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Field trip to the Tauern Window region along the TRANSALP seismic profile, Eastern Alps, Austria

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ABSTRACT

During the TRANSALP project, deep seismic surveys and accompanying geophysical and geological projects were carried out to better understand the deep structure of the Eastern Alps south of Munich. The TRANSALP field trip series roughly follows the route in three parts: the Tauern Window, the Northern Calcareous Alps and its foreland, and the Southern Alps including the Dolomites. In this Tauern Window field trip, we will visit most of the geologically important sites along the middle part of the traverse or in its vicinity. The main topics covered in the Tauern Window will be the early Alpine paleogeographic situation on an extending European continental margin, Alpine nappe stacking and ductile rock deformation, metamorphism, uplift modes and exhumation, lateral escape, and the Brenner normal fault.

Keywords: Eastern Alps, Alpine metamorphism, Brenner fault, Tauern nappes

INTRODUCTION

The Alps are the best-studied mountain range on Earth, following more than two hundred years of detailed geological and mineralogical exploration. The role of nappe tectonics in the Alps was described more than a century ago (Bertrand, 1884; Termier, 1904, discussed by Tollmann, 1981, and Trümpy, 1991). During the past decades, much progress has come from geophysical surveys, large tunnel projects and deep wells. New insights have also come from modeling the evolution of orogenic wedges, cosmogenic surface dating, and measuring the velocity field by Global Positioning System and Very Long Baseline Interferometry techniques.

In recent decades, several research programs were carried out to better understand the deep structure of the Alps that, finally, led to a new tectonic map (Schmid et al., 2004). The French-Italian ECORS-CROP Profile (Etudes Continentale et Océanique par Reflection et Refraction Sismique, and Crosta Profonda) and the Swiss NFP20 (Nationales Forschungs—Programm No. 20) provided three seismic sections through the Western Alps (Roure

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et al., 1996; Pfiffner et al., 1997; Schmid et al., 1996). The most recent effort was undertaken by the German, Austrian, and Italian TRANSALP program, which resulted in a 300-km-long continuous geophysical section through the Alps between 1998 and 2001 (Fig. 1). Vibration and explosion seismics were carried out along the main traverse and the cross lines, accompanied by gravimetric and teleseismic tomographic studies (Lippitsch et al., 2003; Kummerow et al., 2004; Lüschen et al., 2004; Ebbing et al., 2006; Lüschen et al., 2006; Zanolla et al., 2006).

The Eastern Alps differ from the Western Alps in several respects:

(1) They are covered almost completely by the thick Austroalpine nappes (Fig. 1), whose basement was affected by the Pan-African orogeny. Due to long exposures at or near the surface of Pangaea, the basement rocks are strongly oxidized. Starting in the Permian, progressive marine flooding proceeded from east to west until the entire Austroalpine realm was covered. This transgression resulted in carbonate platform deposits up to 5 km in thickness in the time span of middle and late Triassic (Southern Alps, Dolomites, Northern Calcareous Alps, Brenner Mesozoic area, etc.). In contrast, only a relatively thin veneer of sediment was deposited on the European plate during the entire Triassic (Helvetic nappes of Switzerland and the Eastern Alps, Tauern Window). In the Austroalpine nappes, there are two major gaps through which lower tectonic units emerge. In the Engadine window, calc-mica-schists and ophiolites of oceanic origin occur. In the Tauern Window, basement and cover rocks of the margin of the European plate are also exposed beneath the oceanic nappes. The Tauern Window is therefore a unique tectonic structure in the Alps.

(2) The Pusteria Fault—a suspected eastern continuation of the Insubric line—is displaced by ~60 km to the north along the northeasterly trending Judicarie Fault (see Fig. 3). This displacement reflects deep penetration of the Adriatic plate into the eastern Alps (Adriatic indenter). Lateral extrusion of the Tauern Window and the Austroalpine nappes and backthrusting along the Val Sugana Fault are related to this indentation.

(3) Within the Eastern Alps, two orogenic wedges are developed: one to the north, as in the Western Alps, and a second, later one to the south (Dolomites, Southern Alps, Belluno basin) that is actively growing today, as indicated by seismic activity along the southern rim of the Alps (e.g., Friuli earthquake of 1976, with ~1,000 victims; Carulli and Slejko, 2005). In the western Alps, an active retrowedge is missing to the south or is only developed in a narrow strip, as in the Orobic Alps and the Maritime Alps (Castellarin and Cantelli, 2000).

(4) Geophysical studies of mantle tomography show another major difference: In the Western Alps, the presumed subduction is directed to the east (southwestern Alps) or to the south (Swiss Alps). The subducting mantle is connected to the European plate. In the Alps east of the Judicarie Fault, however, the high-velocity zone that reflects recently subducted mantle is displaced to the northeast and appears to be connected to the Adriatic plate. The direction of subduction must have reversed (Lippitsch et al., 2003; Kissling et al., 2007).

Key paleogeographic and tectonic processes responsible for the evolution of the Eastern Alps include the following:

(1) Long-lasting subsidence from the Mid Permian on led to a marine transgression that started in the east and proceeded westwards until Middle Triassic times. In Middle Jurassic times, the Penninic-Ligurian Ocean formed as a small side branch of the North Atlantic, during the disintegration of Pangaea, between Africa (including the Adriatic plate) and Europe. There was no connection with the great Tethys Ocean and the small Hallstadt and Meliata Oceans in the far east (Channell and Kozur, 1997; Stampfli and Borel 2002; Handy et al., 2010). Extensional tectonics and acidic volcanism (Permian quartz porphyries) preceded the opening. During the opening, subsidence accelerated and submarine basins and swells evolved (Ortner and Gaupp, 2007; Ortner et al., 2008). The consequences of this subsidence will be seen on the TRANSALP 3 field trip to the Dolomites, Southern Alps.

(2) The spreading of the Alpine Tethys ("Penninic-Ligurian and Valais Ocean") was extremely slow, allowing substantial cooling of the exposed mantle, and only a small amount of new oceanic crust was formed along an "ultraslow spreading ridge" or magma-poor rifted margin (Schaltegger et al., 2002). Sub-continental mantle was hydrated and metasomatically altered to serpentinites or ophicalcites. It was exposed at the seafloor over vast areas, covered by disintegrated remains of continental crust in tectonic contact ("extensional allochthons") and newly formed sediments.

(3) Contemporaneous with the opening of the North Atlantic and the Penninic-Ligurian Ocean, a subduction zone was active along the complex and poorly understood eastern margin of Pangaea. In Late Cretaceous times, the Adriatic plate experienced the Eoalpine orogeny during the closure of the small Hallstatt-Meliata Ocean in the east (Neubauer et al., 2000; Schmid et al., 2008). Cretaceous eclogite-facies metamorphism and deformation, deep erosion, and deposition of flysch and wildflysch sediments ("Gosau sediments") witness this early stage, which is detectable only in the Austroalpine nappes (Ortner and Gaupp, 2007). We will trace this history on the TRANSALP 2 field trip to the Northern Calcareous Alps.

(4) During the main Paleogene phase of the Alpine orogeny, the Alpine Tethys Ocean was consumed and the Adriatic plate collided with the European plate. The subduction direction was to the south during this phase. Because the European plate was welded to the oceanic lithosphere, it was drawn under the Adriatic plate until buoyancy and

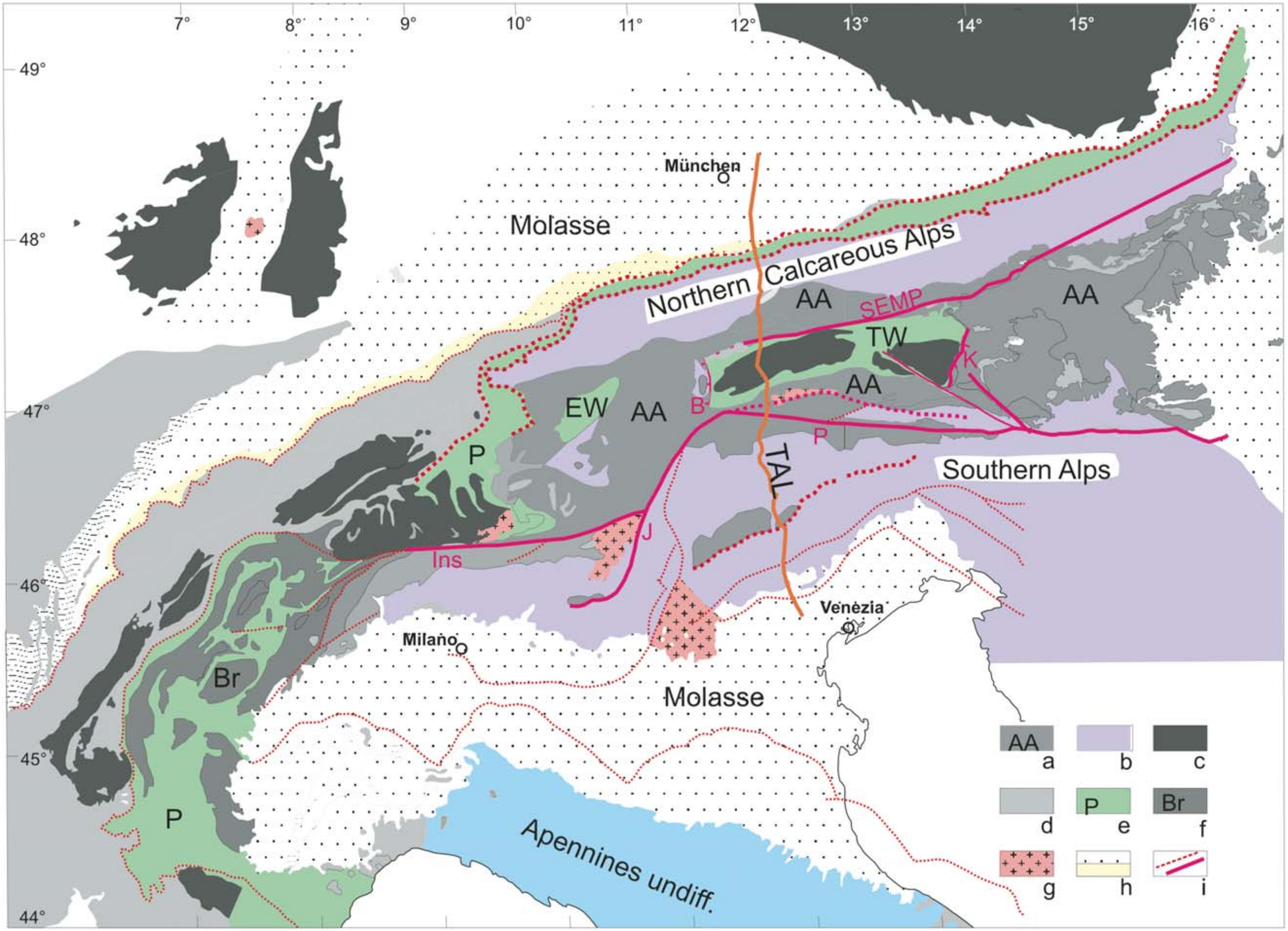

Figure 1. Tectonic map of the Alps. a—Austroalpine basement nappes (AA) and South Alpine basement; b—Austroalpine cover nappes and South Alpine cover; c—European basement; d—European cover nappes; e—oceanic nappes and ophiolites of the Piemontese–Valais Oceans (P); f—Briaçonnais terrane (Br); g—Tertiary intrusives and volcanics; h—molasse sediments, in yellow: folded; i—faults: strike slip (solid line), thrusts (dotted line); EW—Engadine Window; TW—Tauern Window; TAL—TRANSALP Line; B—Brenner normal fault; K—Katschberg normal fault; Ins—Insubric dextral fault; J—Judicarie sinistral fault; P—Pusteria dextral fault; SEMP—Salzach-Ennstal-Mariazell-Puchberg sinistral fault.

friction brought this process to a halt. Abraded sediments of the Alpine Tethys (Bündnerschiefer, Rhenodanubian flysch) and remnants of oceanic lithosphere (e.g., Glockner Nappe in the Tauern Window) overthrust the continental margin of the European plate. The crystalline basement of the Adriatic plate and its overlying sediments (Austroalpine nappes) were in turn thrust over the oceanic nappes, which were completely buried. An orogenic wedge developed to the north and northwest by stacking of Austroalpine, Penninic, and Helvetic nappes. The edge of this nappe pile crops out in the Eastern Swiss Alps and along the northern edge of the Eastern Alps, though only as fragments of the sedimentary cover. The nappe stack will be crossed during this field trip.

(5) Before about 30–40 Ma ago, the subducting oceanic lithosphere broke off and sank into the mantle (von Blanckenburg and Davies, 1995). In response to the sudden lack of negative buoyancy, the central part of the Eastern Alps rose quickly by ~2 km. The associated inflow of hot asthenosphere caused localized melting in the deeper crust. Granites, tonalites and mafic dikes intruded ca. 40–30 Ma ago near the Defereggen-Antholz-Vals Fault (Rieserferner), the Pusteria Fault (Rensen) and the Judicarie Fault (Adamello).

(6) Thereafter, the direction of subduction changed in the Eastern Alps and the lithospheric mantle detached from the Adriatic plate and sank in a northeasterly direction (Lippitsch et al., 2003; Kissling et al., 2007). This reversal of subduction caused a second orogenic wedge to develop in the south (TRANSALP 3 field trip). To the east of the Judicarie Fault, the Adriatic plate pushed ~60 km northward, deep into the nappe stack (Figs. 1 and 3). This indentation led to further imbrication and ductile deformation within the Tauern Window and, finally, to its exhumation (Fig. 2; Fügenschuh et al., 1997; Neubauer et al., 2000; Lammerer et al., 2008).

(7) Part of the orogen escaped to the east, in response to the indentation of the Adriatic plate and to the eastward rollback of the Carpathian subduction zone. This escape was facilitated by conjugate faults such as the sinistral Salzach-Ennstal Fault and the dextral Pusteria and Mölltal Fault (Genser and Neubauer, 1989; Ratschbacher et al., 1989; Frisch et al., 1998; Mancktelow et al., 2001). The large-displacement, north-south–trending Brenner and Katschberg normal faults also record the Neogene east-west extension contemporaneous with north-south

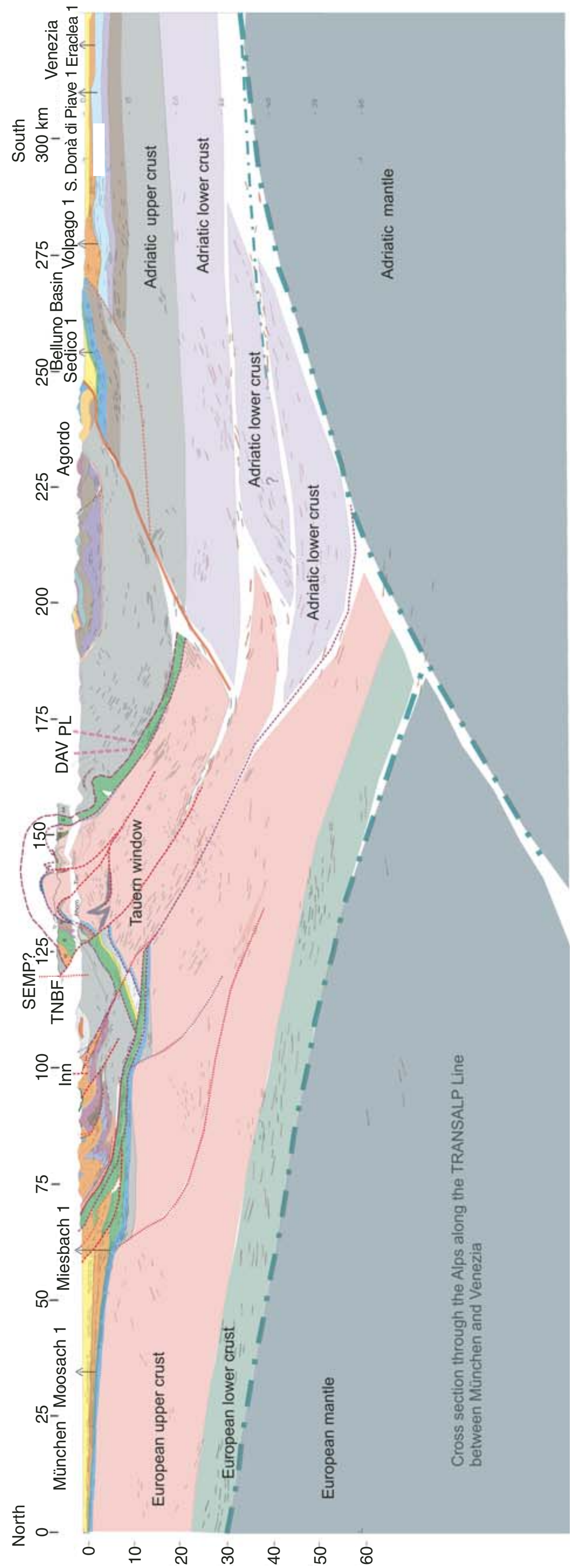

Figure 2. Cross section along the TRANSALP line. The Eastern Alps are characterized here by a thin-skinned wedge in the north (left) and a thick-skinned wedge to the south and the imbricate and upthrust Tauern Window in the center. Lower crustal wedges led to thickening of the South Alpine crust. The actual dip of the Adriatic mantle is to the northeast.

compression in the Eastern Alps (Fügenschuh et al., 1997; Rosenberg et al., 2007).

THE TAUERN WINDOW

The Tauern Window is the largest tectonic window in the Alps. It extends from the Brenner Pass in the west for over 160 km to the Katschberg Pass in the east and covers a total area of ~5600 km ^{2} (see Fig. 1). It is the only place in the Eastern Alps where the European basement is exposed in an area over 100 km wide. The European plate margin was affected by the Variscan Orogeny and the early stages of the breakup of Pangaea. This led to horst and graben structures and small-scale sedimentary patterns at the end the Carboniferous (Veselá et al., 2008). Complex inversion structures developed during subsequent Alpine compression. Because the entire Eastern Alps were re-deformed by the uplift of the Tauern Window, understanding the structural controls exerted by the European basement is crucial for understanding the architecture of the Eastern Alps (Lammerer et al., 2008).

Figures 3 and 4 show the main units of the western Tauern Window in map and cross-section view. The present tectonic structure of the inner Tauern Window results from:

- an early detachment and folding of Post-Variscan cover rocks;
- stacking of basement nappes, e.g., the Ahorn-, Tux-, Zillertal- and Eisbrugg gneisses, which represent former granitoid sills or laccoliths and its host rocks;
- folding of the entire nappe stack with large amplitudes and wavelengths to the Ahorn-Tux dome and the Zillertal dome; and
- a triangle zone at the tip of the sub Tauern ramp led to backfolding at the northern margin, which was first described by Rossner and Schwan (1982).

From north to south—or from the deeper to the shallower nappes—these tectonic units are the Ahorn-, Tux-, Zillertal- and Eisbrugg units. All these units show a common characteristic: they are directly covered by the Late Jurassic Hochstegen marble in the northern sector, but by Late Carboniferous or Early Permian clastic sedimentary rocks in the southern part (Thiele, 1974, 1976). Basement gneisses and granites were exposed and eroded and the debris filled the depressions or tectonic grabens. During the Jurassic, accelerated subsidence related to the breakup of Pangaea resulted in deposition of the Hochstegen marble on top of all the units (Veselá et al., 2008).

The sedimentary cover was locally detached and folded in tight, north-vergent folds. The entire nappe stack was subsequently overprinted by open folds with wavelengths in the range of kilometers. This led, locally, to synformal anticlines and antiformal synclines in the metasedimentary cover, which is evident especially along the northern rim of the window (Frisch, 1968). A final phase of south-vergent backfolding during the uplift of the Tauern Window and the development of a triangle structure on its northern tip, beneath the Austroalpine cover nappes, led to further complications.

METAMORPHIC HISTORY

All units within the Tauern Window underwent metamorphism in response to crustal thickening during the Alpine orogeny. Maximum temperatures were attained at ca. 25–30 Ma (e.g., von Blanckenburg et al., 1989; Christensen et al., 1994), during nearly isothermal decompression following deep burial. In general, metamorphic grade increases from greenschist facies at the margins of the window to mid-amphibolite facies in the central portions (e.g., Morteani, 1974). In detail, however, imbrication and differential movement between units resulted in a more complex picture. Oceanic rocks exposed at the surface today reached a pressure maximum of only 7–8 kbar in the southwestern corner of the window (Selverstone and Spear, 1985), but of 12–17 kbar in the Glockner nappe of the south-central region (e.g., Dachs and Proyer, 2001), where the prograde breakdown of lawsonite into mica-epidote-albite occurred at 30 Ma (Gleißner et al., 2007). In the latter area, they are separated from underlying units of European affinity by a tectonic slice of eclogite-facies oceanic rocks (600 ± 50 °C, 20–25 kbar; e.g., Spear and Franz, 1986; Hoschek, 2007). Maximum pressures calculated from the European units are in the range of 10–12 kbar (e.g., Selverstone et al., 1984; Brunsmann et al., 2000). These data indicate that the basement-cover contact within the Tauern Window was buried to depths of at least 35–40 km during the Alpine orogeny.

All major structures in the Tauern Window, resulting from strong N-S lithospheric shortening and simultaneous minor E-W extension, began developing coevally with high-pressure metamorphism in the Eclogite Zone (ca. 32 Ma). Large-scale strike-slip shear zones such as the Olperer Shear Zone started to form at ca. 32–30 Ma and facilitated the spatial accommodation of simultaneous shortening and extension. The Greiner Shear Zone at Pfitscher Joch shows ages indicating continuous activity from 27 Ma to 17 Ma (Fig. 4). The Tauern Window nucleated in the south-central part of the Eclogite Zone, and most of the regional deformation at ca. 32–30 Ma is today found at the periphery of the window and in the adjacent Austroalpine units. Afterwards, transpression continued, the window grew to the E, W, and N, and deformation progressed to those parts of the window. Ductile deformation in the present-day surface level ceased at ca. 15 Ma (Glodny et al., 2008).

ITINERARY

The field trip begins in Munich and ends at the Pfitscher Joch, 28 km ENE of Sterzing (Vipiteno) in South Tyrol (Fig. 3). We will drive into three valleys—Zillertal, Tuxertal, and Pfitschtal—and take several long hikes to mountain huts. Latitude and longitude coordinates below are given in WGS84 datum.

Day 1. Cross Section from Munich to the Center of the Tauern Window

(170 km drive and three hours walking; driving distances are given from the Munich entrance of the E 52 freeway.)

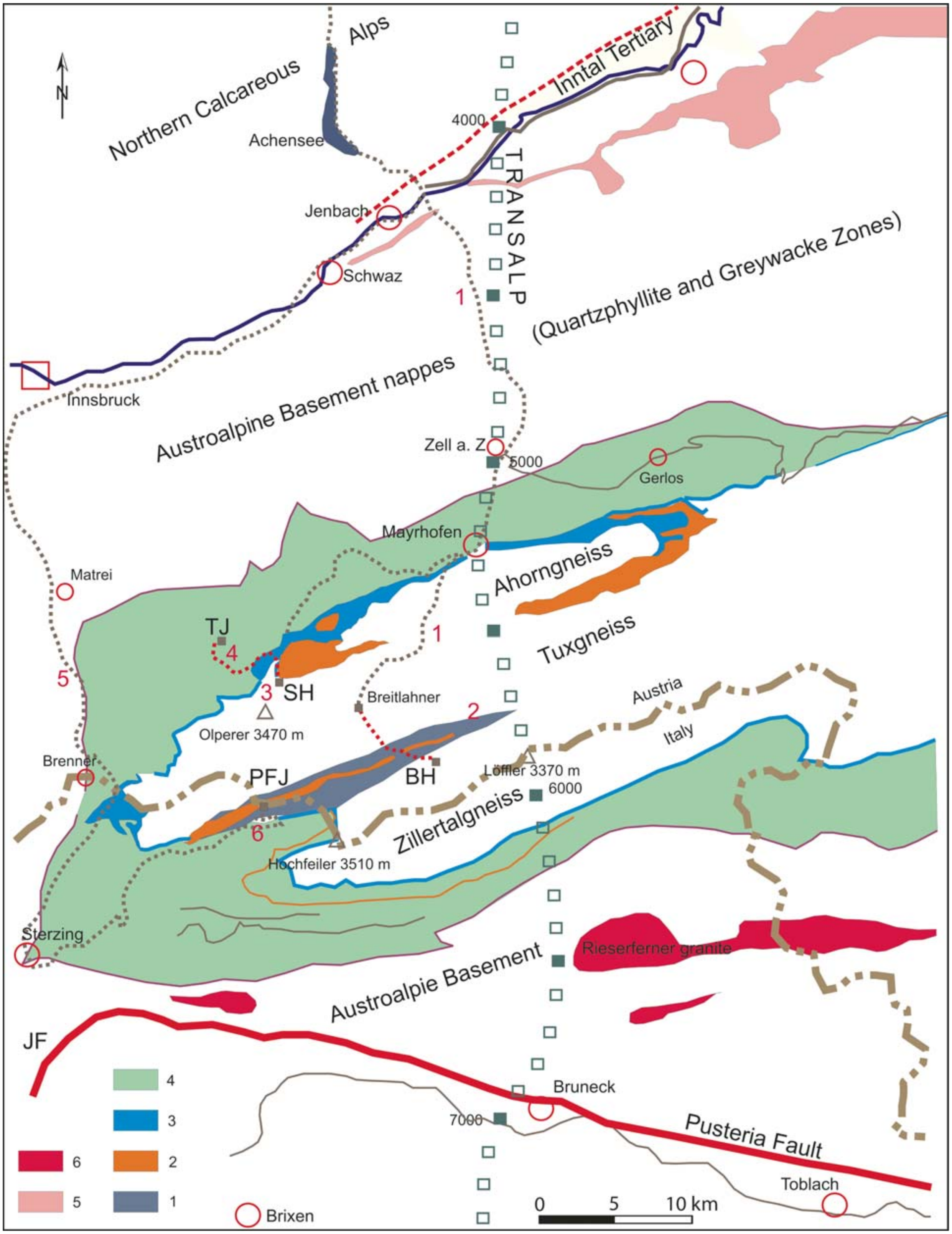

Figure 3. The western Tauern Window and adjacent areas and the excursion route (dotted line, red indicates hiking parts), with the day number indicated by numbers in black boxes. TRANSALP line with Common Depth Point numbers (CDP 4000–7000) is shown. Legend: 1—Early Paleozoic metamorphic Greiner series; 2—Late Paleozoic clastic metasediments; 3—Late Jurassic Hochstegen Marble; 4—Glockner nappe system (Bündner schists with ophiolites and Permo-Triassic remnants; 5—Basal clastic red bed sediments of the Northern Calcareous Alps; 6—Tertiary granites; Dashed-dotted Line—Austrian-Italian border. JF—Judicarie Fault, TJ—Tuxer Joch Haus, PFJ—Pfitscher Joch Haus, SH—Spannagel Haus, BH—Berliner Hütte

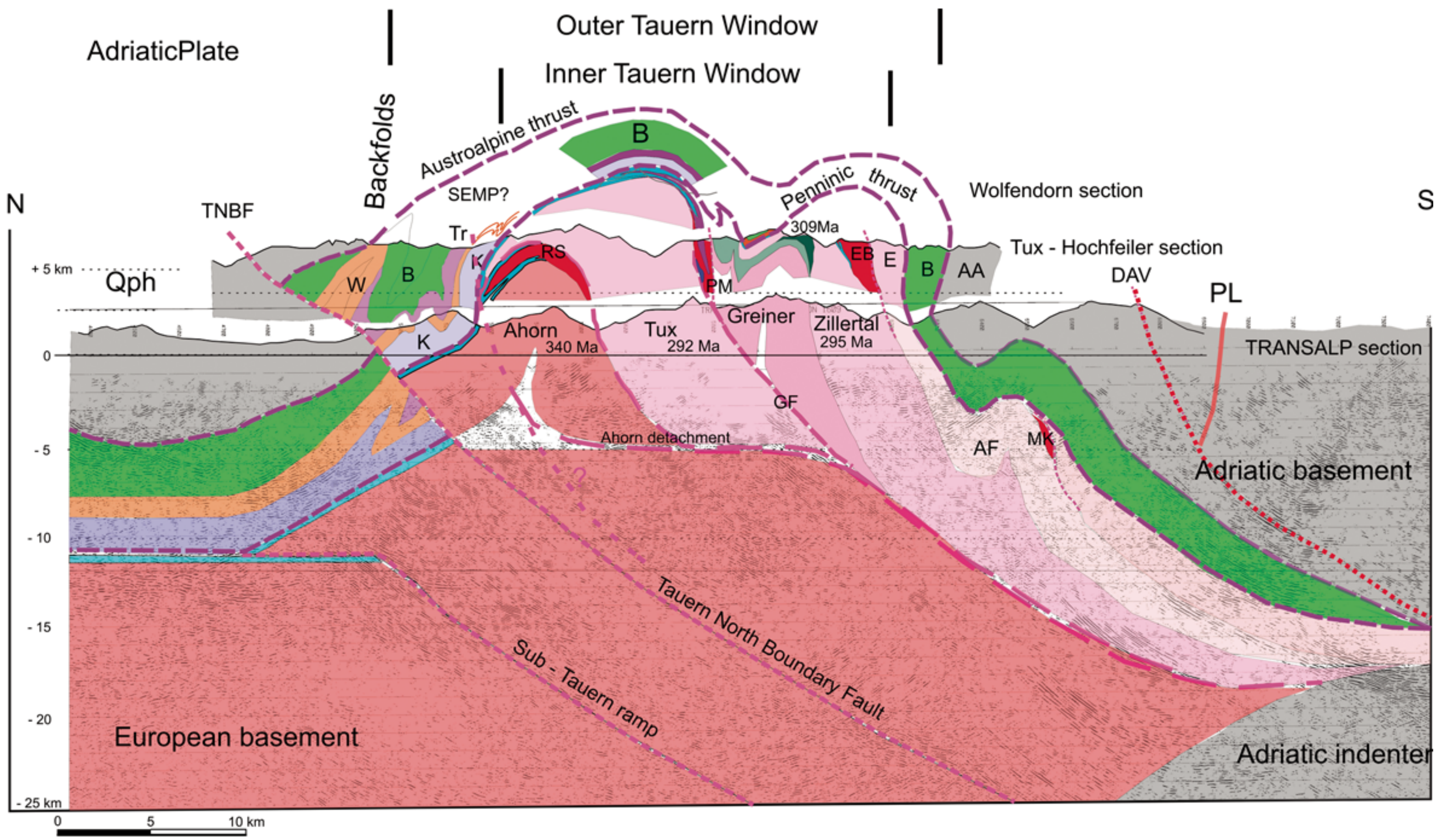

Figure 4. Composite section through the Tauern Window with seismic reflectors from the TRANSALP line. The internal structure is characterized by an early detachment of cover rocks followed by stacking of basement nappes, refolding with large amplitudes and wavelengths. A triangle zone at the tip of the sub Tauern ramp led to backfolding at the northern margin. The south vergent backfolding was first described by Rossner and Schwan (1982). The trace of the Salzach-Ennstal-Mariazell-Puchberg Fault (SEMP) is drawn after Rosenberg and Schneider (2008). Legend: Qph—Quartzphyllite zone; W—Wustkogel series (Early? or Late? Triassic clastic metasediments); B—Bündner schists; Tr—Middle Triassic carbonates; K—Kaserer series (Devonian–Carboniferous colored mélange); RS—Riffler-Schönach clastic basin; PM—Pfitsch-Mörchner clastic basin; EB—Eisbrugg clastic basin, E—Eisbrugg gneiss nappe; AF—Ahrntal fault; MK—Maurerkees basin; AA—Australpine south of the Tauern Window; TNBF—Tauern North Boundary Fault; SEMP—Salzach-Ennstal-Mariazell-Puchberg Fault; Sub-TR—Sub Tauern Ramp; DAV—Defereggen-Antholz-Vals Fault.

We follow the freeway (E 52) from Munich southward, cross the flat, late glacial plain of Munich (Münchner Schotterebene), and near Holzkirchen reach the moraines of the Riss Ice Age. We leave the freeway at the Holzkirchen exit and drive through gently rolling moraine landscape to the Tegernsee (km 47). Here, we enter the Alps and its closely imbricated and folded Flysch and Helvetic zone. At the bottom of the Tegernsee, small quantities of crude oil seep out from Helvetic units. At St. Quirin, monks of the monastery sold this oil during the Middle Ages as a health remedy and as oil for lamps. Modern oil exploration started in 1912 in Bad Wiessee. They found no oil, but warm iodine water, which gave the locality a big boost as a medicinal bath.

From Tegernsee to the lake of Achensee and further down into the Inn Valley near Jenbach we pass through the entire Northern Calcareous Alps, but no stops are planned, as this area is covered in detail on the TRANSALP 2 field trip.

Stop 1-1. Entrance of the Ziller Valley, Quarry near St. Gertraudi
(47° 24′19″N, 11° 50′35″E)

In a large abandoned quarry, we see the base of the Northern Calcareous Alps and we can touch here the Late Paleozoic surface of Pangaea, dipping 70° to the north: Red sandstones of the Alpine Buntsandstein (Scythian) with detrital muscovite grade downward into a few meters thick, reddish-purple, poorly sorted breccia with dolomite as a main component. The breccia unconformably covers a steeply inclined, massive, whitish-gray crystalline dolomite of Early Devonian age (Schwazer Dolomit). The dolomite reaches up to 600 m in thickness and represents the youngest member of the weakly metamorphic Greywacke Zone, which is part of the metamorphic basement of the Adria plate. It ranges in age from Early Ordovician to Early Devonian (Schönlaub 1980).

Within the dolomite, traces of copper ores may be seen in veins. Tetrahedrite is the main mineral, a copper-antimony sulfosalt. By oxidation and hydration, green malachite or blue azurite has formed. Nearby, in Schwaz and Brixlegg, copper, silver, and mercury sulfosalts were mined in the period between the fifteenth and nineteenth century and contributed much to the wealth of Tirol.

South of the Schwaz dolomite, the fine-grained Ordovician and Silurian Wildschönau schists occur. Locally, they show nice kink folds with steeply plunging axes, but generally they are poorly exposed and form rounded mountains with smooth surfaces. The schists contain layers or lenses of fine-grained gabbro and of rhyolites.

The border to the next deeper tectonic unit, the Quartzphyllite zone, is marked by the Kellerjoch orthogneiss, an Ordovician (Wenlock) sill that intruded ~425 million years ago (Satir and Morteani, 1979).

Stop 1-2. Hofer Supermarket on the Southern Outskirts of Zell am Ziller
(47° 13′22″N, 11° 52′50″E)

From the parking lot of the Hofer Supermarket, we follow the Schweiberweg road for about one hundred meters to the southeast, where a steeply south-dipping quartz phyllite is visible in a roadcut. The age of the phyllite is Ordovician here, but in other places (e.g., in the Southern Alps near Agordo, along the Val Sugana Fault) Late Cambrian acritarchs can be found in related rocks. Nearby, at Hainzenberg, gold occurs in quartz veins within the quartz phyllite and was mined in the seventeenth and nineteenth century.

Our outcrop is situated only ~50 m north of the limit of the Tauern Window (Fig. 5). It is influenced by two independent fault systems: the sinistral Salzach-Ennstal-Mariazell-Puchberg Fault which was active since Oligocene (Rosenberg and Schneider, 2008) and the Neogene reverse Tauern North Boundary Fault (Lammerer et al., 2008). The dark gray and fine-grained quartz phyllite occurs here in an overturned position and displays quartz fiber crystals on small fault planes, indicating sinistral aseismic movement, as is typical for the Salzach-Ennstal-Mariazell-Puchberg Fault. This Miocene fault runs partly along the northern contact of the Tauern Window and enters eastwards the Northern Calcareous Alps. It is still active (Plan et al., 2010).

A set of south-dipping microfaults produced sigmoidal micro wrinkles that indicate reverse movement and relative uplift of the southern side. This movement is attributed to the Tauern North Boundary Fault.

Stop 1-3. Mayrhofen: Visitor Center of the Verbund Austria Hydro Power plant

The Verbund controls four large reservoir lakes in the Zillertal catchment area. These mainly serve as pumped storage for power plants with a total capacity of ~1.1 GW and an annual production of 1.5 GWh. Benefit is taken from the high relief of that area and a constant water supply by several glaciers. Water is pumped into the reservoirs when excess electricity is available and can be released within seconds when needed.

Stop 1-4. Old Bridge at Hochsteg over the Zemmbach, South of Mayrhofen
(47° 09′17″N; 11° 50′09″E)

This is the type locality of the Late Jurassic Hochstegen marble (Oxfordian, Kimmeridgian, Portland; Kiessling 1992): From the wooden nineteenth century covered bridge, one has a spectacular view down the steep north-dipping contact between Hochstegen marble and Ahorn granite.

We descend to the river and encounter the Hochstegen marble (Kiessling, 1992). Up to 500 m in thickness, the bluish-gray Hochstegen marble is more variable in its lower and older part. Sometimes it is dolomitic or contains mica and quartz, indicating shallow marine conditions. In this portion, an ammonite from the *Perisphinctes* genus was found by v. Klebelsberg (1940) that is now recognized as a Late Oxfordian *orthospinctes semiradskii n. nom*.**[[n. nom. should not be in italics, correct?]]** (Kiessling and Zeiss, 1992). The upper portion of the Hochstegen marble is more homogeneous and limy with occasional chert nodules. Sponge spicules and several species of radiolaria document a deepening of the water and an age from Kimmeridgian to Early

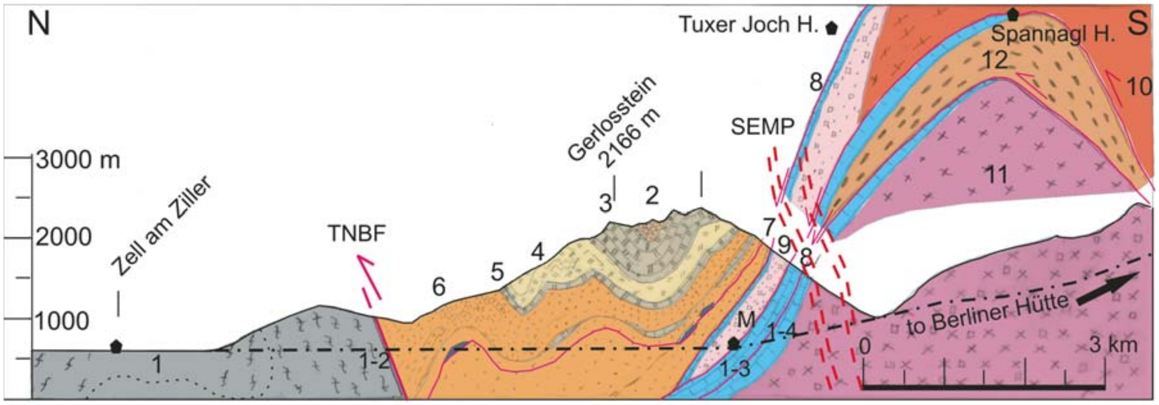

Figure 5. The northern margin of the Tauern Window with Stop locations 1-2 to 1-4 and projected positions of the Spannagel Haus (Day 3) and Tuxer Joch (Day 4). Legend: 1—Austroalpine Innsbruck quartzphyllite, overturned in its southern part; 2—clastic metasediments of unclear age (Late Triassic?); 3—Mid Triassic limestones and dolomites, weakly metamorphic; 4—clastic metasediments ("Wustkogel series," Late Permian–Early Triassic?); 5—dolomite-cargneul horizon; 6—clastic metasediments similar to 4; 7—Kaser series, mainly clastic metasediments, with lenses of marbles and serpentinites; 8—Hochstegen marble (Late Jurassic); 9—Meta rhyolite ("Porphyrmaterialschiefer"); 10—Tux gneiss nappe; 11—Ahorn alkaligranite; 12—clastic metasediments of the Riffler Schönach basin; TNBF—Tauern North Boundary Fault; SEMP—Salzach-Ennstal-Mariazell-Puchberg Fault.

Tithonian (Kiessling and Zeiss, 1992). The massive Hochstegen marble dips steeply to the north and exhibits horizontal striation due to sinistral fault movement along the contact. A few meters of a blackish quartzite (Liassic?) and brownish limestone (Dogger?) are locally present along the contact with the Ahorn granite but are not well exposed here.

The Ahorn granite is rich in biotite and K-feldspars. The Alpine foliation dips 70°–80° to the north. The Ahorn granite gneiss is the oldest and most deeply exposed intrusive body in the Tauern Window. Potassium-rich porphyritic biotite granites (in Europe called Durbachit or Redwitzit) intruded into migmatic host rocks 335.4 ± 1.5 Ma ago (Veselá et al., 2011). Here, in its northern part, the granite is covered by the Hochstegen marble.

Stop 1-5. Breitlahner

(Parking lot; 47° 03′40″N; 11° 45′00″ E, 1240 m- Grawandhütte [1½ hours walking] 47° 01′55″N; 11° 46′35″E, 1640 m)

Immediately south of the Breitlahner guesthouse some mafic varieties (tonalite, diorite) of the intrusive suite of the Tux gneiss may be observed along the creek (Fig. 6). On the hike along the gravel road, mostly granodioritic scree of the Tux gneiss is crossed. The uniform gray and medium grained granodiorite of the Tux unit has an age of 292.1 ± 11.9 Ma (Veselá et al., 2011), which is significantly younger than the Ahorn granite. Muscovite dominates over biotite in this two-mica granite.

The valley sides were smoothed by glacial grinding and show surface-parallel exfoliation by post-glacial pressure relief. About 50 m north of the Grawandhütte the tectonic contact between Tux gneiss and a serpentinite from the Greiner series will be crossed.

Stop 1-6. Grawand-Alpenrose

(1873 m, 1½ h walking; 47° 01′31″N; 11° 48′05″E)

We enter the Grawandtrett, gentle grazing land that developed over an old sagging mass, and enter the gorge of the Zemmbach (Fig. 6). Here, the rocks of the Greiner Series are best exposed. The Greiner Series belongs to the basement complex. The main rock types are hornblende garbenschists, amphibolites, and graphitic schist (locally called Furtschaglschiefer). The garbenschist texture (characterized by radiating bundles of hornblende; garben = "sheaves") is developed in rocks with a range of bulk compositions. The garbenschist protoliths were likely marls with variable amounts of volcaniclastic input. After crossing the gorge, poorly exposed graphitic schists and paragneisses follow until the Alpenrose guesthouse (see Fig. 10).

From north to south, we pass in the Zemmbach gorge the following rock types:

- Amphibolite with some biotite and chlorite.
- Amphibole-bearing graphitic schist, banded with hornblende garben.
- Calc-silicate amphibole gneiss with garnet and epidote; hornblende sheaves grow along pre-existing joints or foliations.
- Graphite-garnet-hornblende schist with graphite-free reduction spots around clear almandine garnets; some of the amphiboles are postkinematic.
- Alternation of calc-silicate–amphibole–gneiss and graphitic schist with large quartz veins.
- Dark amphibolites with aplitic veins.
- Lighter quartz- and garnet-rich hornblende garbenschists with graphite- and calcite-rich layers.

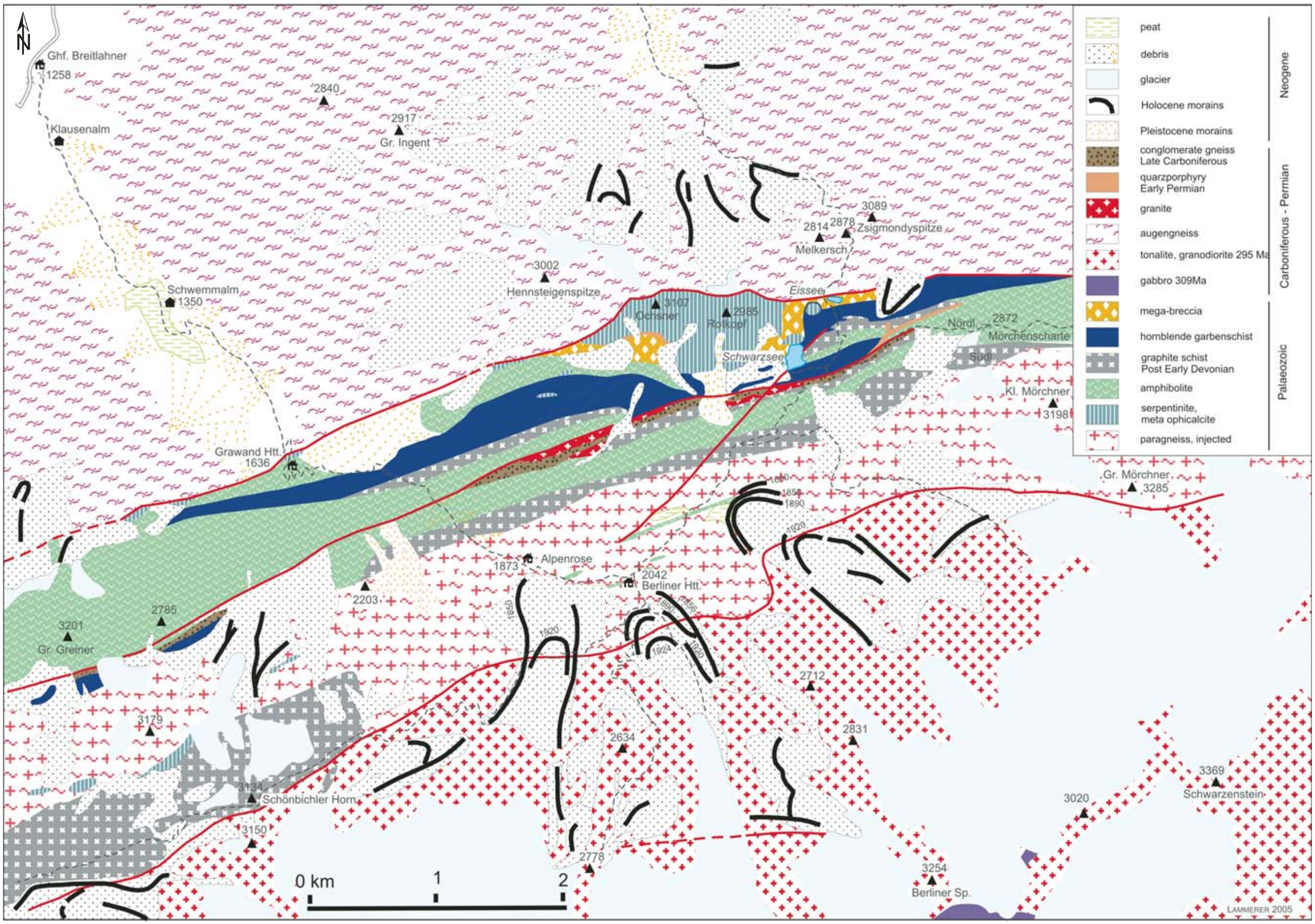

Figure 6. Geological map of the Berliner Hütte area (Zillertal Alps).

- Garnet-rich amphibolite and carbonate-garnet-amphibolite with rotated garnets (southern part upwards), found after crossing a side stream.
- Garnet amphibolites with Fe-carbonates, injected by aplitic dikes or apophyses.

Along three horizons, ~20 larger and smaller bodies of serpentinite are embedded, the largest of them, the Ochsner-Rotkopf Massif measures more than 1 km^3. Because the serpentinites contain particularly abundant Mg-carbonates and calc-silicate minerals, they probably derive from ophicalcite rocks of an Early Variscan colored mélange zone.

The stratigraphic age of the Greiner Schists is indirectly estimated by zircon dating of comparable rocks from the central Tauern Window. An upper limit is given by Early Devonian detrital zircons (Kebede et al., 2005). A lower age limit of 293 Ma results from the dating of a rhyolite that cuts the Ochsner serpentinite and the Greiner schists and by the intrusive contacts against the Zillertal gneiss (Veselá et al., 2008, 2011).

Stop 1-7. Alpenrose Guesthouse—Berliner Hütte
(½ h walking; 47° 01′28″N; 11° 48′47″E; 2042 m)

The Waxeggkees with its distinctive lateral moraines of the Little Ice Age (1600–1890) and some recessional moraines come into focus. From here to the Berliner Hütte we will walk over paragneisses that are injected by granites, giving them a migmatitic appearance. The Berliner Hütte itself stands on beautiful injected amphibolites, which are well exposed in a glacier-polished outcrop in front of the hut.

Stop 1-8. Glacially Polished Bedrock below the Berliner Hütte
(47° 01′23″N; 11° 48′87″E; 2022 m)

After crossing two moraine walls (from 1850 and 1890) we reach after 5 minutes the glacially polished outcrops of Zillertal gneiss. On the bedrock surface grooves in two different directions are developed and superimposed: the older and deeper scratches are relics of the mighty glacier of the last glaciation (Würm glaciation, corresponding to the Wisconsinian stage). The younger and smoother striations developed during the cold period of the seventeenth to nineteenth century, the "Little Ice Age." The same applies to linear groups of crescent cracks. The cracks of the great glacial period are larger and deeper and east-west oriented, those of the Little Ice Age are smaller and document an ice flow from south to north.

The bedrock consists of younger, fine-grained homogeneous granite and older porphyric granite with schlieren or nebulitic migmatitic features. In the fine-grained granite, rounded clusters of biotite and quartz in the core and potassium feldspar in the rim are present (proto-orbicules). The contact of the two granites is well exposed. The migmatitic streaks are cut by the fine-grained granite, clearly showing the age relationships. Amphibolitic xenoliths are found in all stages of assimilation. The amphibolites were already metamorphosed and foliated before intrusion.

This outcrop marks the base of the Zillertal gneiss, a variable series of ultramafic to acidic intrusives, with a large proportion of tonalite and with ages of 309 Ma for the mafic rocks and 295 Ma for the youngest granites (Cesare et al., 2002). Numerous aplitic, pegmatitic or lamprophyric dikes cut the Zillertal gneiss.

Like the Ahorn and Tux granites, the Zillertal gneiss is directly covered by Hochstegen marble in its main portion—except the southern segment at Eisbruggjoch, where is covered by clastic rocks. At the Maurerkees to the southeast of the Berliner Hütte, in a similar tectonic position, late Carboniferous remnants of fossil plants can be found (Franz et al., 1991; Pestal et al., 1999).

Day 2. The Paleozoic Suture Zone in the Tauern and the Alpidic Metamorphic History of the Garbenschists

All-day walk on mountain trails to Schwarzsee (2470 m) and Eissee (2680 m) to cross through the Greiner schists.

Stop 2-1. Berliner Hütte—Schwarzsee
(47° 02′23″N; 11° 49′46″E; 2470 m)

Leaving the Berliner Hütte, we follow the well-marked mountain path to the Schwarzsee (Fig. 6). We first cross schlieren gneisses with xenoliths or disrupted layers of amphibolite that were injected by granitic melts. Locally, garnet or potassium feldspar megacrysts occur.

From the trail, the Schwarzenstein glacier and its Little Ice Age moraines will be visible. The heavily vegetated outermost wall is attributed to the year 1610, the oldest moraine of the post-glacial cold period. Nevertheless, it is very well preserved. The younger moraines are much less vegetated and contain coarser blocks. The marked difference in vegetation is due to soil formation during the long warm periods before the earliest Little Ice Age glaciation. The first glacier advance scratched off this soil and deposited it along its front.

We continue through graphitic schists and amphibolites, which have an andesitic composition and show a nice boudinage. Immediately before the Schwarzsee, we reach a post-Variscan metaconglomerate, which rests unconformably on the Greiner schists. It can be traced from here to the Pfitschtal (see Day 5). Coarse blocks of serpentinite are fallen from the Rotkopf Mountain.

At the Schwarzsee, the typical hornblende garbenschists show a large range of textures. In many cases, hornblende appears to be post-kinematic. Steffen et al. (2001), however, argued that development of the garbenschist texture records grain-boundary diffusion creep during shearing. Rapid growth of large hornblende crystals subsequently strengthened the rocks and shifted deformation to weaker horizons.

The fabulous Schwarzsee is a typical tarn and a relic of the Great Ice Age. It is dominated in the northwest by the mighty dark serpentinites of the Ochsner and Rotkopf peaks. The main serpentine mineral here is antigorite, with chrysotile found only in crevices. Abundant carbonates (ankerite, breunnerite) and calc-silicate minerals such as diopside, grossular, vesuvianite, tremolite, and others (Koark, 1950) record a pre-metamorphic phase of calcium metasomatism. The abundance of calcic minerals supports the interpretation that the serpentinite is a former ophicalcite. West of the summit of the Ochsner, the serpentinite is cut by early Permian quartz porphyry confirming the pre-Alpine emplacement age of the serpentinite. Along the contact, the serpentinite is sometimes chloritized and often bears idiomorphic magnetite octahedra. Famous two-colored diopside crystals—green at the base and colorless at the tips—also occur here.

Stop 2-2. From Schwarzsee to the Mörchnerscharte
(47° 02′33″N; 11° 50′29″E)

We take the steep trail in direction to the Mörchnerscharte. We follow roughly the contact to the deformed metaconglomerates to an elevation of 2630 m. Here, the syncline of the conglomerate ends in a narrow upright fold with an axis plunging 40° to the west. The fold limbs dip generally 65°–70° northward and southward in the Greiner schists.

We move into the northern of two main synclines in the Greiner series. The southern syncline is only visible at the Schönbichler Horn to the west of the Berliner Hütte. Graphitic schists and amphibolites are here deformed together with an underlying granitic sill. The presence of the younger conglomerate in the center of the fold indicates a true syncline and not just a synform. This does not rule out more complex folding of parts of the crystalline basement during an earlier phase of deformation.

Stop 2-3. Mörchnerscharte-Eissee
(47° 02′40″N; 11° 50′03″E)

Without a trail, we cross a mélange of different garbenschists, metarhyolites, quartzites, graphite schists, and several serpentinite bodies of a few cubic meters in size.

Around the Eissee, several smaller ultramafic bodies are exposed: serpentinites of varying sizes (m^3 to km^3), metaophicalcites, and rock bodies that are completely transformed into chlorite or actinolite blackwall zones are embedded in a metapelitic or conglomeratic matrix (Barnes et al., 2004). The rock association resembles an olistostrome or a mélange-type complex (100–500 m). Thin bands of quartzites containing bright chromium-bearing white mica (“fuchsite”) and marble are present, but cannot be traced for long distances.

Stop 3-4. From the Eissee to the Rotkopf Serpentinite

The dominant serpentinite mineral is antigorite, with chrysotile only present along the contacts or in shear planes and fissures. In some places, idiomorphic octahedra of magnetite may be found in a chlorite matrix. Colorless and green transparent diopside, uvarovite and grossular garnet, titanite, actinolite, fuchsite, platy hematite, amethyst, and many other minerals were also found in this area.

The Greiner schists bend around the body of the Ochsner-Rotkopf serpentinite, but the post-Variscan metaconglomerate that forms the core of the Greiner basin is unaffected by the underlying structures. These observations indicate that the conglomerate was deposited in angular unconformity over already deformed Greiner schists. From the Eissee we head back to the Berliner Hütte.

Day 3

We cross the margin of the inner Tauern Window and enter the folded Ahorn gneiss and the Paleozoic postvariscan clastic metasediments of the Riffler-Schönach basin, and we visit the highest karst cave of Austria.

Stop 3-1. Gasthof Schöne Aussicht near Finkenberg
(47° 09′03″N; 11° 49′27″E)

We hike down to the parking lot at the Breitlahner guesthouse (2 h) and continue by car to Finkenberg. Along the small road and at the parking lot of the guesthouse, an imbricated contact of Zentralgneis and its sedimentary cover dips steeply to the northwest. Granite-orthogneiss, graphitic schists, brownish limestone, and gray Hochstegen marble are well exposed here. The sequence is doubled by a small low-angle thrust. The detachment runs beneath a thin slice of granite—probably an exfoliation sheet from unloading at the postvariscan surface.

Stop 3-2. Hintertux Parking Lot
(47° 06′30″N; 11° 40′ 33″E; 1500 m)

Between Finkenberg and Hintertux we cross the oceanic Bündnerschist series without stopping. Hintertux, like Mayrhofen, is situated 1500 m a.s.l. on the northern slope of the inner Tauern Window. It is known for excellent year-round skiing possibilities and for its thermal water, which comes from several springs along the rim of the Tux gneiss with temperatures up to 22 °C. The thermal waters have been used for wellness and medical purposes since 1850, but were known in earlier times. The water of this highest thermal spring of Europe is relatively poor in minerals, but it is slightly radioactive due to small amounts of radon and uranium.

Stop 3-3. Tuxerferner House
(47° 04′38″N; 11° 40′16″E; 2660 m)

From Hintertux, we take the cable lift up to the Sommerbergalm and further to the Tuxerferner House. The house is built on a migmatitic Tux gneiss thrust sheet of only ~100 m in thickness.

From here, we have a nice panoramic view: To the north, we recognize the grassy Bündnerschiefer Mountains with the northern Calcareous Alps in the background. To the east, the synformal anticline of the Höllenstein (Höllenstein Tauchfalte; Frisch, 1968) bends around the Ahorn granite core. Metaconglomerates and Hochstegen marble of the Riffler-Schönach basin were detached, squeezed out and folded by the advance of the Tux granite-gneiss nappe and later refolded together with the Ahorn gneiss. The conglomerate horizon ends on the northern ridge of the Hohe Riffler (3231 m) at the thrust plane of the Tux gneiss.

The southern sector is mostly glaciated and the bedrock is made from Tuxer granodioritic orthogneiss. Its sedimentary cover of Hochstegen marble can be seen in the western sector. Here, the clastic basal rocks are missing. The strata dip around 40° to the northwest and are visible along the steep wall of the Kleiner Kaserer (3095 m), the type locality of the Kaserer series, which we will visit the next day. The outcrop runs subparallel to the fold axis, which gives the fold a somewhat strange appearance.

Stop 3-4. Spannagelhaus
(47° 04′48″N; 11° 40′16″E; 2529 m)

The refuge was built on Hochstegen marble, which shows nice folds immediately in front of the hut. Three meters of brownish marble and another meter of black quartzite may represent earlier Jurassic beds (Fig. 7A).

Stop 3-5. Outcrops of Metaconglomerates
(~500 m along the trail to the Friesenbergscharte)

From the refuge, we follow the trail to the east in direction to the Friesenbergscharte. On the way down, we cross metaconglomerates of the Riffler Schönach basin, which can be traced for over 40 km into the central Tauern Window. The pebbles are strongly flattened here and kinked or folded. Finer-grained meta-arkoses are found in deeper sections, and their color changes from gray to greenish, indicating climatic or depositional changes.

Stop 3-6. Spannagel Cave (Spannagelhöhle)

The entrance to the highest cave in Austria is directly under the hut. It reaches at least 800 m horizontally to the west and at least 500 m downward. The cave is cut into banded Hochstegen marble, which is topped by the thrust plane of the Tux gneiss. This contact is visible in the cave. We find a strongly black- and white-banded variety of the marble and initial travertine and stalagmite formation. Karst waters have obviously enlarged preexisting fractures in the marble.

The cave formed during glacial periods, beginning at least 550 ka ago. U-Pb and U-Th dates on flowstones in the cave reveal several episodes of growth around 550 ka, 350 ka, 295 ka, and 267 Ka (Cliff et al., 2010).

Day 4. All-Day Walk from Spannagel Haus to Tuxer Joch Haus

We cross from the Riffler Schönach basin through the Tux gneiss nappe and proceed into the base of the Glockner nappe. We touch the enigmatic Kaserer Series and a Cambrian gabbro and walk through backfolded area.

Stop 4-1. Outcrop in Glacially Polished Rocks to the South of the Sommerbergalm

We take the gravel road down to the Sommerbergalm for about one kilometer to an elevation of 2100 m. We follow roughly the contact between the Hochstegen marble and its substratum of Permo-Triassic clastic metasediments and the thrust plane on top, and we cross in the lower part the Tux gneiss nappe. After crossing the lateral moraine of the year 1850, we can study the contact between the Tux gneiss and the Hochstegen marble above it in detail on the glacially eroded surface. The migmatitic gneiss is strongly sheared in its uppermost part and covered by two meters of brown, sandy limestone that grades into the bluish-gray banded Hochstegen marble. The marble is generally limy but contains boudinaged dolomitic layers. Graphitic bands alternate with graphite-free bands in a cm to dm scale. They are cut by a synsedimentary normal fault, which is smoothed out by sedimentation. The marble appears less deformed than the granite gneiss, which suggests an extensional detachment fault developed on the seafloor (possibly a metamorphic core complex).

Stop 4-2. Kaserer Scharte
(47° 04′52″N; 11° 38′41″E; 2446 m)

We ascend for ~250 m, in the lower part over grassy slopes and sheep pastures and reach, after 40 minutes, the Kaserer Scharte to the north of the Kleiner Kaserer, the type locality of the Kaserer series. From here, we have a spectacular view of the tightly folded Triassic marbles on the Schöberspitzen in the west (Fig. 8).

Stop 4-3. Frauenwand

We follow the small trail to the Frauenwand, crossing chlorite schists, graphitic schists, thin marble bands, and arkosic gneiss layers of the Kaserer series. A shallow-water or turbiditic facies is discussed; sometimes weak graded bedding may be visible. The small peak of the Frauenwand is made of Hochstegen marble, which comes up here in an isoclinal anticline. It is disrupted by slope tectonics and shows karstification.

Stop 4-4. Trail to the Tuxer Joch

On the way down to the Tuxer Joch, we again cross the Kaserer series with green and black schists and meta-arkoses, and reach the Weisse Wand (white wall). The white color results from Triassic dolomitic and limy marbles. We cross (from south to north): 25 m of white dolomite; 5–7 m of dark gray dolomite; 15–20 m of light gray dolomite, 5 m of yellowish cargneuls and a few meters of greenish chlorite and schists.

Stop 4-5. Ski Lift Building South of the Tuxer Joch

At a small ski lift building, a fine-grained metagabbro or metadolerite is exposed for 20 m. The grain size is at mm scale, between a dolerite and microgabbro, and the rock is sheared at its basal contact. This rock was thought to be Cretaceous in age by Frisch (1974), but its zircons show a Cambrian age (Veselá et al., 2008). Two contrasting interpretations can be made: the rock contains inherited zircons from older crust, or this is a tectonic sliver of a basement gabbro at the base of the Glockner nappe.

Stop 4-6. Trail Approaching the Tuxer Joch
(47° 05′56″N; 11° 38′58″E)

We continue northwards and encounter graphitic schists with one black horizon rich in carbonaceous matter (possibly

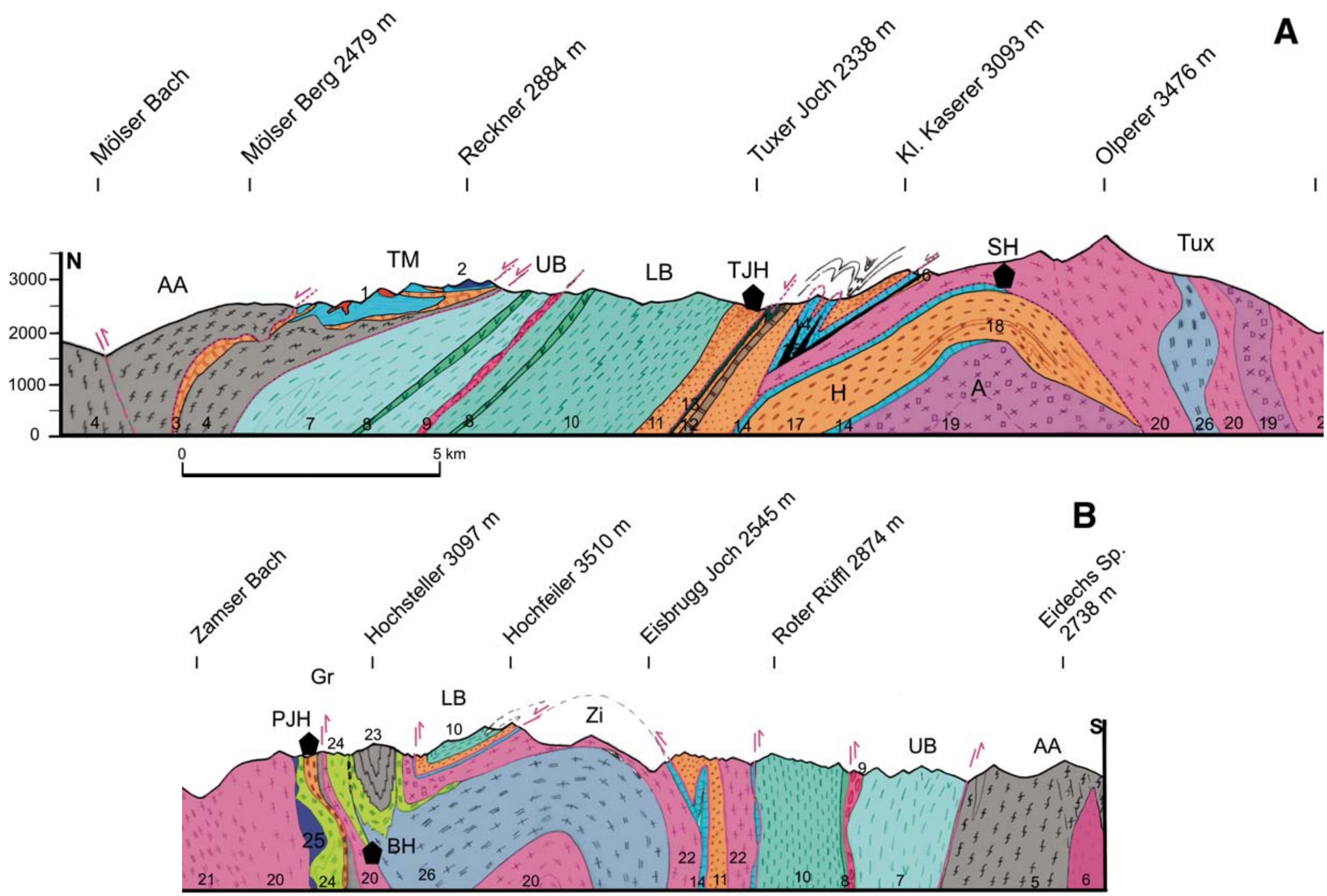

Figure 7. (A) Cross section through the Western Tauern Window, northern part. This is the area around the Spannagel Haus (SH) and Tuxer Joch Haus (TJH). (B) Cross section through the Western Tauern Window, southern part. This is the area around the Pfitscher Joch. Legend to A and B: Austroalpine nappes (AA) and Tarntal Mesozoic nappe (TM): 1—Jurassic shale, marl, limestone, breccia and chert; 2—Serpentinite; 3—Triassic carbonate and cargneul; 4—Quartzphyllite (mainly Ordovician); 5—gneiss south of the Tauern Window; 6—Rensen granite and dykes. Glockner nappes: 7—phyllite and calcphyllite of the higher Bündnerschiefer nappe; 8—Amphibolite and Prasinite; 9—thrust horizon with lenses of serpentinite and Triassic quartzite, Dolomite, gypsum and breccia; 10—Phyllite of the lower Bündnerschiefer nappe; 11—?Permo–Triassic clastic metasediment and cargneul; 12—dolomite marble (Middle Triassic); 13—tectonic horizon with lenses of Cambrian microgabbro. Inner Tauern Window duplex system has the following three parts. (1) Post Variscan metasediments: 14—Hochstegen marble (Upper Jurassic); 17—clastic sediments, metaconglomerates, meta-arkoses (Pre Upper Jurassic); 18—dazitic porphyry. (2) Late Variscan Plutonites: 19—Ahorn porphyric biotitegranite; 20—Tux granodiorite; 21—migmatic rocks and injection gneisses; 22—Zillertal granites, granodiorites tonalites and gabbros. (3) Pre Variscan and early Variscan rocks: 23—black graphiteschists; 24—amphibolites and garbenschiefer; 25—serpentinites and meta-ophicalcites; 26—injected gneisses and amphibolites.

Figure 8. View to the west from the Kaserer Scharte to the Schöberspitzen 2600 m. The isoclinal south-vergent folding of the Triassic dolomites is due to late backfolding.

equivalent to the Late Triassic Lettenkohle horizon of the German basin) and sandy layers; greenish quartzites or quartz-rich schists with some carbonate horizons of centimeters in thickness, and white quartzites up to 20 m thick. Brownish calcschists resemble the Bündnerschiefer series. The Tuxer Joch Haus is built on greenish quartzites of the so-called Wustkogel formation—although it is not entirely clear whether it is the same horizon as at the type locality in the central Tauern Window.

Day 5

We discuss the Brenner normal fault, cross the Bündnerschiefer and enter the Pfitsch valley with its vanished lake; we have a look to the famous Wolfendorn section and reach the Pfitscher Joch.

We descend down to Hintertux and continue by car to Innsbruck and the Brenner Pass, the lowest pass of the central Alps (1360 m). The Brenner Pass marks a major normal fault, the Brenner Line, where the hanging wall of the Ötztal-Stubai crystalline basement (a part of the Austroalpine nappe stack) has been displaced westward relative to the Tauern Window (Behrmann, 1988; Selverstone, 1988). The horizontal component of slip on this structure is estimated to be several tens of kilometers since Miocene times (Selverstone, 1988; Axen et al., 1995; Frisch et al., 2000). Top-to-the-west ductile shearing was dated at ca. 22–18 Ma (Glodny et al., 2008). There is still some minor earthquake activity here. A similar, top-east extensional fault (Katschberg fault) bounds the eastern edge of the Tauern Window.

Stop 5-1. Brennerbad

(46° 58′46″N; 11° 29′05″E)

South of the Brenner Pass, at Brennerbad, a small gravel road leads us to outcrops of mylonitic calc-mica schist of the Bündnerschiefer series. Well-developed S-C-C′ fabrics and late semi-ductile and brittle shear zones indicate top-to-the-west extensional movement associated with the N-S–trending Brenner fault zone. The youngest, brittle incarnation of the Brenner Fault excised ~2 km of the Bündnerschiefer, indicating that the fault dips more steeply than the westward plunge of the Tauern Window. However, top-west extensional mylonites within the Bündnerschiefer and lower Austroalpine units point to an early history as a low-angle, ductile shear zone (Behrmann, 1988; Selverstone, 1988; Axen et al., 2001). Footwall uplift was accomplished by subvertical simple shear along numerous, closely spaced, high-angle normal faults. West-down structures were active at depths of 10–20 km and ~450 °C and were overprinted by east-down faults active at 2–10 km depths and 300 ± 50 °C (Selverstone et al., 1995).

Stop 5-2. View to the Landslide of Afens

We continue into the Pfitsch valley until the bridge west of Afens. A postglacial landslide within the calc-mica schist unit filled the valley at least 300 m deep and caused a natural reservoir lake to form in the upper part of the Pfitsch valley. Around the year 1100, the barrier failed and the lake flooded the lower Pfitsch and Sill Valleys and destroyed the Roman Garrison station of Vipitenum (Sterzing/Vipiteno today).

Stop 5-3. Standing on an Ancient Lake Ground South of Kematen and Discussing the Wolfendorn Section

Near Kematen, an old fisherman's village with houses older than one thousand years, we stop at the former lake floor. Nice terraces and deltas mark the former water level of the barrier lake, which vanished in the beginning of the twelfth century.

From here, we have a perfect look to the Wolfendorn (Spina Del Lupo, 2771 m) to the north. The west-plunging Zentralgneis is covered by ~10 m of brownish Triassic marble and by 20 m of black kyanite-mica schist. Kyanite is black because of inclusions of graphite (Rhätizit, rheticite). Two meters of brown, sandy limestone mark the beginning of the Hochstegen marble, which is upright in the lower part and inverted in the middle part and again upright in the top at the peak of the Wolfendorn (Fig. 9).

Several workers tried to understand the section exposed on the Wolfendorn (Tollmann, 19663; Frisch, 1974; Fenti and Friz, 1973; Lammerer, 1986). As the crest runs subparallel to the axial plunge direction, the isoclinal fold within the Hochstegen marble of the Wolfendorn was not recognized for a long time.

To the west, the Kaserer series follows. It was here that a stratigraphic contact was proposed by Frisch (1974), but this is doubted by other workers (Tollmann, 1963; Baggio et al., 1969). The Kaserer Series is topped by Mid Triassic dolomites of the Kalkwandstange and the Bündnerschiefer (Frisch, 1974). The Weißspitze is topped by a whitish dolomite klippe which may either mark the base of the Austroalpine nappes, or the upper part of the Brenner Mesozoic sequence, juxtaposed against the Bündnerschiefer by the Brenner normal fault (Selverstone, 1988). In the latter interpretation, ~10 km of the Austroalpine nappe stack has been excised by the fault.

Stop 5-4. The Quarry of Stein

(46° 58′46″N; 11° 38′25″E)

Vertically oriented 1 quartzites and phengite-chloritoid-quartz schists of the Middle or Late Triassic from the base of the Glockner nappe are mined here for flagstones and façade panels. A local increase in thickness of the weathering-resistant quartzite forms this economically important outcrop.

Stop 5-5. 200 m along the Trail to the Hochfeiler

At the third bend of the road, we park and walk 200 m upwards along the creek. We encounter calcschists of the Bündnerschiefer and we may find in the talus boulders of amphibolite with pseudomorphs of albite, white mica and clinozoisite after the high-pressure mineral lawsonite.

Stop 5-6. Acid Waters and Metaconglomerates at the Fourth Bend of the Road

We continue by car up the gravel road. After the third bend, we cross a small creek with red ferrous precipitation from acidic iron-rich water escaping from a pyrite-rich layer. At the fourth bend we reach conglomerate gneisses with flattened pebbles that form the southern limb of the tight Pfitsch syncline. After the curve we enter graphitic schists ("Furtschagelschiefer," Early Carboniferous?) that are tightly to sub-isoclinally folded. Further up we cross arkosic gneisses and marble bands of the Kaserer series.

Stop 5-7. Scenic View to the Griesscharte and the Glockner Nappe

At the sixth bend of the road to Pfitscher Joch we have a good view of the rocks of the Glockner nappe: In the south,

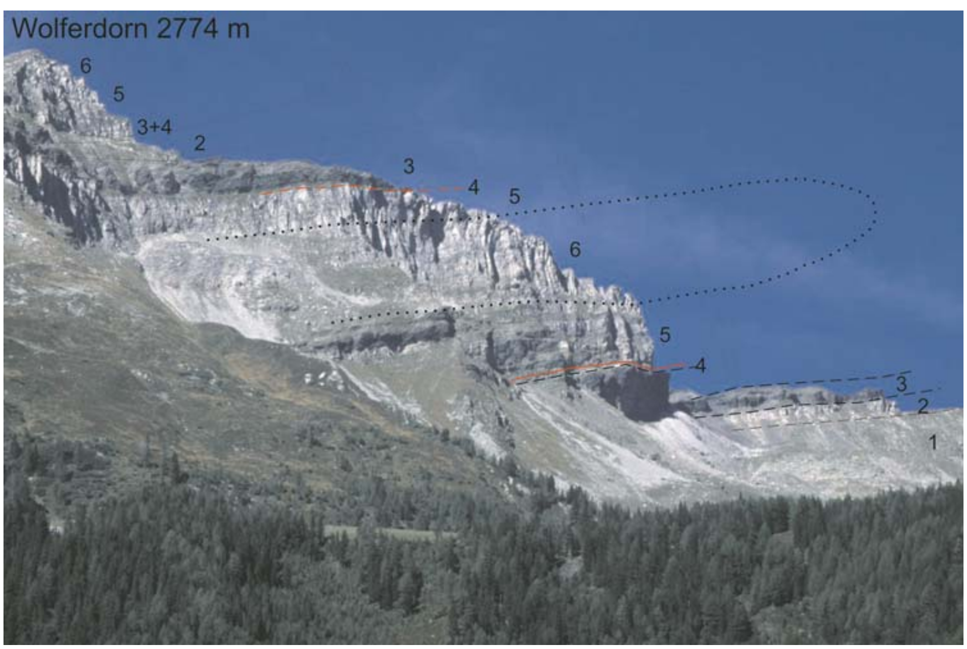

Figure 9. The Wolfendorn seen from the Pfitsch valley near Kematen. 1—Tux granite gneiss; 2—dolomitic marble with some hematite bearing quartzite at the base (Triassic); 3—graphitic quartzitic schist with black kyanite and some black marble (Liassic?); 4—brownish sandy limestone, 5—lower Hochstegen marble, banded and locally dolomitic; 6—homogeneous Hochstegen marble with occasional chert nodules. The lower part of the section is in normal position, the middle part inverted due to isoclinal folding with an axis subparallel to the outcrop, and the upper part is again in an upright position.

tightly folded calcschists and greenschists form impressive walls in the Bündnerschiefer. Two hanging glaciers come down the steep mountain flank of the Hochferner Massif. To the east, at the Griesscharte, strata from the base of the Glockner nappe dip vertically: white marbles and quartzites (the continuation of the series from Stop 5-4), graphitic schists and arkosic gneisses from the Kaserer series and two thin bands of Zentralgneis and Hochstegen marble crop out. They are in contact with graphitic schists from the Greiner series to the north.

Stop 5-8. Pfitscher Joch Haus
(46° 59′32″N; 11° 39′28″E; 2276 m)

From here, we have a good panoramic view over the western Tauern Window. The Zillertal anticline in the south and its nappe cover of the Glockner nappe plunges 25° to 30° to the west. Down in the Pfitsch valley and beyond the silted lake floor, the late Alpine syncline between the Tux and Zillertal anticlines is clearly visible. The rock mass of the Weißspitze is topped by a white Austroalpine klippe of marble, and in the far background the Austroalpine nappes of the Stubai Mountains protrude. The southern flank of the Tux anticline with the Hochstegen marble cover bends down from the Wolfendorn into the valley.

Day 6

In the Pfitscher Joch area, we discuss the kinematics of the tight syncline, the sedimentary facies of the post-Variscan rocks and the strain history of the Greiner shear zone and surrounding area. We visit the post-Variscan unconformity surface and its soil horizon.

Stop 6-1. Pfitscher Joch Area (Fig. 10)

We start in the Tux gneiss, which is in tectonic contact with a Paleozoic amphibolite that shows a prominent mineral stretching lineation gently plunging to the west. Stretching continued until the brittle stage, documented by fissures filled with biotite, chlorite, feldspar, quartz, laumontite, and other low-grade minerals. A porphyritic granite dike showing nice shear sense indicators (delta clasts, S-C fabrics) and late feeder veins cut the amphibolite.

The Pfitsch metaconglomerate or metabreccia is only moderately deformed along the northern limb of the Pfitsch syncline. Original bedding and sedimentary features can still be recognized. Poor sorting, angular components up to 30 cm in size, and poorly selected pebbles from granite to limestone and shale are typical for this coarse-grained clastic sediment (Veslá and Lammerer, 2008). The unit fines upward and is overlain by an Early Permian metarhyolite that is dated at 280 Ma (Veselá et al., 2011). Epidote-ankerite-biotite schists, which are considered to be former playa sediments, and hematite-bearing quartzites overlie the metarhyolite. The white to light gray appearance of the quartzites comes from finely disseminated, platy hematite, indicating that the protolith was a red sandstone (possibly equivalent to the Early Triassic Buntsandstein of the German basin). In a special horizon, which can be followed eastwards for ~1 km, kyanite, staurolite, and lazulite are found together with several rare aluminum phosphates (Morteani and Ackermand, 1996). This quartzite is crosscut by isoclinally folded tourmalinite veins, indicating a post-Triassic hydrothermal activity.

The axis of the syncline plunges 40° or more to the west in this sector. The younger Mid Triassic dolomites and cargneuls and the Hochstegen marble are therefore only exposed farther to the west.

Figure 10. The Greiner schists seen from northwest. To the left: the Greiner (3199 m), to the right of the Center the glacier covered Möseler (3478 m) in the background and in front of it, the ridge of dark graphite schists (Furtschagelschiefer) of the Hochsteller (3097 m) and, closer to the right, the Rotbachlspitze (2895 m) with the characteristic brownish altered rocks of the Greiner shear zone. At the right margin in the middle ground: Bündnerschiefer and whitish marbles at the Griesscharte (2901 m) in vertical position. The lighter gray Tux granodioritic gneisses to the left contrast clearly with the darker Greiner Schists and the Tux conglomerates.

The southern limb of the syncline exhibits the sequence in mirror symmetry, except that the thickness of the units is greater, even where the flattening strain is much higher. It is suspected that this reflects a deepening of the basin to the south.

Stop 6-2. Rotbachlspitze

(2895 m)

Hiking east toward the Rotbachlspitze (Fig. 9), we traverse both the Permo-Mesozoic metasedimentary units and the older hornblende garbenschist of the Greiner series. Locally, lenses of magnetite-rich, staurolite-chloritoid schist decorate the contact between the Pfitsch metaconglomerate and the garbenschist. These lenses are extremely enriched in aluminum and iron and depleted in silicon, calcium, and potassium. In general, Al+Fe contents are highest immediately adjacent to the metaconglomerate, and decrease over a distance of a few meters toward the garbenschists. These unusual rocks are interpreted to represent a paleosol developed along the unconformity between Paleozoic rocks of the Greiner Series and the Pfitsch conglomerate (Barrientos and Selverstone, 1987). The extreme enrichment in Al+Fe and the scale of the chemical zoning are consistent with deep weathering and formation of a lateritic soil. Metamorphism of this unusual bulk composition resulted in growth of Fe ± Al-rich minerals such as chloritoid, staurolite, and magnetite. Chloritoid within these rocks occurs in radiating sprays that are intergrown with quartz. These chloritoid-quartz intergrowths are likely pseudomorphs after Fe-Mg carpholite. If this interpretation is correct, it indicates that the rocks passed through blueschist-facies conditions prior to equilibration in the amphibolite facies.

Below the cliff to the south of the soil horizon, intense shearing has transformed rocks of the Greiner Series into quartz-pyrite schists. These rocks give the Rotbachlspitze (red stream peak) its name. Continuing to the southeast, we encounter highly graphitic schists (Furtschaglschiefer) that locally contain hornblende garben, and then to garnet-biotite ± hornblende schists that locally contain garnets up to 5 cm in diameter. These latter schists were dated by Christensen et al. (1994) to constrain the duration of garnet growth (<5 m.y.) and the timing of the thermal peak of metamorphism (30 ± 1 Ma) in this part of the Tauern Window.

Day 7

We discuss the large scale and small-scale deformation of the large intrusions, which are folded and sheared, then we drive back to Munich.

Stop 7-1. Polished Area with Shear Zones and Dikes of the Stampflkees

Depending on the weather conditions and the actual schedule, a morning hike toward the Stampfl Kees can be made. The tour goes along the eastern moraine of the glacier and we can see firstly the strongly deformed varieties of the Zentralgneiss, which gradually transition into less deformed metagranites. Intrusion relations of different types of Zentralgneiss are still well preserved. A leucocratic metagranite variety is associated with molybdenite-quartz veins, which were mined at the Alpeiner Scharte further northeast. This former molybdenite porphyry is also enriched in Be and may contain blue beryll (aquamarine). Aplitic dikes are abundant and show Alpine deformation, concentrated in shear zones. The protoliths of the gneisses were crosscut by Triassic-Jurassic (?) mafic dykes, probably associated with the early stages of extension. During the Alpine metamorphism they were transformed into biotite-schist. The hike continues crossing the outcrops below the glacier and we can hike back on the western moraine.

From the Pfitscher Joch we drive back to Munich via Innsbruck and Garmisch.

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