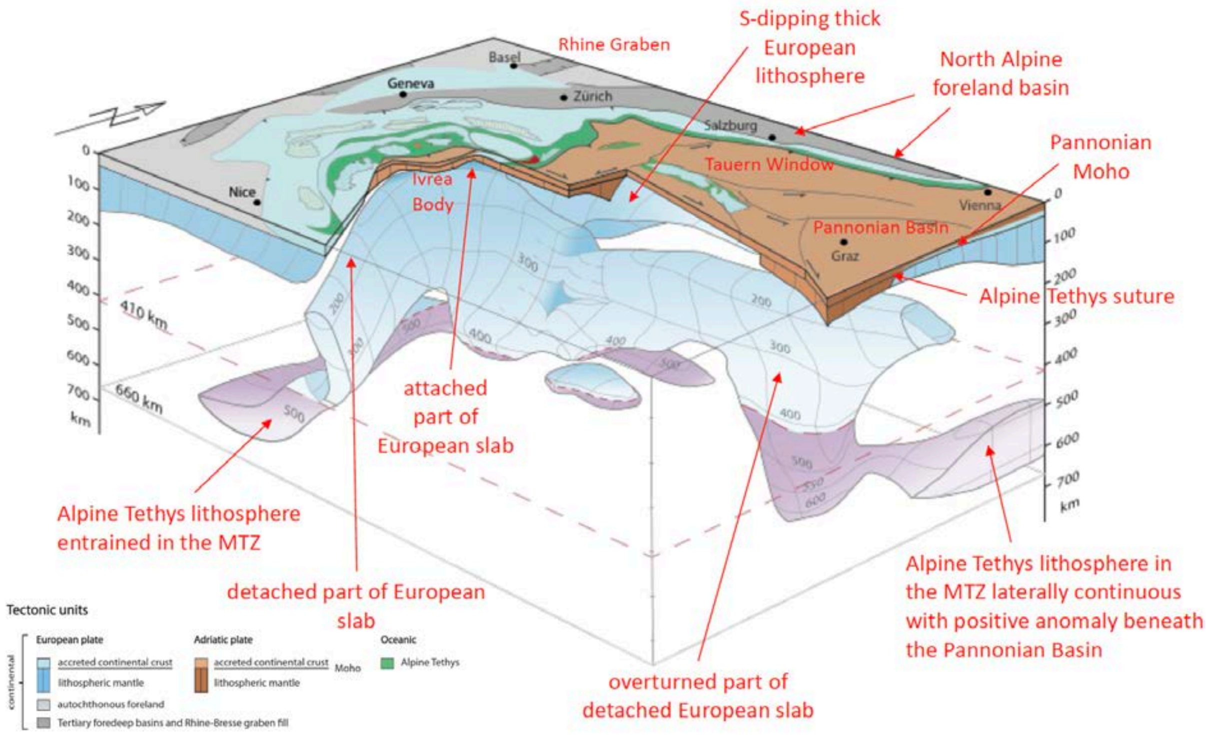


Figure 2-15a *(above): Tectonic synthesis of the Alpine orogen along a N-S cross section of the transect on this field trip (modified from HANDY ET AL., 2015; SCHMID ET AL., 2013, based on LIPPITSCH ET AL. 2003). Crustal units have same colours as in Figs. 1-15, 1-16.*
Figure 2-15b *(below): Interpretation of slab geometry in the Alps in light of AlpArray (HANDY ET AL., 2021). The north-dipping slab beneath the Eastern Alps is interpreted to be European rather than Adriatic lithosphere and to have delaminated and detached in Miocene time.*



Day 3: Periadriatic Faulting, active Adria-Europe convergence

Route: Spittal-an-der-Drau 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 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

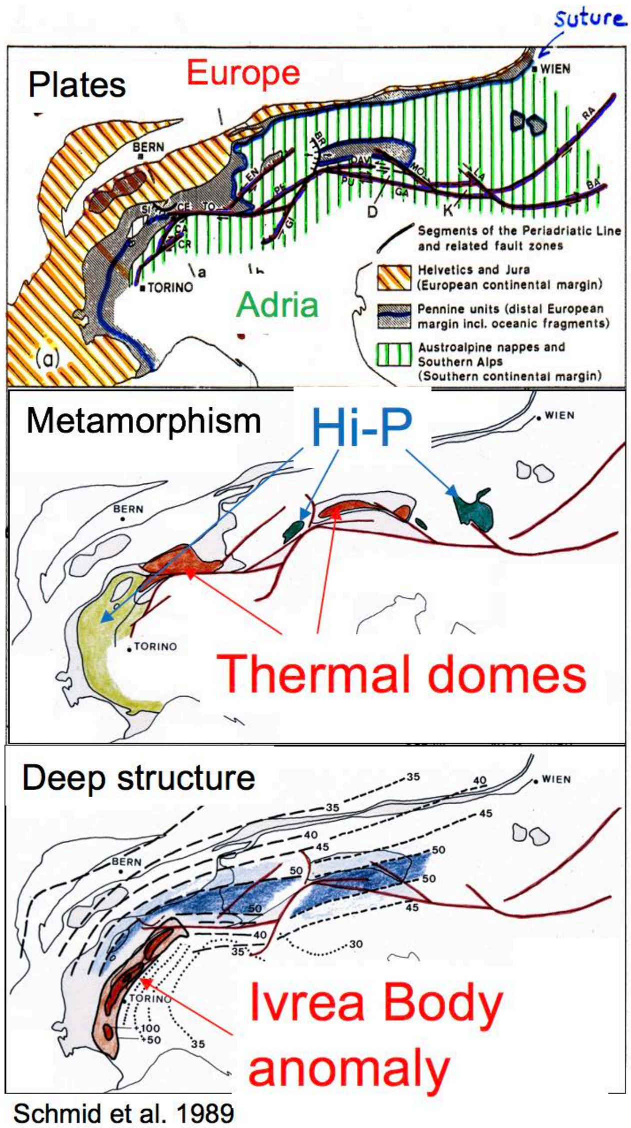


Figure 3-1: Periadriatic Fault System (dark red) and its relationship to the Mesozoic-Paleogene tectonic plates (top), Alpine metamorphism (middle) and deep structure (Moho and gravity anomalies, bottom) after SCHMID ET AL. 1989.

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)

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 (**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.

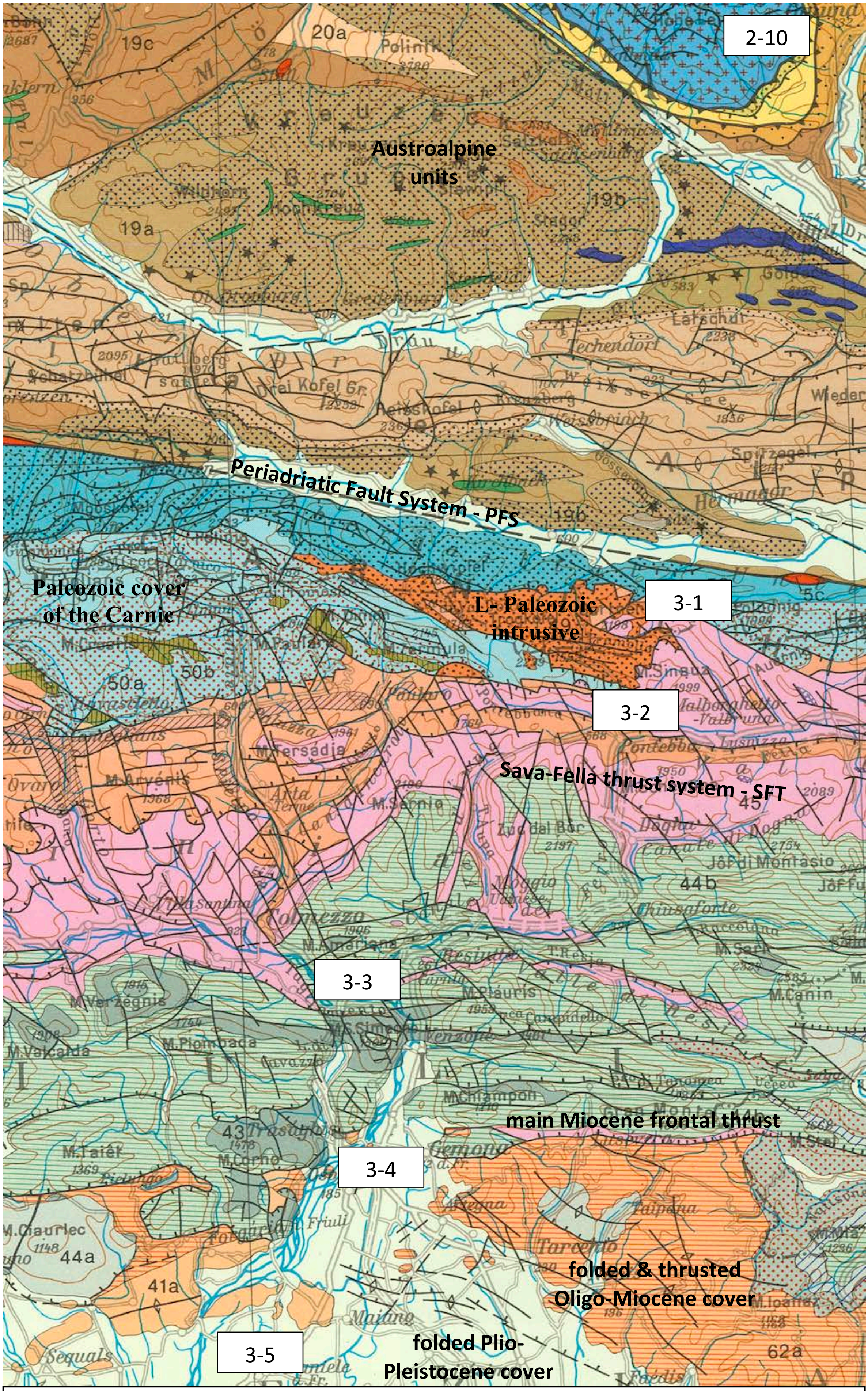


Figure 3-2: *Structural Map of Italy (BIGI ET AL. 1981) showing the Periadriatic Fault System (PFS) and subsidiary faults thereof, the Sava-Fella thrust (SFT), and folds and thrusts of the Southern Alps affecting the Oligo-Miocene and Plio-Pleistocene cover of the Veneto Plain. Numbers indicate stops.*

Stop 3-1b: 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.

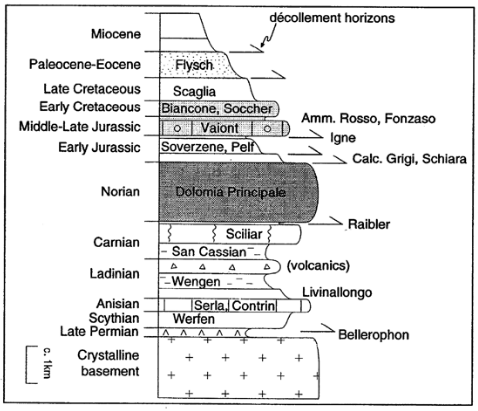


***Figure 3-3**: Generalized stratigraphy of the Southern Alps (from Fig. 6 of SCHÖNBORN 1999). Detachment layers indicated with arrows. Note that thickness and facies of l.-m. Jurassic layers vary significantly.*

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 was formerly attributed to a change in subduction polarity from S- to N-directed after detachment of the European slab in Oligocene and again in Miocene time (HANDY ET AL. 2015). However, in light of the seismological images from AlpArray (see refs in the Introduction) we now interpret the polarity change to a change in the dynamics of the orogenic wedge during Miocene breakoff of the European slab (HANDY ET AL. 2022).

Outcrop: This is the starting point for a hike 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.

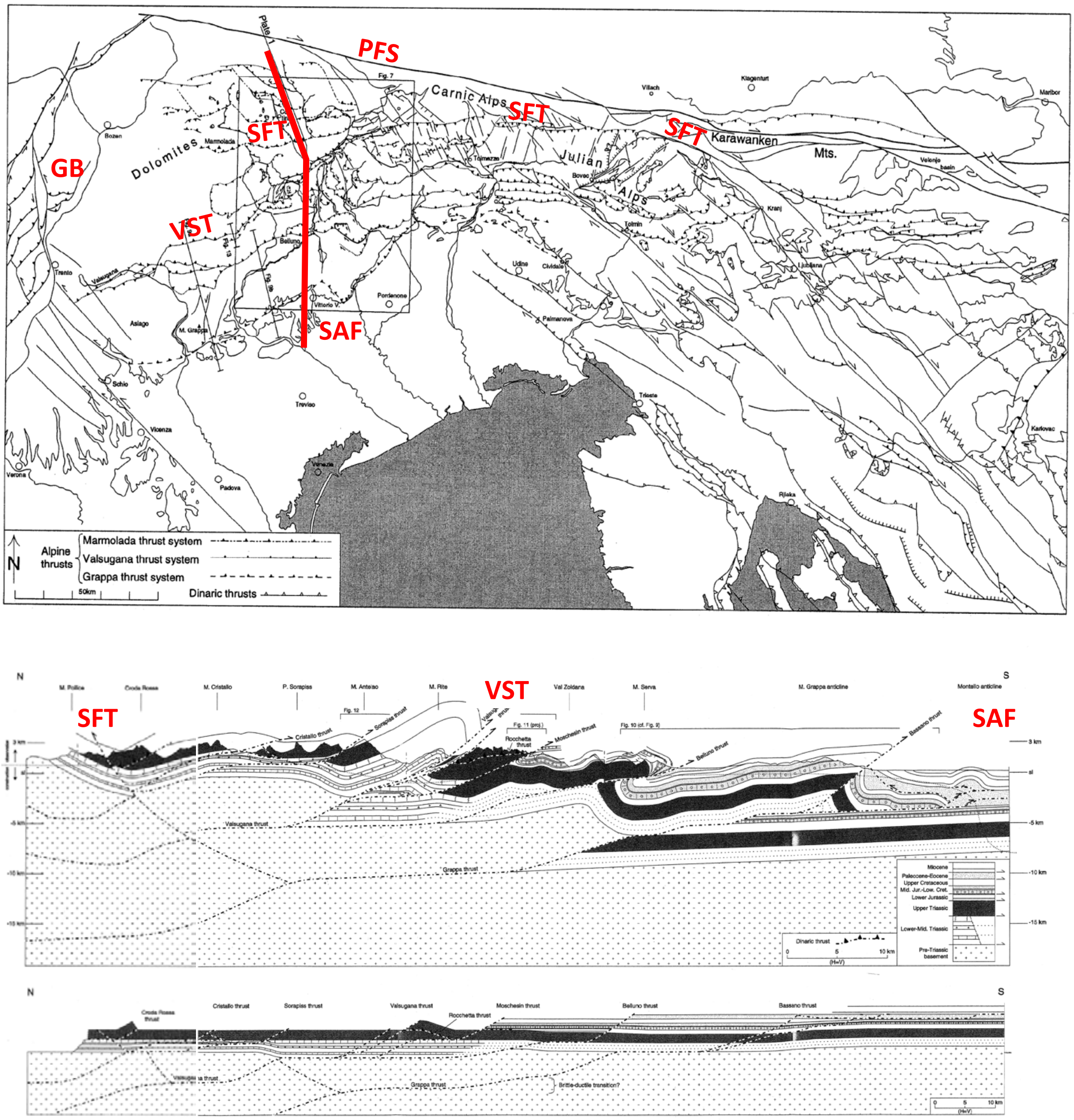


Figure 3-4: *Map (top) and cross section (middle) of the Southern Alps along red trace marked in map. Modified from Fig. 2 and Plate 1 in SCHÖNBORN (1999). Minimum shortening based on line-length balancing of sedimentary layers is 50 km (bottom). PFS – Periadriatic Fault System, SFT – Sava-Fella thrust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

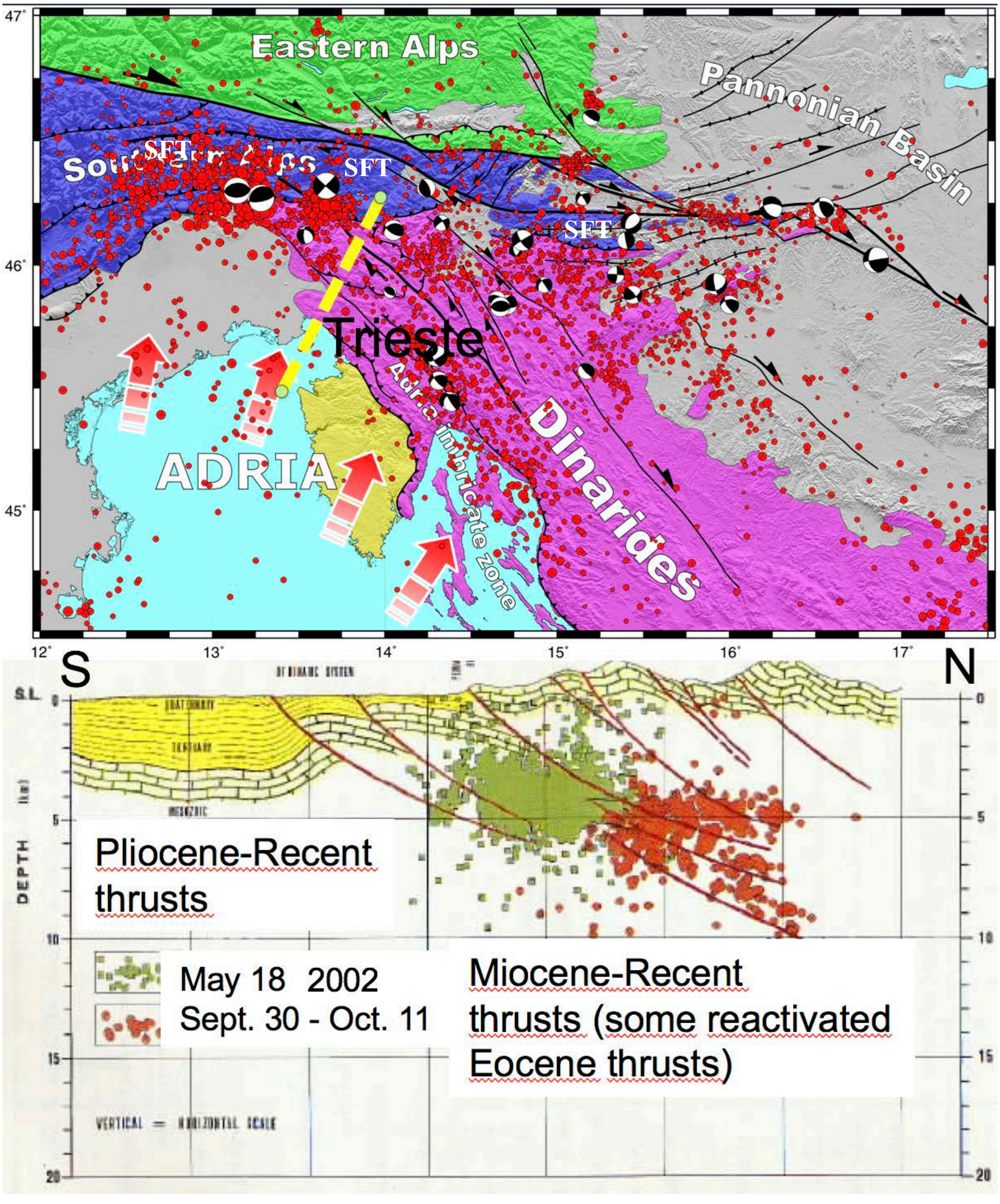


***Figure 3-5**: Seismo-tectonic map of the Southern and Eastern Alps, and the northern Dinarides from VRABEC ET AL. 2006; Cross section of seismically active part of Southern Alps from MERLINI ET AL. 2002 (section along yellow dashes in map). SFT – Sava-Fella Thrust*

<u>Stop 3-2</u>: 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 at cemetery for view to the E **(**N46°30' 32.39'', E13° 18' 09.96" is only good if climb very steep hill behind the cemetery) 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**).

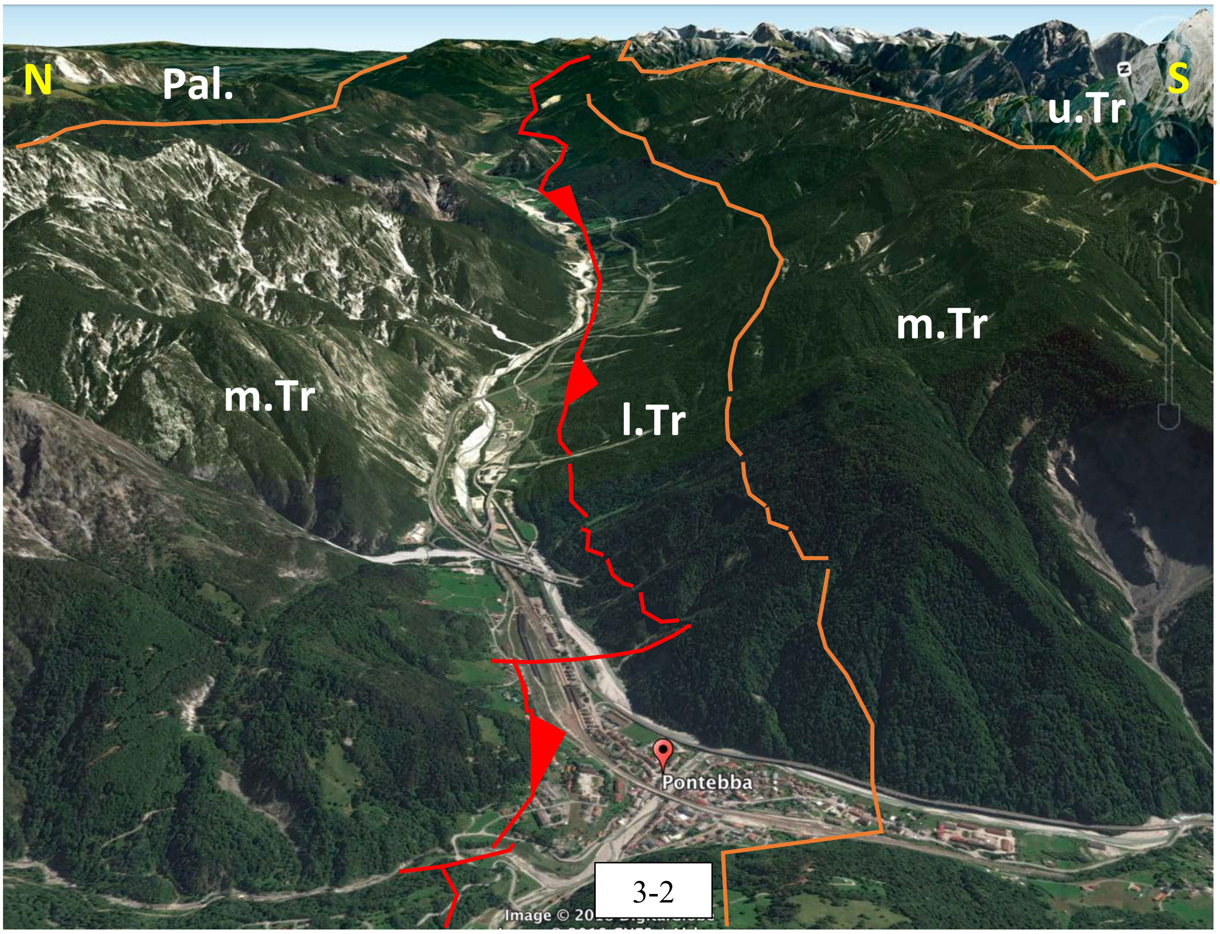


Figure 3-6*: View to ESE along the Sava-Fella Fault in the upper Val Tarvisio (Tagliamento River valley) of the Southern Alps.*

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 (**Figs. 3-7, 3.8**). This section is interesting because the thrusting direction is to the S, typical for Miocene transport direction in the eastern Southern Alps. However, the Eo-Oligocene flysch in the footwall of the lowest thrust (Fig. 3-8) is typical for Paleogene "Dinaric" thrusting to the SW. A possible explanation for this discrepancy is that the Dinaric thrust has been rotated into a Southern Alpine orientation.

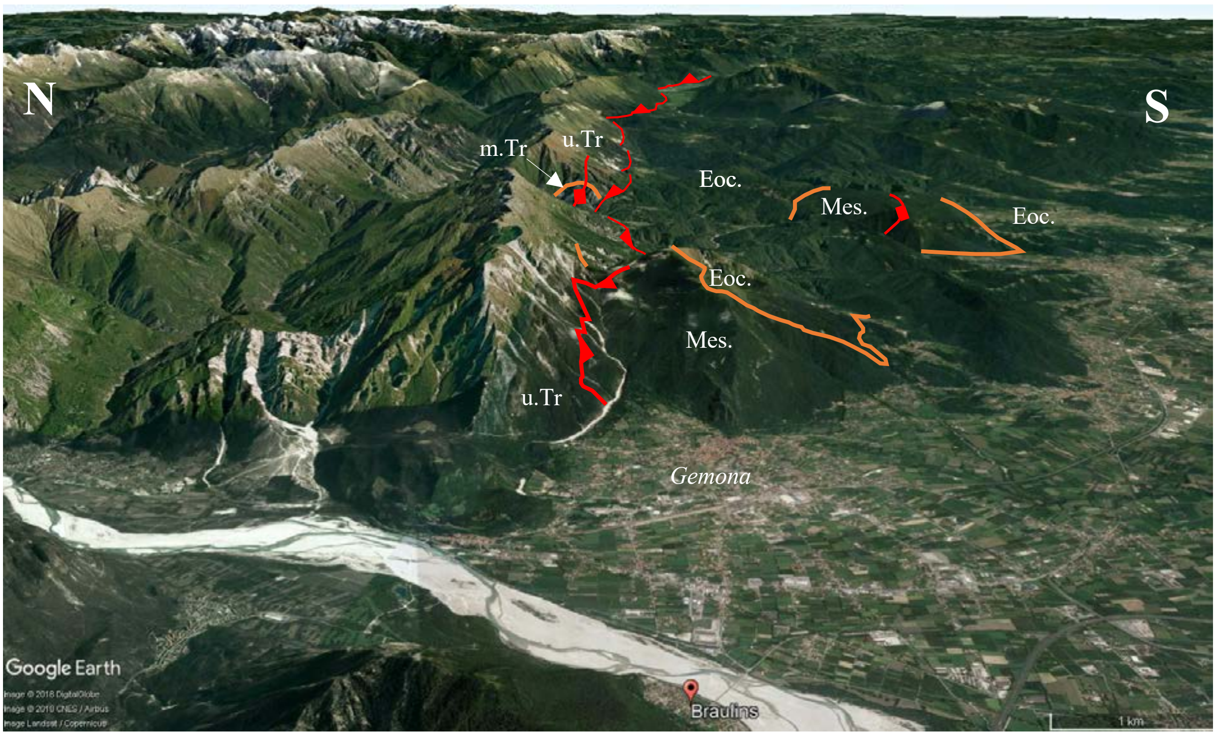


***Figure 3-7**: View to E of Southern Alps along the upper Tagliamento River with stops at* Tolmezzo and/or Simeone *to see folds (left) and at Gemona for frontal thrust of Mesozoic strata onto Tertiary flysch (right).*

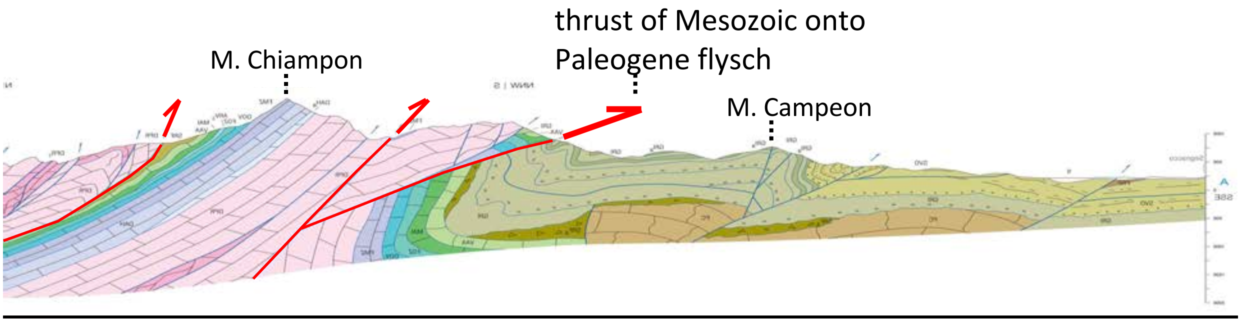


Figure 3-9: Geological cross section of the view to the E from the west bank of the Tagliamento River near Trasaghis (stop 3-4). Folie 49 "Gemona, Geological map of Italy.

Stop 3-5: Pleistocene (active) faulting

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

Outcrop: The Tagliamento River is diverted by a N-directed thrust in Miocene flysch to Pleistocene river (Fig. 3-9). The hill (M. Ragagno) is the morphological expression of large S-vergent anticline that deforms Tortonian-to-Messinian layers in the hangingwall of a thrust onto Plio-Pleistocene sediments (Fig. 3-10). The farmland to the E of M. Ragagno is the site of an older river channel that was abandoned when the antiform formed. This area is near the epicentre of the 1976 Friaul earthquake (Fig. 3-11).

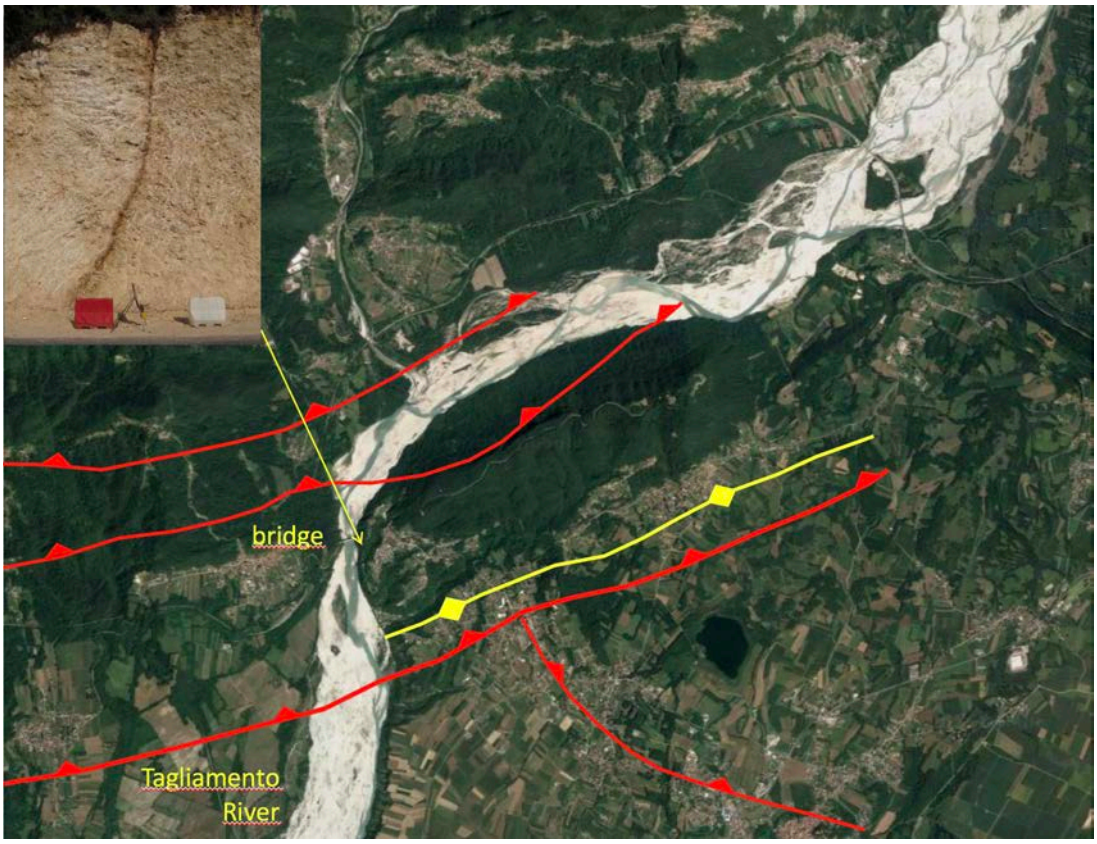


Figure 3-9: Tectonically induced bend in the Tagliamento River between the towns of Pinzano and San Pietro. Inset shows road outcrop with faulted Pleistocene now hidden behind netting on the E side of bridge.

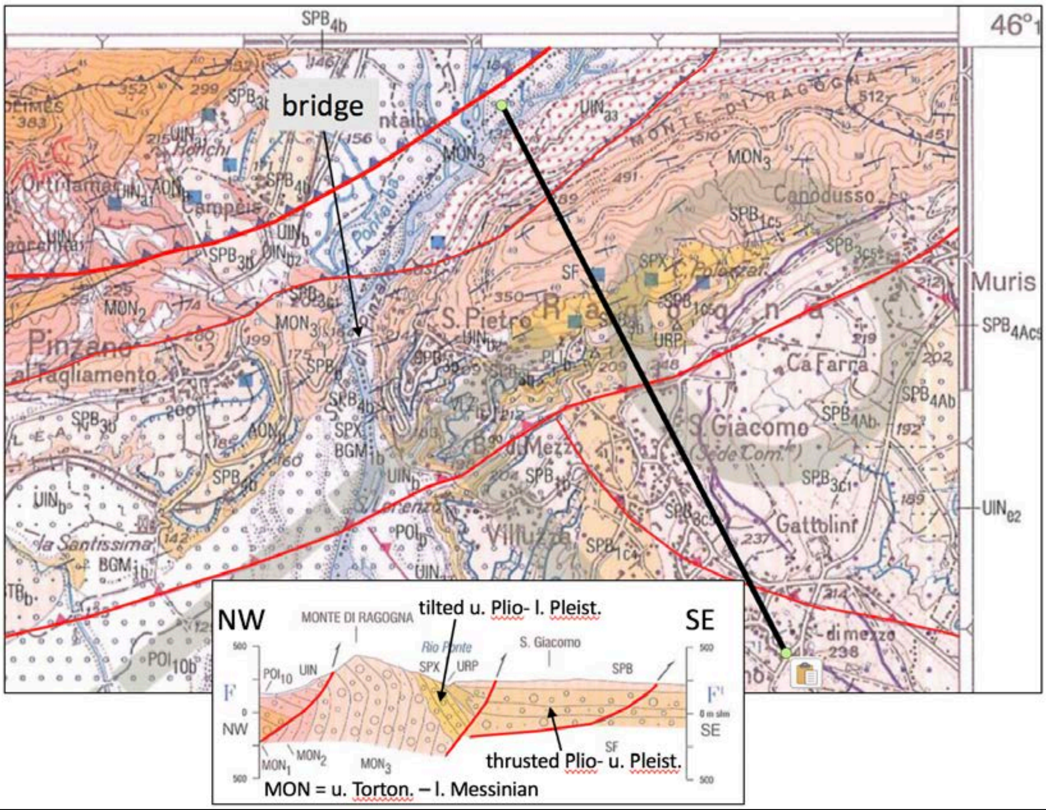


Figure 3-10: *Geological map and cross section of area around bridge across the Tagliamento River between the towns of Pinzano and San Pietro. Cross section of uplifted area at M. Ragogno east of the bridge. Map is screenshot from Foglie 65 "Maniago", Geological Map of Italy.*

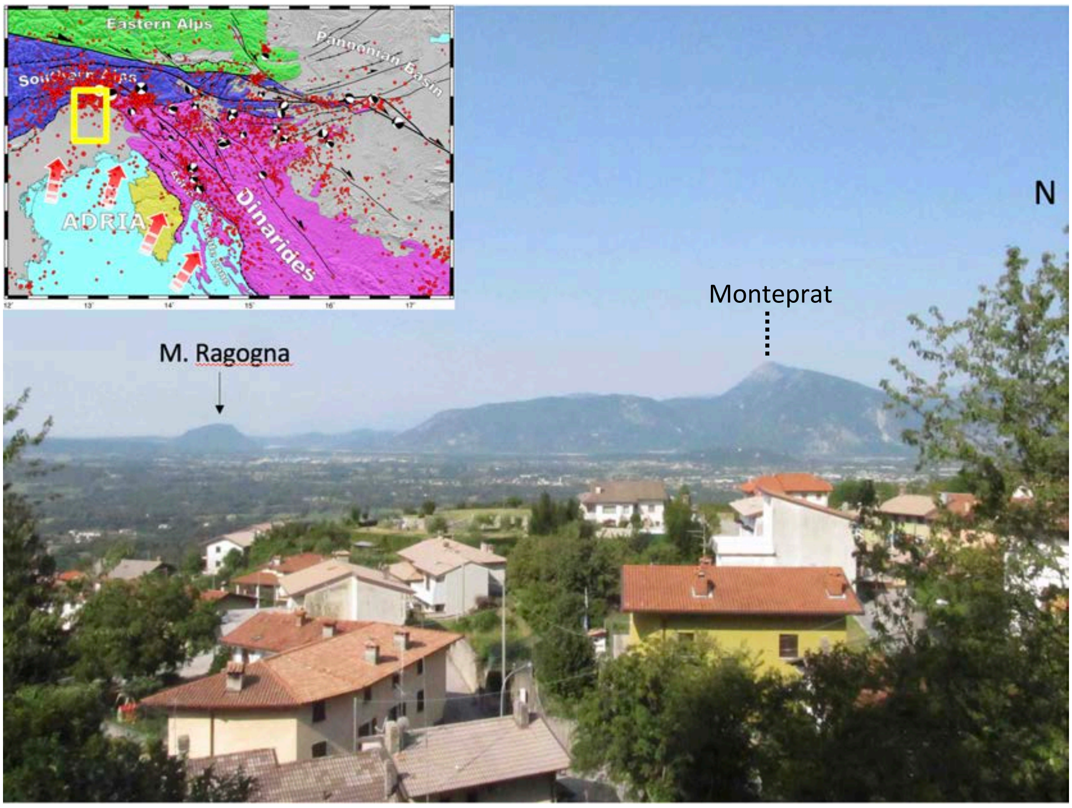


Figure 3-11: *View to the east from Gemona, the epicentre of the Friaul M 6.5 event of May 6, 1976 that killed 989 people. Note M. Ragogna in the distance (stop 3-5). Inset shows that the area is located at the site of head-on convergence between Adria and Europe.*

Overnight in Tarcento Albergo Al Tarcentino
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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, G., Castellarin, A., Coli, M., Dal Piaz, G.V., Sartori, R., Scandone, P. (1990a). Structural model of Italy sheet 1, 1:500000. Consiglio Nazionale delle Ricerche, Progetto Finalizzato Geodinamica, SELCA Firenze

Bigi, G., Castellarin, A., Coli, M., Dal Piaz, G.V., Vai, G.B. (1990b). Structural model of Italy sheet 2, 1:500000. Consiglio Nazionale delle Ricerche, Progetto Finalizzato Geodinamica, SELCA Firenze

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

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, L., Nagymarosy, A., Horváth, F. & Kovác, M., (1992). Tertiary evolution of the intra-Carpathian area: a model, *Tectonophysics*, 208, 221–241.

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, C. (1987). Tectonics of the Dolomites (Southern Alps, Northern Italy). J. Struct. Geol., 9, 2, 181–193

Doglioni, C., Bosellini, A. (1988). Eoalpine and mesoalpine tectonics in the Southern Alps. Geol. Rundschau, 76, 735-754.

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. (2017). Changing patterns of exhumation and denudation in front of an advancing crustal indenter, Tauern Window (Eastern Alps). *Tectonics,* 36, 1053-1071, doi: 10.1002/2016TC004448

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.

Fodor, L., Jelen, B., Marton, E., Skaberne, D., Čar, J., Vrabec, M. (1998). Miocene–Pliocene tectonic evolution of the Slovenian Periadriatic fault: implications for Alpine–Carpathian extrusion models. *Tectonics*, 17, 5, 690–709

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.

Groß, P., Pleuger, J., Handy, M.R., Germer, M., John, T. (2020): Evolving temperature field in a fossil subduction channel during the transition from subduction to collision (Tauern Window, Eastern Alps). *Journal of metamorphic Geology*, 00, 1–23, DOI: 10.1111/jmg.12572

Groß, P., Handy, M.R., John, T., Pestal, G., Pleuger, J. (2020): Crustal-scale sheath folding at HP conditions in an Exhumed Alpine Subduction Zone (Tauern Window, Eastern Alps). *Tectonics*, 39, doi: 10.1029/2019TC005942

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.

Handy, M.R., Schmid, S.M., Paffrath, M., Friederich, W. and the AlpArray Working Group (2021): Orogenic lithosphere and slabs in the greater Alpine area - Interpretations based on teleseismic P-wave tomography. *Solid Earth*, 12, 2633-2669, https://doi.org/10.5194/se-12-2633-2021

Handy, M.R. (2022). A new model of slab detachment in the Alps and its geodynamic consequences. EGU22-13517, https://doi.org/10.5194/egusphere-egu22-13517, EGU General Assembly 2022, Vienna, Austria

Hetényi, G., Plomerová, J., Bianchi, I., Kampfová Exnerová, H., Bokelmann, G., Handy, M.R., Babuškae, V. (2018): AlpArray-EASI Working Group From mountain summits to roots: Crustal structure of the Eastern Alps and Bohemian Massif along longitude 13.3°E. *Tectonophysics,* 744, 239-255.

Hetényi, G. Molinari, I., Clinton, J., Bokelmann, G., Bondár, I., Crawford, W.C., Dessa, J.X., Doubre, C., Friederich, W., Fuchs, F., Giardini, D., Gráczer, Z., Handy, M.R., Herak, M., Jia, Y., Kissling, E., · Kopp, H., Korn, M., · Margheriti, L., Meier, T., Mucciarelli, M., Paul, A., Pesaresi, D., Piromallo, C., Plenefisch, Th., Plomerová, J., Ritter, J., Rümpker, G., · Šipka, V., Spallarossa, D., Thomas, Ch., Tilmann, F., Wassermann, J., · Weber, M., Wéber, Z., Wesztergom, V., Živčić, M., AlpArray Seismic Network Team , AlpArray OBS Cruise Crew, AlpArray Working Group. (2018): The AlpArray Seismic Network: A Large-Scale European Experiment to Image the Alpine Orogen. *Surveys in Geophysics*, https://doi.org/10.1007/s10712-018-9472-4

Hinsch, R. (2013). Laterally varying structure and kinematics of the Molasse fold and thrust belt of the Central Eastern Alps: Implications for exploration. *AAPG Bulletin*, 97, 10, 1805– 1831. DOI:10.1306/04081312129

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.

Ji, W. Q., Malus., M. G., Tiepolo, M., Langone, A., Zhao, L., & Wu, F. Y. (2019). Synchronous Periadriatic magmatism in the Western and Central Alps in the absence of slab breakoff. *Terra Nova*, 31(2), 120–128.

Jozi Najafabadi, A., Haberland, C., Verwater, V., Le Breton, E., Handy, M.R., Heit, B., Weber, M. and the AlpArray Working Group (2022): Crustal and Upper Mantle Structure of the Eastern and Eastern Southern Alps: Evidence from Vp and Vp/Vs Local Earthquake Tomography. *Journal of Geophysical Research: Solid Earth*, 127, e2021JB023160. https://doi.org/10.1029/2021JB023160

Kind, R., Schmid, S. M., Yuan, X., Heit, B., Meier, T., and the AlpArray and AlpArray-SWATH-D Working Groups (2021). Moho and uppermost mantle structure in the greater Alpine area from S-to-P converted waves, Solid Earth Discuss. [preprint], https://doi.org/10.5194/se-2021-33

Kummerow, J., Kind, R., Oncken, O., Giese, P., Tyberg, T., Wylegalla, K., Scherbaum, F., TRANSALP Working Group (2004). A natural and controlled source seismic profile through the Eastern Alps: TRANSALP, *EPSL*, 225, 115–129.

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).

Lüschen, E., Lammerer, B., Gebrande, H., Millahn, K., Nicolich, R., 2004: Orogenic structure of the Eastern Alps, Europe, from TRANSALP deep seismic reflection profiling. *Tectonophysics*, 388, 85-102.

Malusa., M. G., Guillot, S., Zhao, L., Paul, A., Solarino, S., Dumont, T., et al. (2021). The deep structure of the Alps based on the CIFALPS seismic experiment: A synthesis. Geochemistry, Geophysics, Geosystems, 22, e2020GC009466. https://doi.org/10.1029/2020GC009466

Merlini, S., Doglioni, C., Fantoni, R., Ponton, M. (2002). Analisi strutturale lungo un profilo geologico tra la linea Fella-Sava e l'avampaese adriatico (Friuli Venezia Giulia-Italia), *Mem. Soc. Geol. Italia*, *57*, 293-300.

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.

Ortner, H.S., Aichholzer, M., Zerlauth, R., Pilser, R., Fügenschuh, B. (2014). Geometry, amount, and sequence of thrusting in the Subalpine Molasse of western Austria and southern Germany, European Alps. *Tectonics*, 34, doi:10.1002/2014TC003550.

Paffrath, M., Friederich, W., Schmid, S.M., Handy, M.R. and the AlpArray and AlpArray-Swath D Working Groups (2021). Imaging structure and geometry of slabs in the greater Alpine area – a P-wave travel-time tomography using AlpArray Seismic Network data. *Solid Earth* 12, 2671–2702, 2021 https://doi.org/10.5194/se-12-2671-2021

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.

Rosenberg, C. L.: Shear zones and magma ascent: A model based on a review of the Tertiary magmatism in the Alps. *Tectonics*, 23, TC3002, https://doi.org/10.1029/2003TC001526, 2004.

Rosenberg, C. L., Schneider, S., Scharf, A., Bertrand, A., Hammerschmidt, K., Rabaute, A., and Brun, J.-P. (2018). Relating collisional kinematics to exhumation processes in the Eastern Alps, *Earth-Sci. Rev*., 176, 311–344, doi.org/10.1016/j.earscirev.2017.10.013, 2018.

Rosenberg, C.L., Kissling, E. (2013). Three-dimensional insight into Central-Alpine collision: lower-plate or upper-plate indentation? *Geology,* 41, 1219-1222. doi: 10.1130/G34584.1

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. (2013a). 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., 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, S.M., Aebli, H.R., Heller, F., Zingg, A. (1989). The role of the Periadriatic Line in the tectonic evolution of the Alps. *Geol. Soc. Lond. Spec. Publ*., 45, 153–171

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 thermobaromentric investigations of high-pressure mineral assemblages in metapelites of the Moderecke Nappe Complex (Tauern Window, Austria). *M.Sc. thesis*, 85 pp., Freie Universität Berlin

Schmidt, T., Blau, J., Kázmér, M. (1991). Large-scale strike-slip displacement of the Drauzug and the Transdanubian Mountains in early Alpine history: Evidence from permo-mesozoic facies belts. *Tectonophysics*, 200, 1–3, 213-232.

Schönborn, G. (1999). Balancing cross sections with kinematic constraints: the Dolomites (nothern Italy). *Tectonics*, 18, 3, 527–545

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.

Sun, W., Zhao, L., Malus., M. G., Guillot, S., & Fu, L. Y. (2019). 3-D Pn tomography reveals continental subduction at the boundaries of the Adriatic microplate in the absence of a precursor oceanic slab. *Earth and Planetary Science Letters*, 510, 131–141.

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, Davies JH. (1995). Slab breakoff: A model for syncollision magmatism and tectonics in the Alps. *Tectonics* 14, 1, 120-131.

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, M., Fodor, L. (2006). Late Cenozoic tectonics of Slovenia:structural styles at the northeastern corner of the Adriatic microplate. In: Pinter N, Grenerczy G, Weber J, Stein S, Medak D (eds) The Adria microplate: GPS geodesy, tectonics and hazards, vol 61: *Nato Science Series, IV, Earth and Environmental Science,* vol 61. Springer, Dordrecht, pp 151–158

Zahorec, P., Papo, J., Pašteka, R., Bielik, M., Bonvalot, S., Braitenberg, C., Ebbing, J., Gabriel, G., Gosar, A., Grand, A., Götze, H.-J., Hetényi, G., Holzrichter, N., Kissling, E., Marti, U., Meurers, B., Mrlina, J., Nogová, E., Pastorutti, A., Salaun, C., Scarponi, M., Sebera, J., Seoane, L., Skiba, P., Szucs, E., and Varga, M. (2021). The first pan-Alpine surface-gravity database, a modern compilation that crosses frontiers. *Earth Syst. Sci. Data*, 13, 2165–2209, https://doi.org/10.5194/essd-13-2165-2021