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Field trip 3

Metamorphic transect through the Eastern Alps: the tectonometamorphic evolution of the Western Austroalpine and Southalpine basement

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1 Goals and highlights of the excursion

The visited area highlights the polyphase tectonic and metamorphic evolution of the western end of the Eastern Alps (Fig. 1). While the Austroalpine units bear substantial information related to the Cretaceous evolution/orogeny, the Tauern window exposes units and rocks of European provenance, metamorphosed and deformed during Tertiary collision. With additional stops in the Southern Alps the excursion provides insight in the pre-Alpine (e.g. Variscan) evolution of this area. During the Neogene the final shaping of this area occurred in the context of lateral extrusion and exhumation.

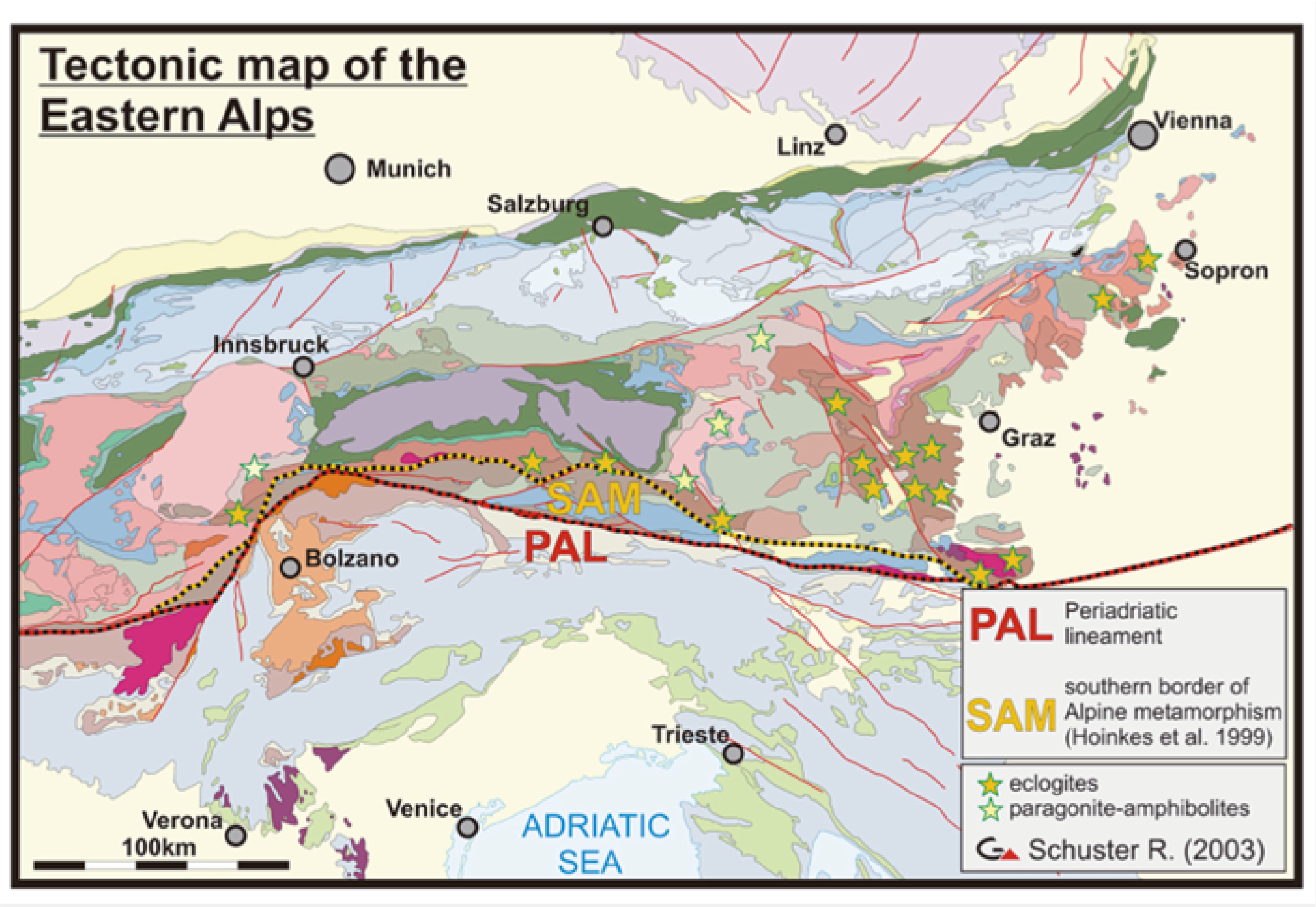


Fig. 1: Tectonic map of the Eastern Alps after Schuster (2003, written comm.).

2 Geologic setting

2.1 Tectonic and metamorphic evolution

Based on their position within the Alpine orogen (Fig. 2) the individual lithostratigraphic units of the Austroalpine unit experienced different metamorphic histories during these four metamorphic events mentioned above. Most of the units are polymetamorphic, but several of them experienced only one imprint: e.g. in the Silvretta-Seckau-, Ötztal-Bundschuh- and Drauzug-Gurktal nappe systems, as well as in the Greywacke zone units with a dominating Variscan metamorphic imprint occur. In many cases they are transgressively overlain by unmetamorphosed or very-low grade metamorphic Permomesozoic sequences, whereas others experienced an additional eo-Alpine overprint. Most of the units in the Koralpe-Wölz nappe system experienced a Permio-Triassic imprint and an eo-Alpine overprint which reached up to eclogite facies conditions. However, parts of the Wölz- and Radenthein Complexes show only the eo-Alpine metamorphic imprint.

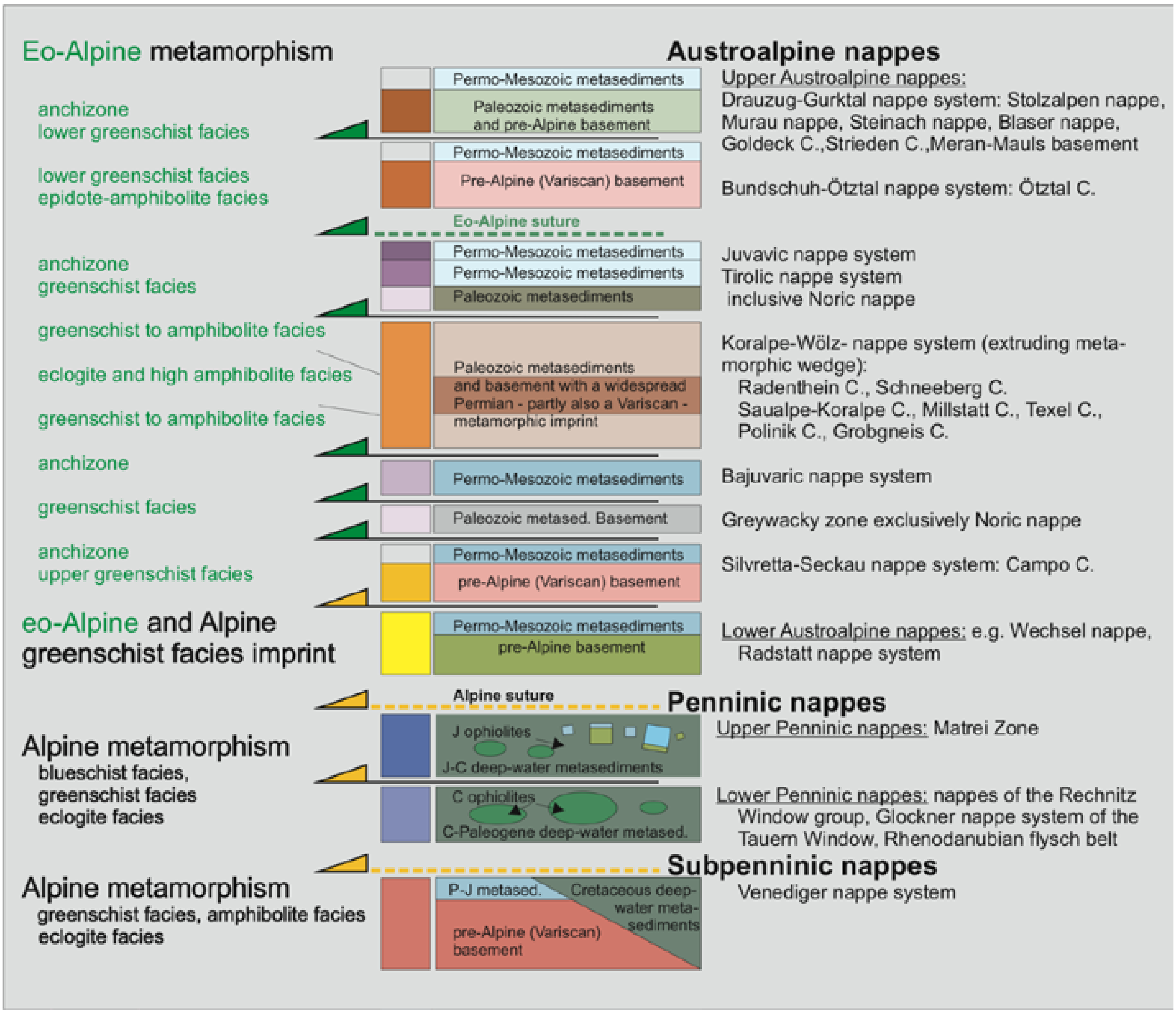


Fig. 2: Tectonostratigraphy of the Austroalpine, Penninic and Subpenninic nappes after Schuster (2003, written comm.).

In the Eastern Alps, the metamorphic Austroalpine basement typically shows polymetamorphism due to a sequence of metamorphic overprints, affecting this part of the Alps (Oberhänsli et al., 2004; Schuster et al., 2004). The most dominant metamorphic overprints are the Variscan- and the Eo-Alpine metamorphic event (Hoinkes et al., 1999; Neubauer et al., 1999; Thöni, 1999). In recent years, geochronological data also point to a widespread Permian thermal overprint mainly observed in the eastern part of the Austroalpine units (Schuster et al., 2001). Since Paleozoic times it was affected by four regional metamorphic events (Oberhänsli et al., 2004, Schuster et al., 2004) in the Ordovician (Fig. 3), the Late Devonian to Carboniferous (Fig. 3), Permian (Fig. 4), Cretaceous (Fig. 5) and Oligocene to Miocene times. The Ordovician metamorphic event occurs only locally in the Ötztal Complex as migmatites. The Late Devonian to Carboniferous imprint is related to the Variscan orogenic cycle and occurs throughout the Austroalpine. In Permian times large parts of the Austroalpine units were affected by lithospheric extension and related high-temperature/low-pressure metamorphism. The eo-Alpine tectonothermal event in the Cretaceous is due to intracontinental shortening within the Austroalpine unit. Finally in Oligocene to Miocene times a thermal influence of the Alpine metamorphic event, related to the continental collision after the closure of the Penninic oceans can be recognised in the tectonically lowermost Austroalpine units to the south of the Tauern Window.

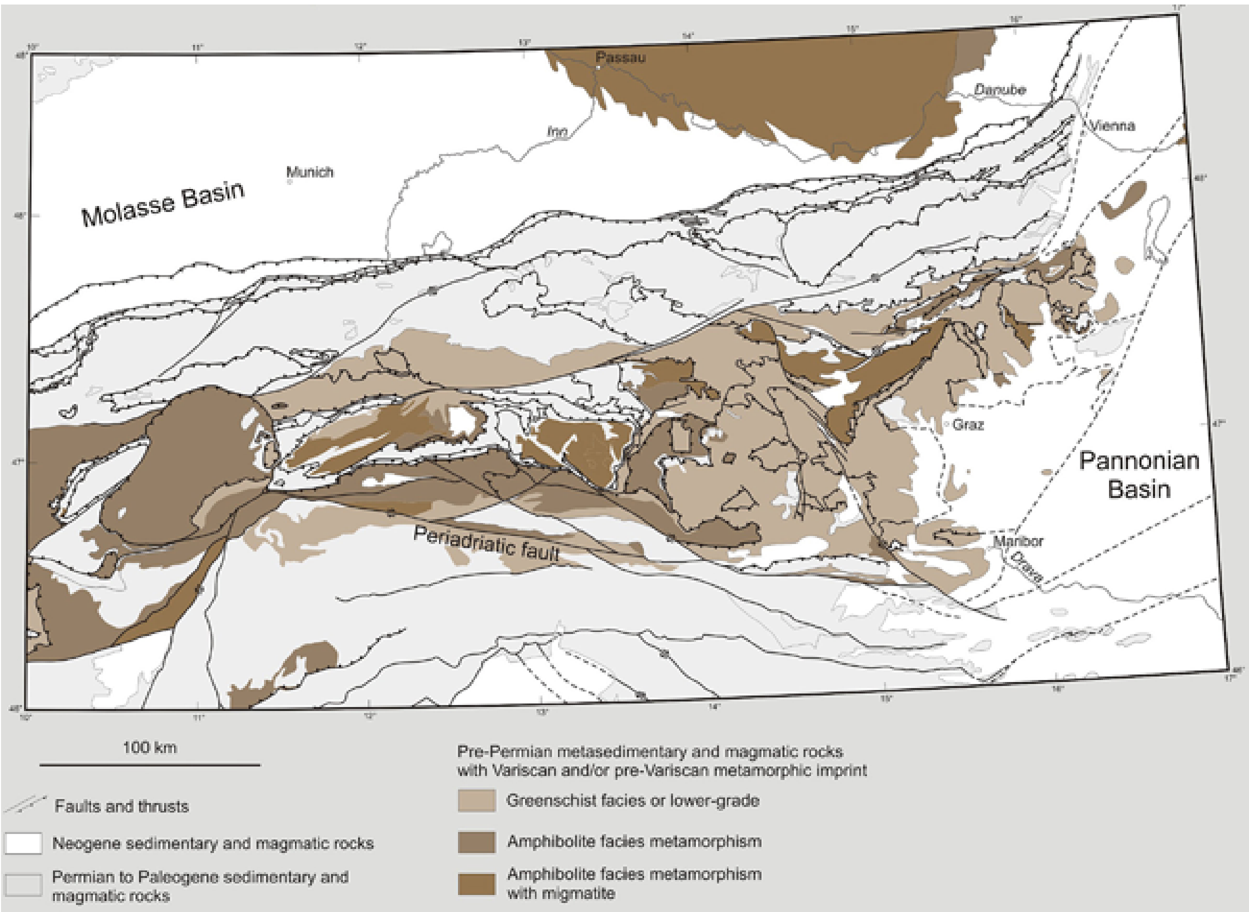


Fig. 3: Regional distribution of the pre-Variscan- and Variscan metamorphic overprint in the Eastern Alps (modified after Schuster, 2013, written comm.).

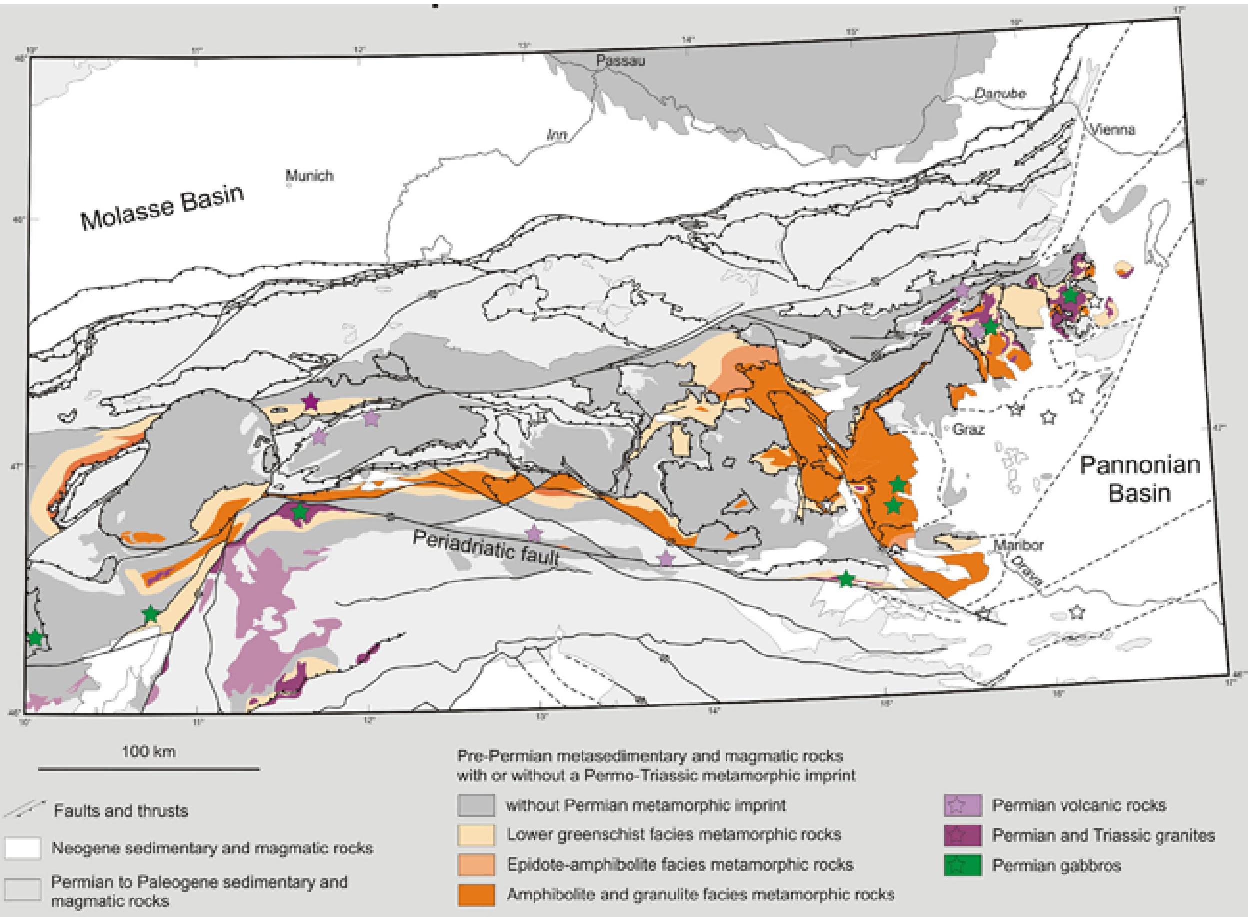


Fig. 4: Regional distribution of the Permian metamorphic overprint in the Eastern Alps (modified after Schuster, 2013, written comm.).

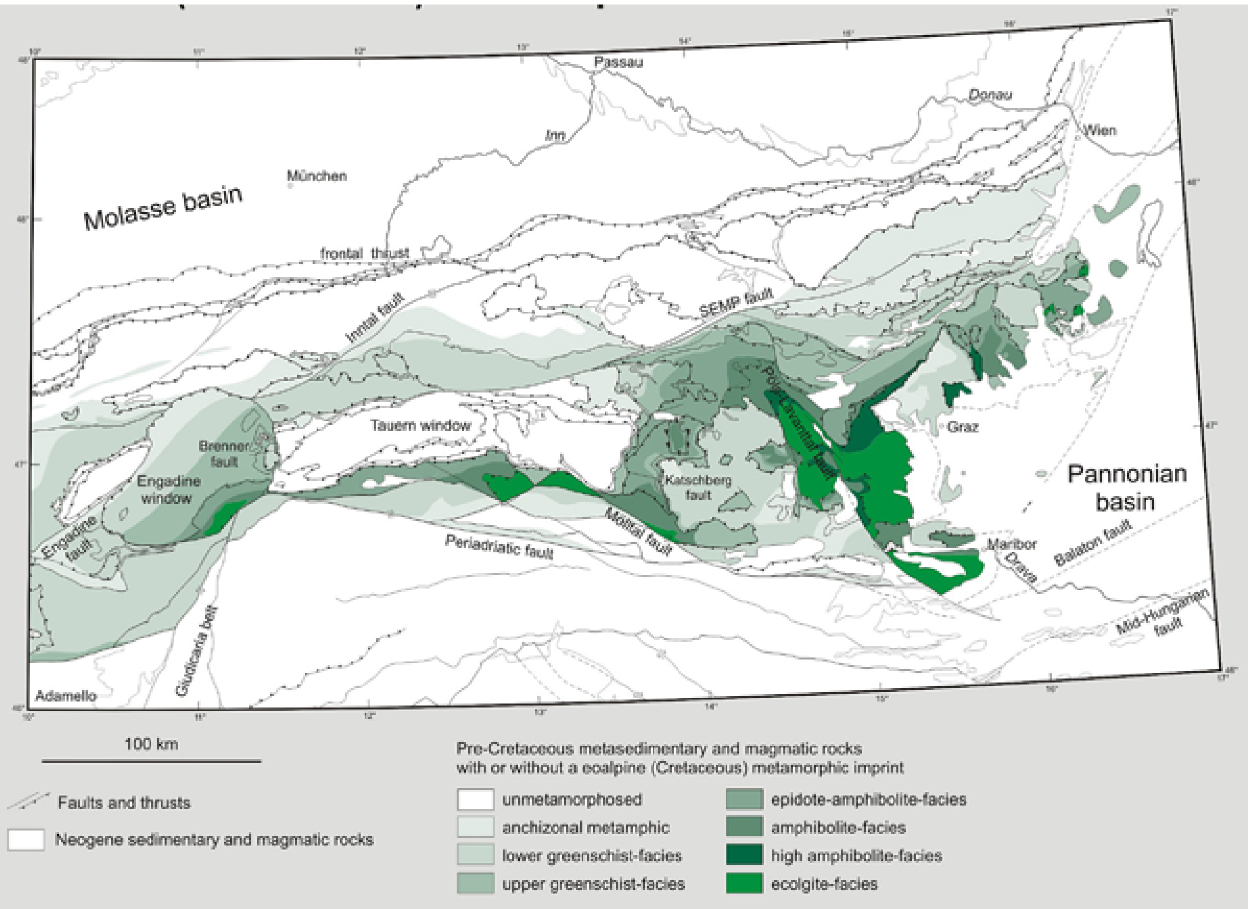


Fig. 5: Regional distribution of the eo-Alpine metamorphic overprint in the Eastern Alps (modified after Schuster, 2013, written comm.).

2.2 Tectonic overview

In the following a brief description of the different units as shown in Fig. 6 will be given:

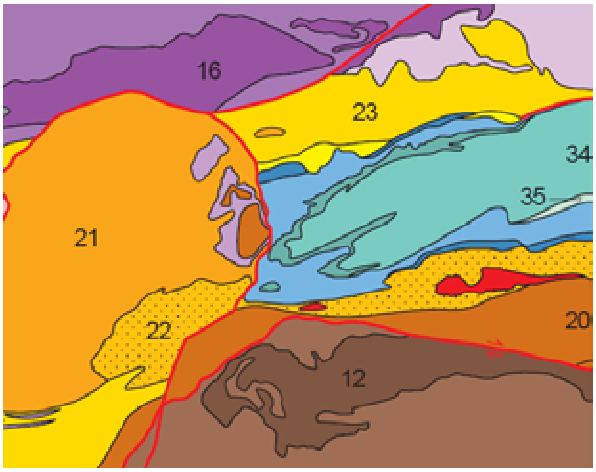


Fig. 6: Tectonic map of the Brenner area (from Schmid et al., 2004): 12: upper crust Southern Alps, 13: post Variscan cover Southern Alps, 16, 17, 18: Upper Austroalpine nappes (NCA and GWZ), 21: Upper Austroalpine basement nappe ÖC, 22: Upper Austroalpine basement nappe Texel complex, 23: Upper Austroalpine basement nappes (Campo, Innsbruck quartzphyllite), 24: Lower Austroalpine basement nappe, 26: Upper Penninic nappe, 32: lower Penninic nappe, 33: Sub-Penninic: Mesozoic cover, 34: Sub-Penninic: non eclogitic basement, 35: Sub-Penninic: eclogitic basement.

The **Tauern Window** (Fig. 6, units 32-35) exposes Penninic and sub-Penninic (European distal margin) units in the footwall of the Austroalpine nappe complex, which forms the hanging-wall plate during Tertiary plate collision. The units within the Tauern Window are separated into several nappes that are characterized by typical lithofacial assemblages. From the footwall to the hanging-wall, the nappe stack includes:

(1) The Venediger Nappe and the Wolfendom Nappe comprising a pre-Variscan basement intruded by Variscan granitoids (Zentralgneis cores) and a cover sequence of Jurassic metacarbonates, and Cretaceous metapelites and metapsammites.
(2) The Storz and Riffl Nappes comprising Variscan and Alpidic polymetamorphic basement rocks covered by the late Palaeozoic(?) or Cretaceous(?) metapelites and graphitic quartzites.
(3) The Eclogite Zone which is restricted to the central southern Tauern Window and which is characterized by a Mesozoic volcano-sedimentary sequence.
(4) The Rote Wand-Modereck Nappe, consisting of basement rocks which are covered by Permian to Triassic quartzites and Triassic metacarbonates, Jurassic breccias, calcareous micaschists and metatuffs as well as Cretaceous metapelites and metapsammites.
(5) The Glockner Nappe, which contains an oceanic basement (serpentinites and ultramafic rocks) and a partly incomplete ophiolithic sequence.
(6) The Matrei Zone, interpreted to represent an accretionary wedge that is characterized by metamorphic flysch sediments, breccias and olistolithes mainly of Austroalpine derivation.
(7) The Klammkalk Zone, consisting of calcareous schists, massive marbles and minor phyllites, forming a low-grade metamorphic equivalent to the 'Bündnerschiefer' in the Glockner Nappe.

These units are surrounded by the remnants of Lower Austroalpine units. The Eclogite Zone contains mafic eclogites of tholeiitic and slightly alkaline chemical composition (Miller, 1974, 1977, 1987). The protoliths are assumed to be basalts with an intra-plate character (Höck and Miller, 1987). They are often retrogressed to garnet-amphibolites and garnet-bearing greenschists due to a Barrovian-type, greenschist to amphibolite-facies overprint. The associated metasediments experienced the same high-pressure metamorphism (Franz and Spear, 1983; Dachs, 1986, 1990; Spear and Franz, 1986). The rocks exposed within the Eclogite Zone experienced a polyphase metamorphic evolution. Starting with inclusions in garnets, which are sometimes interpreted as pseudomorphs after lawsonite, a first stage of metamorphism at ca. 400°C can be deduced (Miller, 1977, 1986; Frank et al., 1981, 1987). Eclogite-facies metamorphism is only rarely documented and is only observed clearly in the Eclogite Zone. The eclogite-facies rocks were buried to a depth of at least 65 km (20 kbar, 600°C; Holland, 1979; Dachs, 1986, 1990; Frank et al., 1987a; Droop et al., 1990; Selverstone et al., 1992; Zimmermann et al., 1994; Getty and Selverstone, 1994). On the other hand, the entire nappe pile of the Tauern Window was subsequently affected by pervasive blueschist-facies metamorphism with *P-T* conditions ranging from 7-15 kbar and ca. 450°C (Raith et al., 1980; Holland, 1979; Zimmermann et al., 1994; Holland and Richardson, 1979; Selverstone et al., 1992; Cliff et al., 1985; Droop, 1985; Holland and Ray, 1985; Frank et al., 1987; Selverstone, 1993). Finally, the entire nappe pile was affected by Barrovian-type upper greenschist to lower amphibolite-facies metamorphism (e.g., Frank et al., 1987a; Selverstone, 1993). Phengite ^{40}Ar-^{39}Ar mineral ages of ca. 36-32 Ma (Zimmermann et al., 1994) from the Eclogite Zone are interpreted to represent cooling ages subsequent to Eocene blueschist-facies metamorphism (Zimmermann et al., 1994).

The **Innsbruck Quartzphyllite** (Fig. 6, unit 23) outcrops between Mittersill in the east and Innsbruck in the west. It is typically a rather monotonous, fine-grained, greenish to grayish phyllitic schist, with the mineral assemblage muscovite + chlorite + albite + quartz ± calcite. Locally, garnet-bearing schists occur south of the Patscherkofel. It has been divided into three stratigraphical units consisting of Devonian carbonatic black shales, Silurian carbonatic-sericitic phyllites and Ordovician quartzphyllites and greenschists, however numerous transitions may be found (Haditsch and Mostler 1982). Although most of the Innsbruck Quartzphyllites were affected by lower greenschist-facies metamorphism (Hoschek et al. 1980; Sassi and Spiess, 1992; Piber and Tropper, 2005), some central parts of the Innsbruck Quartzphyllite have been affected by middle greenschist-facies metamorphism (Kolenprat et al. 1999; Piber and Tropper, 2007). Geochronological investigations revealed a complex metamorphic history indicating a possible Permian- and Eo-Alpine overprint (Dingeldey et al., 1997; Rockenschaub et al., 1999; Handler et al., 2000). Recently, a number of new results have been obtained concerning the internal structure of the Innsbruck Quartzphyllite (Kolenprat et al., 1999). Large parts of the Innsbruck Quartzphyllite must therefore be considered as highly deformed, retrograde old (Variscan?) basement. These studies revealed a metamorphic zonation with garnet-free phyllites at the northern and southern rims and garnet bearing phyllites in the central part, thus reflecting a slightly higher grade of metamorphism in the center. This observation was interpreted in terms of a km-scale isoclinal fold of the Innsbruck Quartzphyllite (Schmidegg 1964, Rockenschaub 1998; Kolenprat 1998). Kolenprat et al. (1999) show, that the Innsbruck Quartzphyllite has a complex deformation history, with structures ranging from pre-Alpine (Variscan) to late Alpine (Neogene) in age. The pre-Alpine foliation is preserved only locally. During the Eo-Alpine orogeny, intensive mylonitization associated with W- to NW-directed nappe stacking, occurred. The Meso- and Neo-Alpine deformation is characterized by the imbrication of Austroalpine units as a consequence of N-directed thrusting of the Austroalpine nappes over the Penninic Units and subsequent exhumation of the Tauern-Window during N-S-shortening and E-W-extension (Kolenprat et al., 1999). On top of the Innsbruck Quartzphyllite, two units occur in the vicinity of the Brenner base tunnel, namely the Patscherkofel Crystalline Complex and the Kellerjochgneiss.

The **Patscherkofel Crystalline Complex** (PCC) is part of the Austroalpine basement nappes north of the Tauern Window, which is tectonically located on top of the Innsbruck Quartzphyllite. The PCC is mainly composed of mica schists with the mineral assemblage plagioclase + muscovite + biotite + chlorite + quartz ± chloritoid ± garnet$_{1,2}$ ± ilmenite ± clinozoisite ± staurolite ± margarite. Garnet$_1$ + staurolite represent Pre-Alpine relicts, all other minerals are part of the Eo-Alpine mineral assemblage. Thermobarometric investigations of Piber et al. (2008) yielded temperatures between 510°C and 570°C and pressures ranging from 9.5 to 12.2 kbar for the samples from the PCC.

The **Kellerjochgneiss**, or Schwaz Augengneiss is also part of the Austroalpine basement nappes north of the Tauern Window. The Kellerjochgneiss is a former I-type augengneiss and contains the mineral assemblage muscovite + plagioclase + chlorite + quartz ± biotite ± clinozoisite. It tectonically overlies the Innsbruck Quartzphyllite. Multi-equilibrium calculations of samples of the Kellerjochgneiss yielded pressures ranging from 3.2 to 6.8 kbar and temperatures ranging from 285 to 345°C (Piber, 2005).

The **Tarntal Nappe** (Fig. 6, unit 24) is a complex geologic unit at the northern rim of the Tauern Window, which consists of low-grade metamorphic sediments and a dismembered ophiolite body, and is tectonically emplaced between the contact of the Austroalpine Innsbrucker Quarzphyllite nappe and the Penninic Glockner nappe at the northern margin of the Tauern Window (Tirol, Austria). During the Alpine metamorphic overprint, blueschists formed at the contact between the metasedimentary units and the ultramafic units of the ophiolite within the Tarntal Nappe. Dingeldey et al. (1997) and Klier (2005) obtained metamorphic peak *P-T* conditions of 350°C and 8 to 10.5 kbar. The age of the metamorphic overprint was dated with 50-40 Ma depending on the tectonic position of the samples.

The Wildschönau Schists and the Schwaz Dolomite form part of the **Greywacke Zone** (Fig. 6, unit 18). According to Mostler (1973) the Western Greywacke Zone is a stratigraphic sequence of meta-sediments with volcanic intercalations, ranging from the Ordovician to the Late Devonian. The Wildschönau Schists are composed of light gray phyllites similar to the Innsbruck Quartzphyllite. Roth (1983) characterized two different varieties of the Wildschönau Schists, the sandy type and the phyllitic type. The mineral assemblage of the Wildschönau Schists is very similar to the Innsbruck Quartzphyllites containing the mineral assemblage muscovite + chlorite + albite + quartz ± calcite. In the Western Greywacke Zone, modern thermobarometric data were lacking until recently. Based on index minerals, Hoschek et al. (1980) estimated lower greenschist-facies conditions for the Wildschönau Schiefer. Piber (2005) obtained *P-T* conditions of 4.5 kbar and 330°C, based on multi-equilibrium thermobarometry on one sample of the Wildschönau Schists. Geochronological investigations by Handler et al. (2000) and Anglmeier et al. (2000) indicate a Permian metamorphic overprint. Using ^{40}Ar-^{39}Ar and ^{87}Rb-^{87}Sr recently yielded Eo-Alpine ages in the central Greywacke Zone of 102-98 Ma (Schmidlechner et al., 2006) in addition to the ^{87}Rb-^{87}Sr ages of 137 to 127 Ma and ^{40}K-^{39}Ar ages of 113 to 92 and 113 to 106 Ma from the Greywacke Zone close to Zell am See which also give reasonable evidence for an Eo-Alpine metamorphic overprint around ca. 300°C (Kralik et al., 1987).

The **Ötztal Complex** (Fig. 6, ÖC, unit 21) is a large crystalline complex in the western part of the Austroalpine units. The ÖC consists of quartzofelspatic and metapelitic metasediments with various intercalations of orthogneisses, amphibolites and rare metacarbonates. The oldest metamorphic event is "Caledonian" in age (460 - 490 Ma), leading to the formation of orthogneisses (Thöni, 1986) and scattered occurrences of migmatites (Söllner et al., 1982; Söllner and Schmidt, 1981; Klötzli-Chowanetz et al., 1997). Hoinkes (1973) estimated the *P-T* conditions of migmatite formation with 680°C and ≥4 kbar, Thöny et al. (2008) obtained slightly lower pressures of <2.8 kbar. The Variscan metamorphic overprint ranges from 390 - 295 Ma (Thöni, 1999). The first stage of the Variscan event was a high-pressure metamorphism around 373 - 359 Ma, leading to the formation of eclogites in the central part of the ÖC (Miller and Thöni, 1995). The conditions of the eclogite facies were estimated to be 710 - 750°C and 27 - 28 kbar (Miller and Thöni, 1995). The dominant amphibolite facies metamorphism occurred around 330 - 350 Ma, as evident from Sm-Nd garnet-whole rock ages from micaschists (Schweigl, 1993, 1995; Hoinkes et al., 1997; Thöni, 1999). Purtscheller (1969) observed on the basis of the regional distribution of Al_2SiO_5 polymorphs in metapelites a systematic regional zonation and distinguished within the ÖC two zones: (1) the southern and northern kyanite zone and (2) the central sillimanite zone including the andalusite zone in the west. Hoinkes and Thöni (1993) pointed out that the occurring mineral zonation does not have to be the consequence of a single Variscan metamorphic event. Tropper and Hoinkes (1996) estimated *P-T* conditions of 570 - 640°C and 5.8 - 7.5 kbar for the northwestern part of the ÖC. The youngest metamorphic event in this Austroalpine basement occurred during the Cretaceous Eo-Alpine orogeny (100 - 73 Ma, Thöni, 1981; Thöni, 1999; Exner et al., 2001; Habler et al., 2001). The intensity of the Eo-Alpine overprint varies within the ÖC and increases from NW (lower greenschist facies) to SE (epidote-amphibolite facies) and reaches 550 - 600°C and ≥11 kbar in the Schneeberg Complex (Hoinkes et al., 1991; Konzett and Hoinkes, 1996). This zonation ends abruptly at the Passeier-Jaufen Line. This leads also to resetting of Variscan cooling ages from the NW to the SE (Thöni 1981; Thöni, 1999). To the south of the Passeier-Jaufen Line, in the Meran-Mauls basement (MMB) only a weak Eo-Alpine metamorphic overprint can be detected (Spiess, 1995).

The Paleozoic **Schneeberg Complex** (SC) consists of at least three narrow and structurally complicated synclines folded into the southern part of the polymetamorphic ÖC. The metasediments of the SC are characterized by the frequent presence of metamarls and marbles as opposed to the ÖC where such lithologies are missing with few exceptions known from the central ÖC (Hoinkes and Thöni, 1993). Sölva et al. (2001, 2005) define the SC as a tectonic unit associated with the Schneeberg normal fault zone, separated from the ÖC and strongly affected by the Eo-Alpine tectonometamorphic event. Most recently, the discovery of Eo-Alpine andalusite coexisting with staurolite + biotite + garnet at temperatures ≥540°C places tight constraints on the retrograde part of the Eo-Alpine *P-T* path of SC rocks that is characterized by an almost isothermal decompression from the peak of metamorphism into the andalusite stability field. SC rocks do not provide any evidence for an earlier, high-pressure stage. Geochronologic results by Elias (1998) and Fügenschuh et al. (2000) point to a rapid uplift and exhumation of both SC and underlying ÖC after the peak of metamorphism. According to Fügenschuh et al. (2000) initial uplift rates were around 1 mm/year starting around 90 Ma, which decreased to values of 0.2 to 0.7 mm/year (Hoinkes et al., 1991).

The **Texel Complex (TC)** to the south of the SC is a very characteristic example of eo-Alpine high-pressure metamorphism. Interestingly geothermometry shows an increase in P-T over the years. Initially (1991) limiting pressures of 1.1 to 1.2 GPa were obtained using the breakdown of albite to jadeite + quartz. Then (2006) pressures (although again only limiting based upon the breakdown of albite) increased to 1.2 to 1.4 GPa in order to increase (2008) to *P-T* conditions of 1.8-2.2 GPa and 560-600°C. These calculations involved the mineral assemblages garnet + omphacite + epidote + quartz and garnet + omphacite + Na-Ca amphibole + epidote + quartz. In 2013 the *P-T* conditions of eclogites from the Texel Complex climbed to 2.65-2.90 GPa and 630-690°C by using the garnet-phengite-clinopyroxene barometer.

The Variscan basement of the **Southalpine domain** (Fig. 6, unit 13) is confined to the west and north by the Periadriatic (Giudicarie line and Pustertal line) fault system. In the southeast, small basement outcrops within the Cenozoic molasse deposits of the Po Plain occur. Most of the basement is comprised of monotonous quartzphyllites (Brixen Quartzphyllite), which were pervasively affected by the Variscan metamorphic and tectonic overprint. Due to its now slightly tilted position, the basement shows a metamorphic gradient, which increases from southeast towards northwest (Sassi and Spiess, 1993). In the area of Toblach, the basement contains the mineral assemblage quartz + chlorite + white mica + albite and represents the lowest peak metamorphic conditions of the basement with temperatures of 350–400°C and a pressure of ca. 0.4 GPa. The metamorphic conditions increase towards the northwest and reach maximum *P-T* conditions in the area of Brixen/Bressanone. In this area the basement contains the mineral assemblage quartz + biotite + chlorite + white mica + garnet + albite + plagioclase and calculated *P-T* conditions based on garnet-biotite thermometry and plagioclase–biotite–garnet–muscovite barometry yielded temperatures of 450–550 °C and pressures of 0.5–0.65 GPa (Ring and Richter 1994).

In the Southalpine domain the **Permian intrusive complexes** of the Brixen granite, Ifinger granodiorite and Kreuzberg granite cover an area of ~250 km^2 and are thought to have been the result of the collapsing Variscan orogenic belt, which led to the formation of large extensional terrains (Acquafredda et al., 1997; Bargossi et al., 1981; Bargossi et al., 1998; Del Moro & Visona, 1982). Although these intrusive complexes were already mapped (Del Moro & Visona, 1982) and considerable literature concerning their magmatic evolution already exists (Bonin et al., 1993; Schuster et al., 2001; Dal Piaz & Martin, 1998) almost no petrological (Bonin et al., 1993; Aquafredda et al.,

1997) and only few geochronological data (Bonin et al., 1993; Borsi et al., 1972; Rottura et al., 1998) are available so far. The investigated intrusions namely the Brixen/Bressanone granodiorite, the Ifinger/Ivigna granite and the Kreuzberg/Monte Croce granite are all aligned along the Periadriatic Lineament. The major part of the Brixen granite is granitic to granodioritic in composition with the mineral assemblage K-feldspar + plagioclase + biotite + quartz + accessories (zircon, apatite, ilmenite, ± monazite). Zircon ages from three intrusions in the Southalpine basement show ages ranging from 293 ± 12 Ma (Kreuzberg granite), 289 ± 6.1 Ma (Ifinger granodiorite) to 278 ± 12 Ma (Brixen granite). These geochronological data seem to indicate a rejuvenation trend from south-west to north-east, which might be evidence for a plane motion of the north-western realm of the Athesian Volcanic Group (AVG) caldera during the late Variscan orogeny collapse (Thöny, 2008).

3 Brief description of stops

Day 1

Stop 1, Sillschlucht

Located at the southern limit of Innsbruck directly under the ski jump stadium this stop allows to discuss the local geology in the area of the northern entrance of the Brenner Base Tunnel (Fig. 7). The outcrops are located along a small track near the river Sill. Apart from unstable Quaternary deposits, giving rise to mobility right at the tunnel entrance, the local geology is dominated by quartzphyllite. Metamorphosed under lower greenschist-facies conditions during the Variscan cycle the rocks show multiphase tectonic overprint from ductile deformation during pre-Alpine and Alpine times to Neogene brittle deformation. Second phase folding led to the formation of a large recumbent fold, which has granitic basement in its core. Although rather monotonous, different lithologies can be observed along the track, ranging from

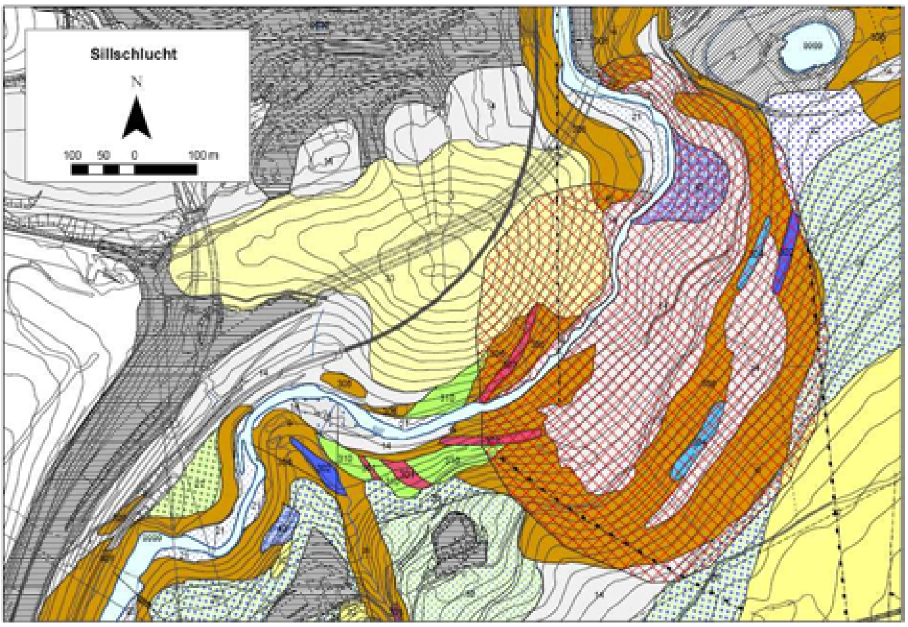


Fig. 7: Detailed geological map of the northern entrance Brenner Base Tunnel (Brandner et al., 2008). Hatched area: rockslide. Brown: quartzphyllite, red: porphyry, green: prasinite, blue: marbles.

porphyries to amphibolites/prasinites to marbles. According to the overall appearance the quartzphyllite unit most likely represents a metamorphosed turbidite sequence.

Stop 2, Stefansbrücke

Some 5 km south of Innsbruck along the federal road to Brennerpass brittle fault rocks related to the Brenner Fault Zone are outcropping in an abandoned quarry. The tectonically overprinted host rock is the basement of the ÖC various stages of brittle deformation can be studied. While the least deformed part still displays the original features (schistosity, folds in paragneiss) deformation intensity increases to finally expose a fault gouge. Depending on the outcrop conditions (due to the brittle deformation the are very erodable) shear sense criteria pointing to top to the west kinematics can be observed (Fig. 8). Seve-ral similar outcrops of fault gouge in the wider Brenner area have been sampled by Zwingmann and Mancktelow (2004) for conventional K/Ar dating of clay minerals. While most of the samples yielded Neogene ages, in accordance with the brittle faulting along the BFZ, the samples from this outcrop are dominated by Cretaceous ages. This clearly points to inherited information from the overwhelming Cretaceous metamorphic overprint within the ÖC.

Stop 3, Nösslach

This overview stop is located south of the village of Steinach along a side road close to the highway exit Nösslach. If the weather is fine this stop offers a beautiful overview into the local nappe pile, exposing, from bottom to top, Zentralgneiss, Schieferhülle, Tarntaler Mesozoic, Innsbrucker Quartzphyllite, Northern Calcareous Alps, Ötztal Stubai Complex and Steinacher nappe. It is also from this point that you can judge the substantial amount of tectonically omitted material due to normal faulting along the BFZ (Fig. 8).

Stop 4, Brennerpass

From the Brennerpass on the Austrian side a small paved road brings us up to an active quarry in the Zentralgneiss. Along the road highly mylonitized rocks of the upper Schieferhülle (Bündnerschiefer)

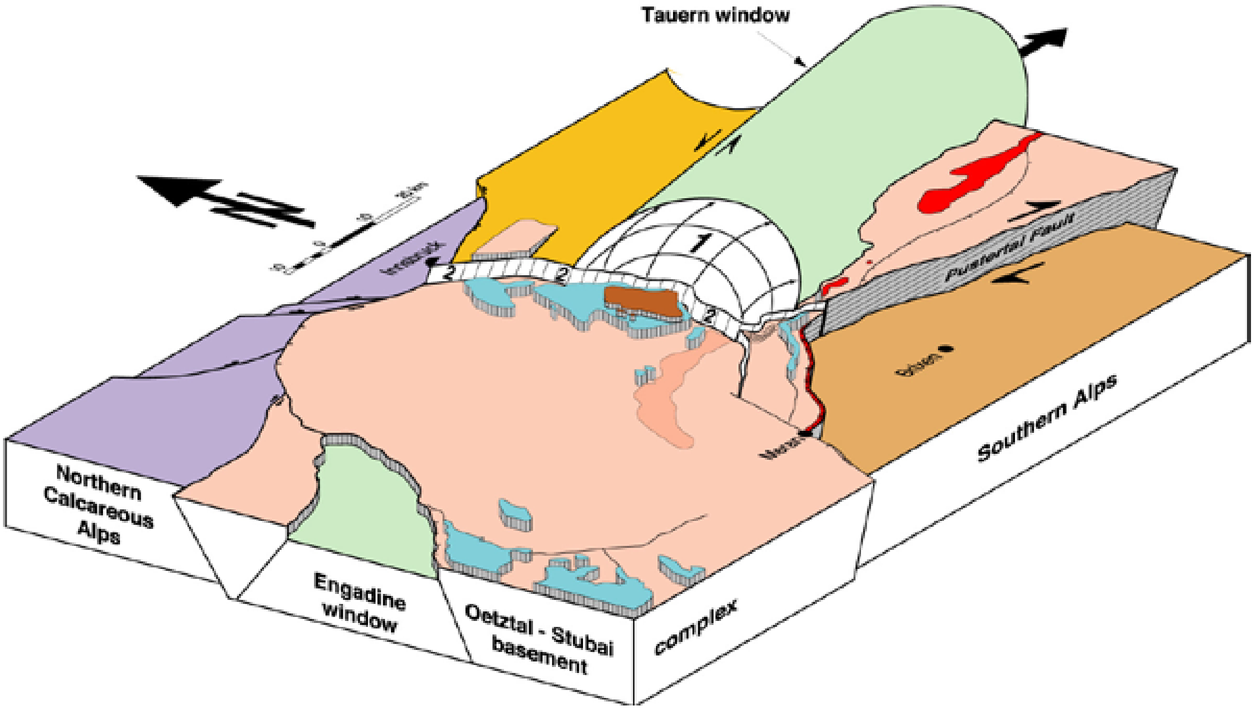


Fig. 8: Simplified block diagram illustrating the Brenner fault zone and the involved units (Fügenschuh et al., 1997).

with beautiful shear sense criteria can be observed. In the quarry the Permian Zentralgneis is tectonically overlain by Mesozoic strata including the limestone mylontes of the Hochstegen formation. The granitic gneis is exposed in the core of a major WSW-ENE trending antiform, related to Tertiary nappe piling and overprinted by Neogene ormal faulting (Fig. 8). Deformation within the granite is varying, ranging from almost undeformed to strongly flattened. This allows for a guess on the width of the BFZ shear zone on the order of 1-2 km. Apart from magmatically zoned feldspars various enclaves and xenoliths can be studied.

Stop 5, Mauls

In the village of Mauls (south of Sterzing) we follow a paved road towards the east entering a small valley. In the riverbed of the "Nöckebach" we can touch the contact between the metamorphosed Austroalpine basement and the unmetamorphosed southern Alpine basement together with a small Oligocene tonalite body. This part of the Periadriatic fault, a first order fault system in the Alps, does not, as elsewhere, represent the suture between Europe and Adria but forms a repeatedly activated fault zone which originally might have formed the retro-wedge of the Cretaceous orogen. The outcrop is prime importance for the construction of the Brenner Base Tunnel since this tectonic zone will be crossed. On the surface it has a clear brittle character yet mylonites can definitively be expected at somewhat deeper levels. Due to its rather vertical dip it is not monitored in the seismic Transalp section, which gave rise to rather provocative models. This part of the Periadriatic fault system is furthermore of great importance for solving the question of an originally straight vs. an already curved fault zone.

Stop 6, Franzensfeste/Mittewald

The major part of the Permian Brixen granodiorite is granitic to granodioritic in composition with the mineral assemblage K-feldspar + plagioclase + biotite + quartz + accessories (zircon, apatite, ilmenite, ± monazite). The south-eastern border is characterized by the occurrence of tonalite,

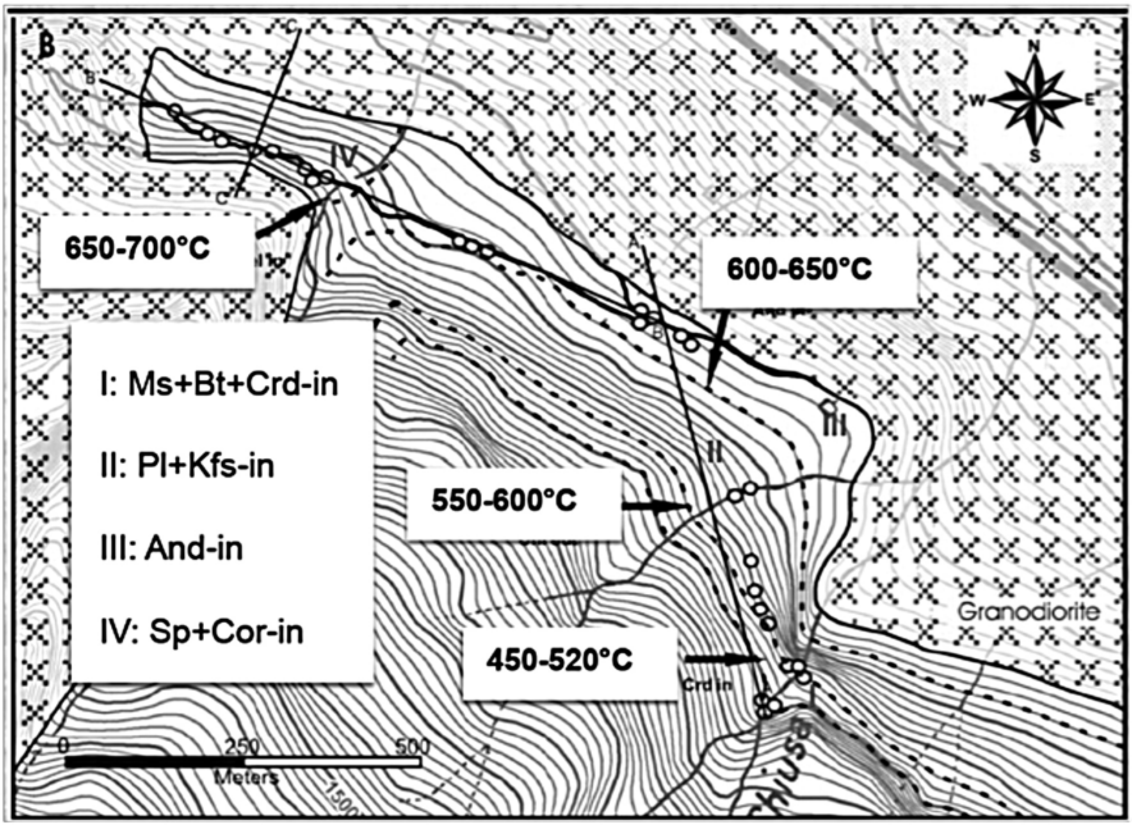


Fig. 9: Observed mineral zones in the contact aureole at the southern rim of the Brixen granite in Franzensfeste/Fortezza.

quartz-diorite and quartz-gabbro. At the northwestern rim, several unusual types of plutonic bodies occur, namely a garnet-fayalite bearing granite near Mittewald and a two mica -andalusite-cordierite granite at the Sattelspitze. The two mica codierite andalusite granite from the Sattelspitze for instance represents a peraluminous pegmatite of the latest stage of magmatic activity. The outcrop next to the road shows the rocks of the Brixen granite as well as small veins of the garnet-fayalite-bearing granite. Geochronological investigations using Sm/Nd garnet-whole rock isochron ages yielded 280 ± 2 Ma (Thöny, 2008). Only a small, about 200 meters wide, contact aureole formed at the southern rim of the Brixen Granodiorite near the village Franzensfeste (South-Tyrol, Italy) as shown in Figure 9. Within the contact aureole four different zones can be distinguished based upon mineralogical, mineral chemical and textural features (Wyhlidal *et al.* 2012). Approximately 200 m from the granite contact zone I occurs. The rocks from this zone are macroscopically still quartzphyllites and are characterized by two texturally and chemically different generations of micas (muscovite, biotite) and the appearance of cordierite. Zone II is characterized by quartzphyllites containing pseudomorphs of cordierite + biotite after garnet. The inner contact aureole (zone III) starts approximately 50 m from the granite contact and shows already typical hornfels textures. This zone is characterized by the first occurrence of andalusite. In the innermost area (zone IV), ca 10 m from the granite contact, spinel and corundum occur. Geothermometry (two-feldspar-, Ti-in-biotite) yielded an increase in temperature from 540°C in the outermost aureole (zone I) to <740°C in the innermost aureole (zone IV).

Stop 7, Gufidaun

Southalpine basement and metagabbro: within the rather uniform Southalpine quartzphyllite basement a large metagabbro/amphibolite

Fig. 10: Hand specimen of the Gufidaun metagabbro showing cm-size black amphibole crystals.

complex occurs in the village Gufidaun (Fig. 10). The amphibolites and gabbros contain the mineral assemblage amphibole + plagioclase + clinozoisite + chlorite + titanite ± ilmenite ± quartz ± calcite. Chemical zoning in idiomorphic amphiboles shows evidence for a prograde growth history. The cores of the chemical zoned amphiboles show actinolite composition and the rims can be chemically classified as Mg-hornblende, edenite, Mg-hastingsite and pargasite. The chemical zoning shows increasing Na[B]-contents and decreasing Ca[B]-contents from core to rim. The increasing glaucophane substitution (Na[B] $Al^{VI}[C] \Leftrightarrow Ca[B]_{-1}Mg[C]_{-1}$) and the increasing edenite- ($Na[A]Al[T] \Leftrightarrow [B]_{-1}Si[T]_{-1}$) and tschermakite- ($Mg[C]Si[T] \Leftrightarrow Al[C]_{-1}Al[T]_{-1}$) substitutions towards the rims indicate increasing *P* and *T* conditions during amphibole growth. Application of multi-equilibrium thermobarometry to the matrix assemblage of the metagabbros (amphibole + albite + epidote/clinozoisite + chlorite + quartz) yielded *P-T* conditions of 488-588 °C and 0.3-0.5 GPa, the amphibolites yielded *P-T* conditions of 536-587 °C and 0.4-0.5 GPa. The metagabbro/amphibolite complex of Gufidaun represents an alkaline magmatic complex, which intruded into the Southalpine Variscan basement.

Fig. 11: Intrusion breccia at the outcrop „Klammwirt" in Schrammbach. The components are quartzphyllite, quarzite and diorite and occur in a diorite/klausenite matrix. The size of the components is highly variable. The components are also clearly visible in the thin section (lower right). The scale bar indicates 10 cm.

Stop 8, Schrammbach

At the bus stop Gasthof Klammwirt in Schrammbach, a Permian intrusion breccia occurs (Fig. 11). This breccia is thought to have formed during intrusion of the Permian diorite into an older kataclastic fault zone. Within this breccia, rock fragments of quartzphyllites, quartzites and diorites occur in a fine-grained altered matrix of diorite. After the Permian contact metamorphic event, late-stage Alpine alteration associated with the Villnöss line occurred. This alteration affected the primary mineral assemblage and led to remobilization of LREE. This led to the formation of a LREE-F-bearing carbonate. Using Raman spectroscopy it was possible to identify it as synchisite-(Ce). Synchisite-(Ce) is a rare late-stage alteration product of granites and syenites and forms by fluid-rock interaction with a F-CO_2-rich fluid.

Stop 9, Klausen

The Klausen Diorite is part of the Permian calc-alkaline plutonic association consisting of Brixen Granodiorite, Ifinger Granite, Kreuzberg Granite and Cima d'Asta Granitoid as the most prominent members. They all intruded into the polymetamorphic basement of the Southalpine Brixen Quartzphyllite. The Klausen dioritcomplex – the common local name is Klausenite – is located to the south of the Brixen Granodiorite in the eastern part of the Southalpine. The mineral assemblage consists of orthopyroxene + clinopyroxene + plagioclase + K-feldspar + quartz (Fig. 12).

A large diorite stock occurs at the monastery-mountain Säben near to Klausen, a small town in South Tyrol (Italy). During the Permian (278 Ma) the diorite intruded into the Brixen Quarzphyllites. The pressure conditions of this intrusion range

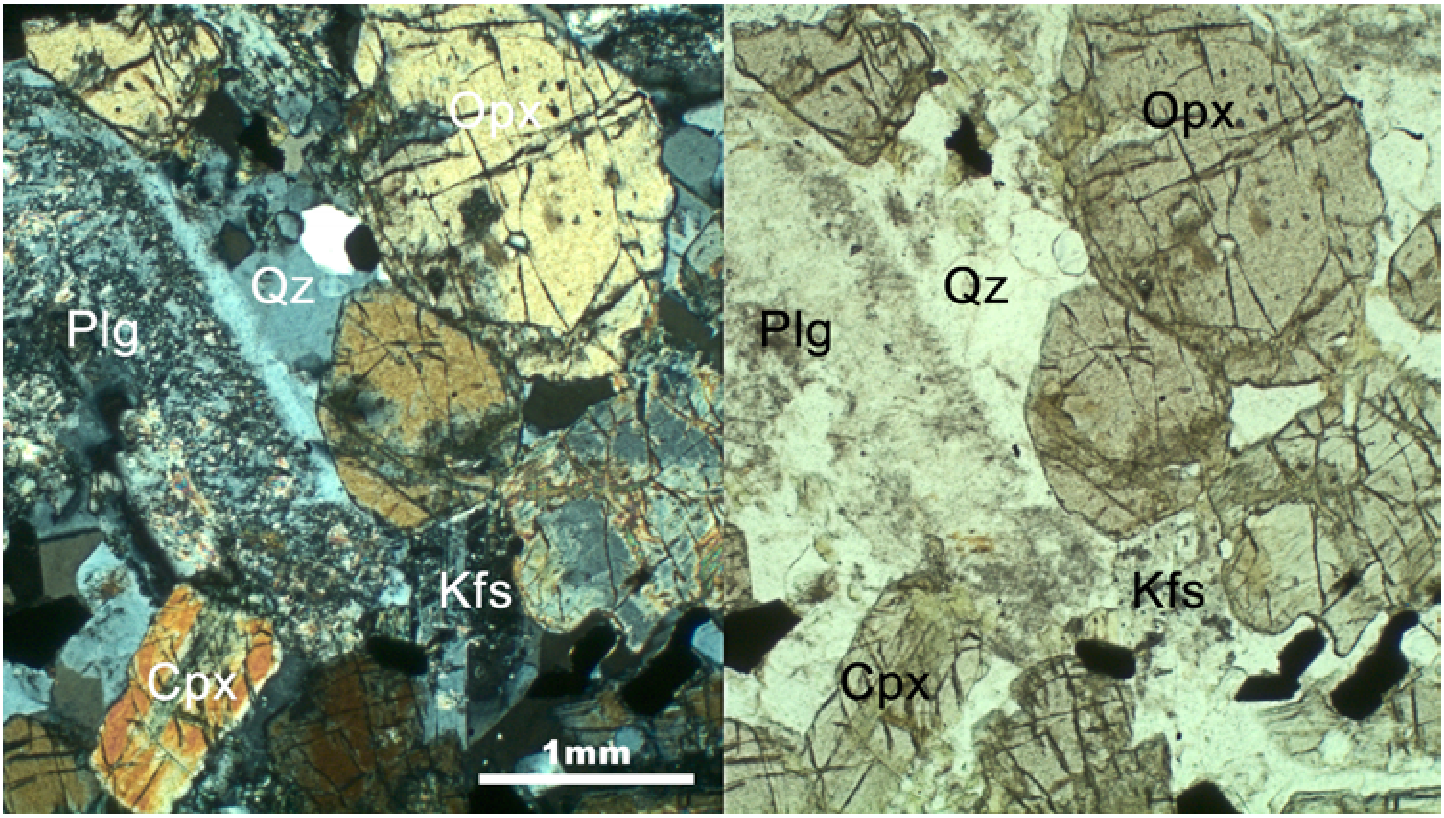
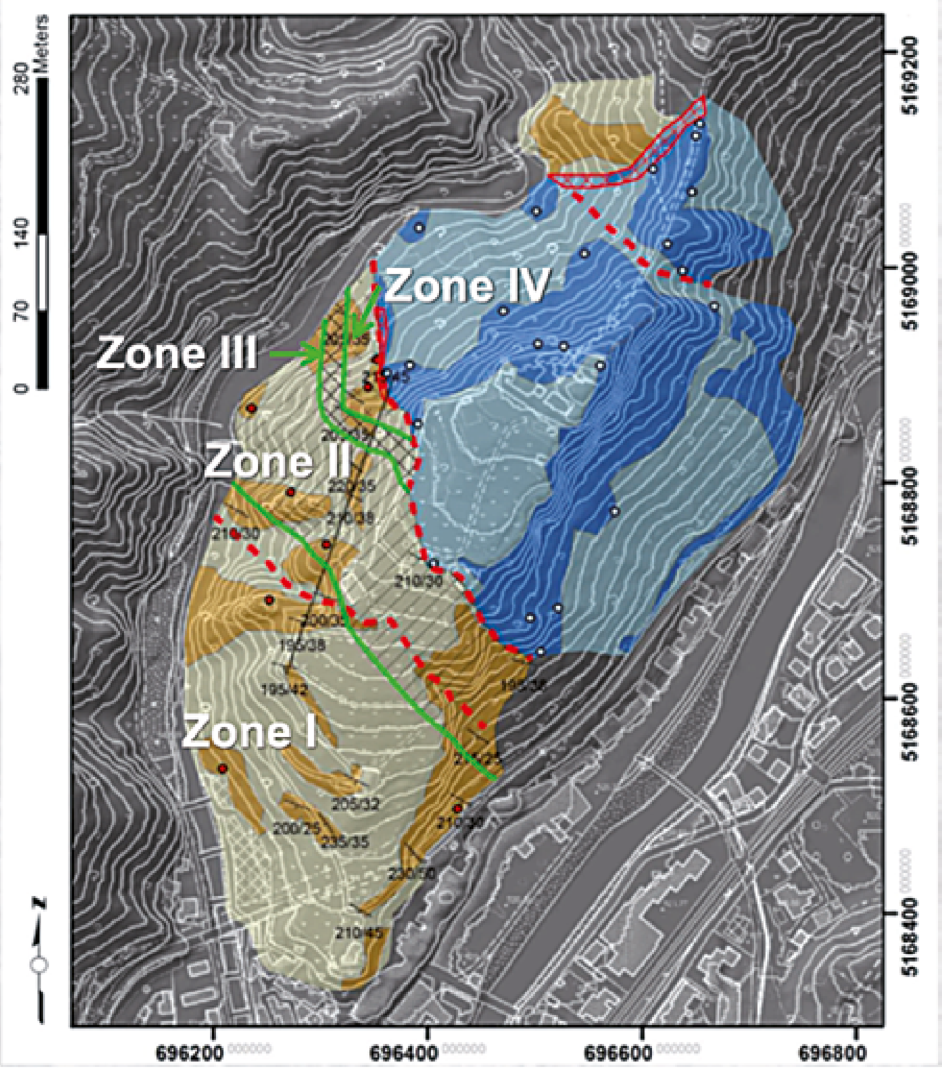


Fig. 12: Photomicrograph of the Klausen diorite showing orthopyroxene (opx), clinopyroxene (cpx), plagioclase (Plg), K-feldspar (Kfs) and quartz (Qz). Left: cross nicols; right: parallel nicols.

from 0.3 GPa to 0.55 GPa, which corres-ponds to a depth of 8 to 17 km. The solidus temperature was between 840°C and 890°C (Opx-Cpx-geothermometer). The intrusion formed a small, about 140 to 180 m wide, contact aureole at the locality of Säben (Fig. 13). The aureole can be divided into four different zones based upon mineralogical, mineral chemical and textural features. In the 20 m wide innermost area (zone IV) the mineral paragenesis cordierite, biotite, plagioclase, quartz and spinel occurs. After 20 m from the contact spinel disappears. The extension of Zone III stretches from 20 to 40 m. In this zone cordierite, biotite, plagioclase, quartz and sillimanite occur. The rocks of zone III and IV also show typical hornfels textures. After 40 m sillimanite disappears. Zone II is characterized by the loss of the typical hornfels textures. The rocks are macroscopically predominated by quartzphyllites and to paragneisses. White micas occur in this zone. This zone can be distinguished from the non-contact-metamorphic quartzphyllites only by the chemical composition of plagioclase, which becomes more calcic. In zone I (>140 m from the contact) the non-contact-metamorphic quartzphyllites occur. Geothermometry using two-feldspar- and Ti-in-biotite yielded 720-760°C in the innermost aureole (zone IV) and 610-730°C in the inner aureole (zone III). Na-in-cordierite geothermometry of samples with comparable Na_2O contents to sample W also yields remarkably similar temperatures namely for zone IV 750 ± 20°C and 690 ± 20°C for zone III.

The entire area is characterized by late-stage hydrothermal alteration.

Fig. 13:
Mineral zone distribution within the Klausen contact aureole at Mount Säben.



Day 2

Stop 10, Jaufenpass
From Sterzing a spectacular road climbs up towards west to the Jaufen pass. The road roughly follows the Jaufen fault zone, separating Cretaveous metamorphic Astroalpine basement (ÖC) from Austroalpine units, which lack substantial metamorphic overprint (Meran Mauls Basement). Across the fault zone a jump in cooling ages occurs from Cretaceous in the NW to Variscan in the SE. Thus the fault has to have a Cretaceous history. Yet recent studies (Viola et al. 2004, Pomella et al., 2008) revealed a polyphase history, the last activity of which occurred in the course of normal faulting along the BFZ. Along the road metamorphic basement of the ÖC as well as the Meran-Mauls basement can be studied together with some outcrops of Jaufen fault mylonites.

Stop 11, Kalmbach
In this locality there is an outcrop of a few m in size along a forest track that branches off the main road from St. Martin – Meran approx. 3 km to the south of St. Martin. Metabasites of the southern Ötztal Complex hitherto mapped as amphibolites, were identified as eclogites in this outcrop. Primary mineral parageneses are tschermakitic to pargasitic green amphiboles, omphacite, garnet, phengite, zoisite, rutile and quartz (Fig. 14). Al-pargasite forms between garnet and omphacite

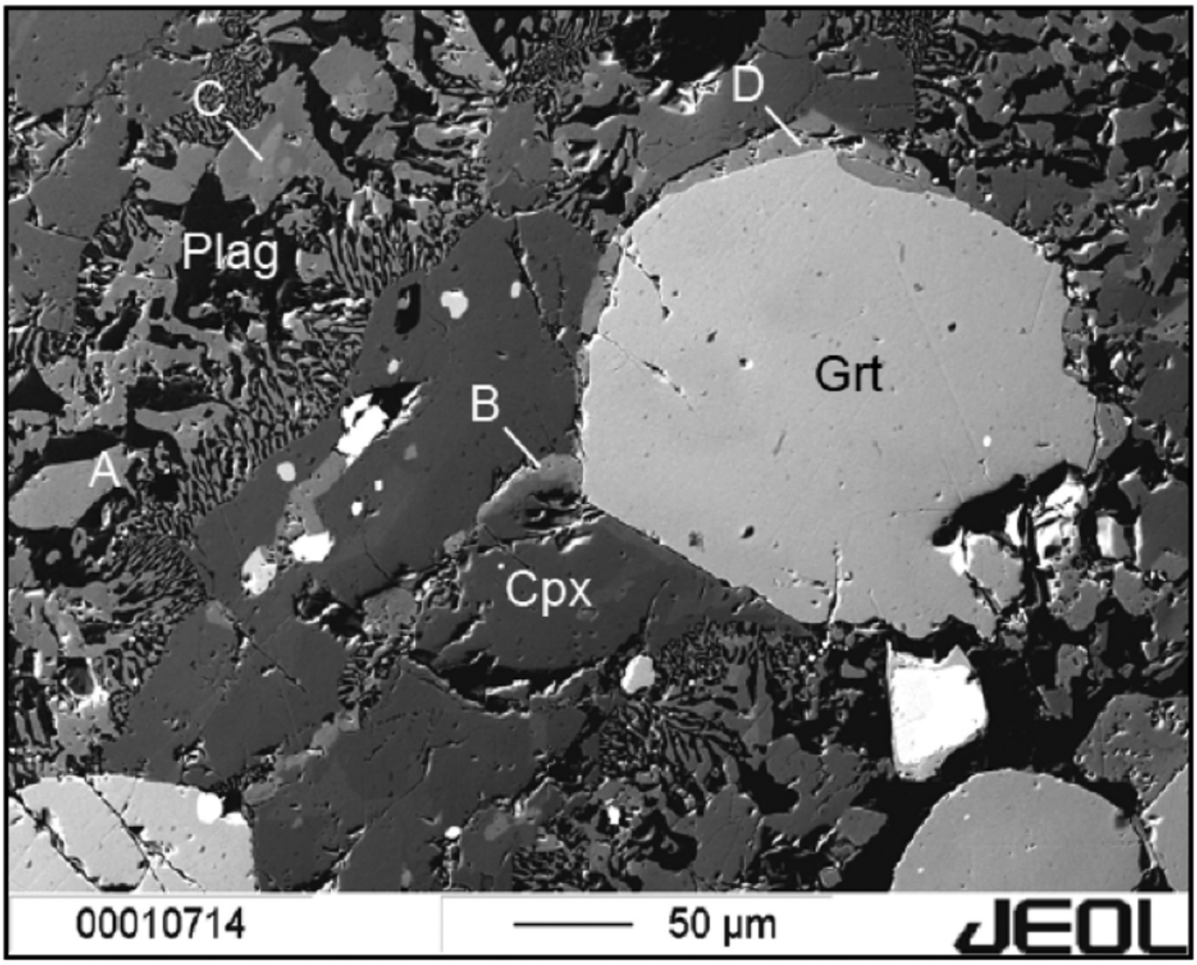


Fig. 14: Backscatter electron (BSE) image of the mineral assemblage of retrogressed eclogites at Kalmbach in the Passeier Valley. Garnet: Grt; omphacite: Cpx; plagioclase: Plag. A, B, C and D denote different amphibole generations ranging from barroisite (A) to katophorite-taramites (D).

and is interpreted as a retrograde reaction products. In addition, retrogression of the eclogitic parageneses reflecting decreasing pressure and increasing temperature conditions are the formation of symplectites of diopside and plagioclase after omphacite, Al- and Na-poor green amphiboles, grossular-poor garnet and symplectites of biotite and plagioclase replacing phengite.

The application of multi-equilibrium geothermobarometry to mineral assemblages from the eclogite-facies peak stage (stage 2) as well as Zr-in-rutile thermometry yielded *P-T* constraints as well as constraints on $a(H_2O)$. The calculations involved the mineral assemblages garnet+ omphacite + epidote + quartz and garnet + omphacite + Na-Ca amphibole + epidote + quartz. Application of the Zr-in-rutile thermometer yields temperatures between 580-740°C, depending which calibration was used. Geothermobarometric calculations with multi-equilibrium geothermobarometry omitting amphiboles from the calculations, only yields an H_2O-bearing invariant point with *P-T* conditions of 1.8 - 2.2 GPa and 560 - 600°C, which have to be considered as upper *P* limits, due to the neglected influence of $a(H_2O)$. Calculations involving amphiboles (average *P-T* mode of THERMOCALC) yield pressures of 1.4-1.8 GPa and temperatures of 540 – 630°C for samples from the Saltaus Valley using H_2O-free equilibria (Fig. 15).

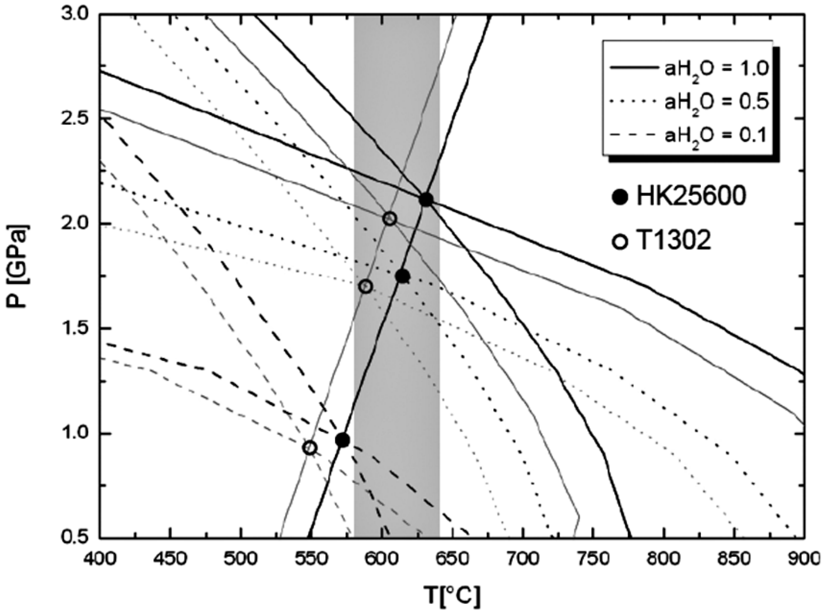


Fig. 15: Geothermobarometry of the Texel eclogites from Elvas.

Stop 12, Timmelsjoch

At an altitude of 2474 m at the Austrian-Italian border, rocks outcropping in the immediate vicinity of the customs building are gneisses of the ÖC that form the northern border of the SC. The gneisses were affected by both Variscian and Eo-Alpine metamorphism: The Variscan metamorphism reached conditions of the amphibolite facies which led to the formation of an assemblage plagioclase + biotite + muscovite + garnet + quartz ± staurolite ± kyanite. The subsequent Eo-Alpine event in this area reached *P-T* conditions slightly below the stability of staurolite. This caused a retrogressive breakdown of staurolite to paragonite + chlorite + quartz. This reaction caused the formation of mica + chlorite + quartz-pseudomorphs after lath-shaped staurolite crystals that may reach several cm in length and can be found on cleavage planes. *P-T* conditions sufficient for Eo-Alpine staurolite formation, however, were reached within the northernmost part of the SC. On the Italian side at an altitude of 2200 m; after the second 180°-road turn, along the roadside over a distance of approx. 100 m, the northern border of the main syncline of the SC towards the underlying ÖC is exposed (Fig. 16). At this location the distinction between both units is unambigous due to the difference in lithologies since the rocks of the ÖC are monotonous gneisses with abundant small (≤1 mm) garnet and biotite and the rocks of the SC are garnet-micaschists with large (0.5 to >1cm) garnets as well as amphibole-bearing rocks with large amphiboles (≥1cm). The SC rocks exposed belong to the marginal series („bunte Randserie“) of intercalated garnet-micaschsists, amphibolites, hornblende garbenschists, marbles and quartzites that delimit the main syncline of the SC. Further downhill, rocks of the central SC main syncline are encountered that are characterized by rather monotonous garnet-micaschists („monotone Serie“). The SC-ÖC boundary is located a few meters uphill from a quartzite band that can unambigously be assigned to the SC. The actual boundary lies within several meters of gneisses containing small garnets and cannot unambigously be localized in the field. A definite criterion for the distinction between SC and ÖC rocks, however, is the zoning pattern of garnets since SC rocks are monometamorphic and thus the garnets show continuous bell-shaped zoning patterns and the ÖC rocks are polymetamorphic thus the garnets show discontinuous chemical zoning.

Stop 13, Burgstein

The eclogites at the locality Burgstein belong to the central amphibolite complex in the ÖC and can be seen next to the tunnel portal. The central amphibolite complex is characterized by the occurrence of ultramafic rocks (peridotites), eclogites, amphibolites and rarely metacarbonates. The eclogites in this outcrop are Fe-eclogites, which appear dark-red and massy. The mineral assemblage is garnet (>50 vol.%), omphacite, amphibole I, clinozoisite, quartz, apatite, pyrite and rutile. During subsequent alteration, symplectites (plagioclase + diopside) and amphibole II form (Miller & Thöny, 1995).

Stop 14, Gries i. Sulztal

Boulders of Ordovician migmatites occur near the bridge at the end of the Sulztal. Within the Ötztal Complex (ÖC), migmatites are the only geological evidence of the pre-Variscan metamorphic evolution, which led to the occurrence of partial anatexis in different areas of the complex (Fig. 17). In the course of this investigation the metamorphic

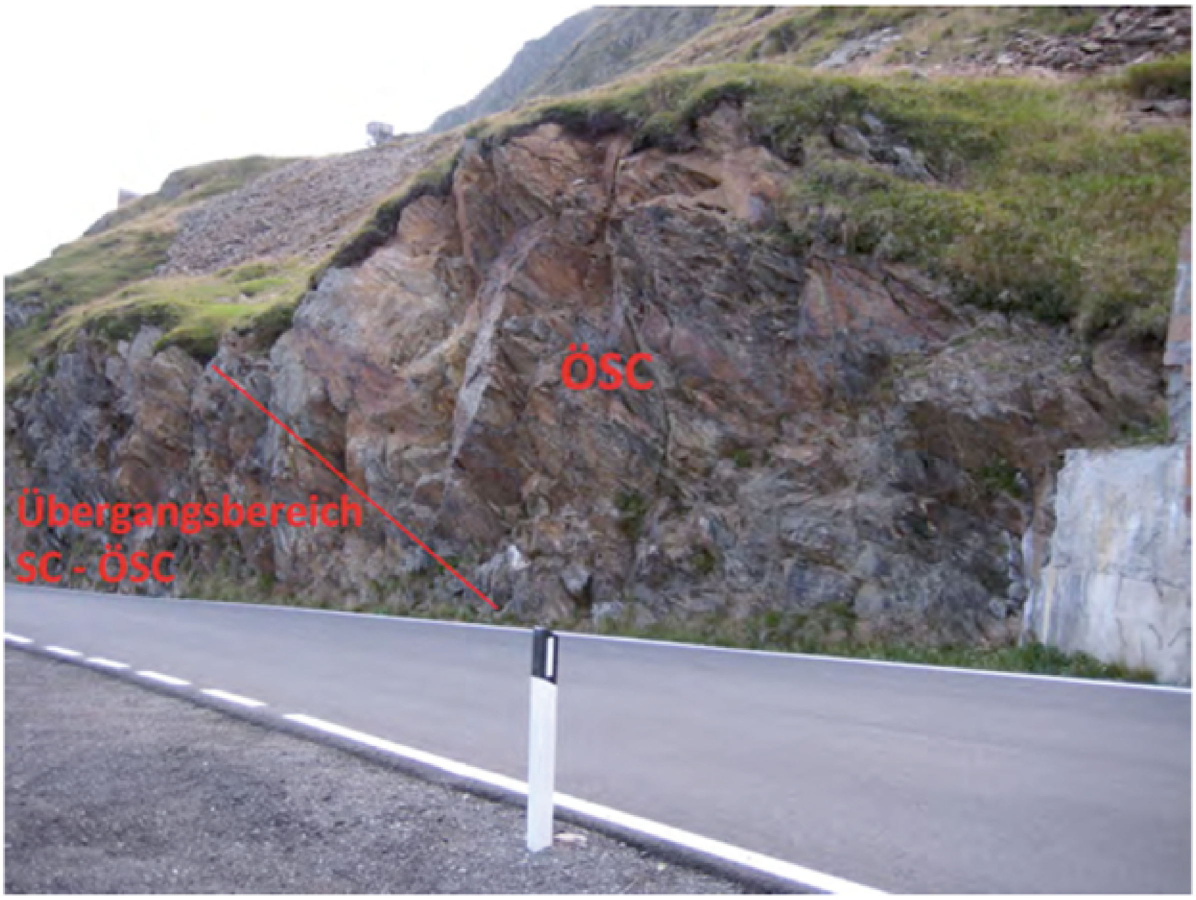


Fig. 16: Photograph of the contact between the Ötztal Complex (ÖSC) and the Schneeberg Complex (Übergangsbereich SC-ÖSC) at the Timmelsjoch Passstrasse at the end of the Passeier Valley in South-Tyrol.

evolution and electron microprobe (EMPA) geochronology of monazites of three migmatites from the central (Winnebach migmatite) and western (Verpeil migmatite, Nauderer Gaisloch migmatite) part of the complex were investigated. All three migmatites show evidence for a polymetamorphic evolution (pre-Variscan, Variscan) and only the Winnebach migmatite shows evidence for the *P*-accentuated Eo-Alpine metamorphic overprint in the central ÖC. *P-T* data range from 670 – 750°C and <2.8 kbar for the pre-Variscan event, 550 – 650°C and 4 – 7 kbar for the Variscan event and 430 – 490°C and ca. 8.5 kbar for the Eo-Alpine metamorphic overprint. U-Th-Pb electron microprobe dating was done on monazites from the leucosomes from all three migmatites in order to obtain the age of the pre-Variscan migmatization. Monazite ages of all three migmatite bodies are in good agreement and range from 408 ± 46 Ma to 472 ± 36 Ma, thus indicating a pervasive Ordovician metamorphic event in the ÖC.

Stop 15, Köfels

The Köfels rockslide is the biggest one in the Alps within basement rocks. It involved augengneisses of granitic composition as well as paragneisses. With a total mass of 3.2 km^2 of material (Brückl et al., 2001) the rockslide was able to fill up the valley by some 100 meters. Due to the formation of a dam up to 100m thick fluvio-lacustrine sediments were deposited in the Längenfelder basin (Heuberger, 1966, 1975). Relative, ^{14}C and dating of exposed surfaces with cosmogenic isotopes yielded an age of ~ 9800 cal BP for its activity (Ivy-Ochs et al., 1998). After the main event at least one smaller event followed. The Köfels rockslide is well known for its frictionite, a pumice rock formed in the context of frictional melting (Erismann et al., 1977).

Fig. 17: Photograph of the Winnebach migmatite at the Bachfallenferner outcrop.

References

Acquafredda, P., Bargossi, G.M., Caggianelli, A. & Rottura, A. (1997): Emplacement depths of Permian granitoids from central-eastern Southern Alps: estimates from hornblende-plagioclase thermobarometry. – Mineral. Petrogr. Acta, XL, 45-53.

Bargossi, G. M., Bondi, M., Landini, F. & Morten, L. (1981): Il plutone di Monte Croce (Alto Adige, Nord Italia). – Soc. Ital. Mineral. Petrol., 38, 155-162.

Bargossi, G. M., Rottura, A., Vernia, L., Visona, D. & Tranne, C. A. (1998): Guida all`escursione sul distretto vulcanico atesino e sulle plutoniti di Bressanone-Chiusa e Cima d`Asta. – Mem. Soc. Geol. It., 53, 23-41.

Angelmaier, P., Frisch, W. & Dunkl, I. (2000): Thermochronological constraints for the TRANSALP section of the Tauern Window. 2nd intern. – TRANSALP Coll., Munich, 17.

Bonin, B., Brändlein, P., Bussy, F., Desmons, J., Eggenberger, U., Finger, F., Graf, K., Marr, C., Mercolli, I.,Oberhänsli, R., Ploquin, A., Quadt, A. v., Raumer, J. F. v., Schaltegger, U., Steyrer, H. P., Visona, D. & Vivier, G. (1993): Late Variscan Magmatic Evolution of the Alpine Basement. – In: Raumer, J. F. v. & Neubauer, F. (Eds): The pre-Mesozoic Geology in the Alps, Springer, 169-199.

Borsi, S., Del Moro, A. & Ferrara, G. (1972): Studio radiometrico delle rocce intrusive del massico di Bressanone, Ivingna, Monte Croce (Alto Adige). – Boll. Soc. Geol. Ital., 91, 387-406.

Brandner, R., Reiter F. & Töchterle, A. (2008): Überblick zu den Ergebnissen der geologischen Vorerkundung für den Brenner-Basistunnel. – Geo.Alp, 5, 165-174.

Brückl E., Brückl, J. & Heuberger, H. (2001): Present structure and prefailure topography of the giant rockslide of Köfels. – Zschr. Gletscherkde. Glazialgeol., 37, 49-79.

Cliff, R.A., Droop, G.T.R. & Rex, D.C. (1985): Alpine metamorphism in the south-east Tauern Window, Austria, II. Heating, cooling and uplift rates. – J. Metam. Geol., 3, 403-415.

Dal Piaz, G. V. & Martin, S. (1998): Evoluzione litosferica e magmatismo nel dominio austro-sudalpino dell`orogenesi varisica al rifting mesozoico. – Mem. Soc. Geol. It., 53, 43-62.

Del Moro, A. & Visona, D. (1982): The epiplutonic Hercynian Complex of Bressanone (Brixen, Eastern Alps, Italy). – N. Jb. Miner. Abh., 145, 66-85.

Dachs, E. (1986): High-pressure mineral assemblages and their breakdown products in metasediments South of the Grossvenediger, Tauern Window, Austria. – Schweiz. Mineral. Petrogr. Mitt., 66, 145-161.

Dachs, E. (1990): Geothermobarometry in metasediments of the southern Grossvenediger area (Tauern Window, Austria). – J. Metam. Geol., 8, 217-230.

Dingeldey, C., Dallmeyer, D. R., Koller, F. & Massonne H.J. (1997): P-T-t history of the Lower Austroalpine Nappe Complex in the „Tarntaler Berge" NW of the Tauern Window: implications for the geotectonic evolution of the central Eastern Alps. – Contrib. Mineral. Petrol., 129, 1-19.

Droop, G.T.R. (1985): Alpine metamorphism in the south-east Tauern Window, Austria, I. P-T variations in space and time. – J. Metam. Geol., 3, 371-402.

Elias, J. (1998): The thermal history of the Ötztal-Stubai Complex (Tyrol, Austria, Italy) in the light of the lateral extrusion model. – Tüb. Geowiss. Arb., 42, 172 pp.

Erismann, T., Heuberger, H. & Preuss, E. (1977): Der Bimsstein von Köfels (Tirol), ein Bergsturz-"Friktionit". – Mineral. Petrol., 24, 67-119.

Exner, U., Fusseis, F., Grasemann, B., Habler, G., Linner, M., Sölva, H., Thiede, R. & Thöni, M. (2001): Cretaceous eclogite-facies metamorphism in the Eastern Alps: New Insights, data and correlations from an interdisciplinary study. – J. Conf. Abstr., 6/1, 387.

Frank, W., Miller, Ch., Petrakakis, K., Prochaska, K. & Richter, W. (1981): Das penninische Kristallin im Mittelabschnitt des Tauernfensters und die Rieserferner Intrusion mit ihrem Kontakthof. – Fortschr. Mineral., 59, 97-128.

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

Franz, G. & Spear, F. (1983): High pressure metamorphism of siliceous dolomites from the central Tauern Window, Austria. – Am. J. Sci. 283, 396-413.

Frisch, W., Dunkl, I. & Kuhlemann, J. (2000): Postcollisional orogenparallel large-scale extension in the Eastern Alps. – Tectonophysics, 327, 239–265.

Fügenschuh, B., Seward, D. & Mancktelow, N. (1997): Exhumation in a convergent orogen: the western Tauern window. – Terra Nova, 9, 213-217.

Fügenschuh, B., Mancktelow, N.S. & Seward, D. (2000): The Cretaceous to Neogene cooling and exhumation history of the Oetztal-Stubai basement complex, Eastern Alps: a structural and fission-track study. – Tectonics, 19, 905-918.

Getty, S.R. & Selverstone, J. (1994): Stable isotopic and trace element evidence for restricted fluid migration in 2 GPa eclogites. – J. Metam. Geol. 12, 747-760.

Habler, G., Linner, M., Thiede, R. & Thöni, M. (2001): Eo-Alpine Andalusite in the Schneeberg Complex (Eastern Alps, Italy/Austria): Constraining the P-T-t-D Path during Cretaceous Metamorphism. – J. Conf. Abstr., 6, 340.

Haditsch, G. & Mostler, H. (1982): Zeitliche und stoffliche Gliederung der Erzvorkommen im Innsbrucker Quarzphyllit. – Geol. Paläont. Mitt. Innsbruck, 12, 1-40.

Handler, R., Genser, J., Friedl, G., Heidorn, R., Neubauer, F., Fritz, H. & Tenczer, V. (2000): Ar-Ar ages of white mica from Austroalpine basement units along the TRANSALP section: Tectonic implications. – 2nd intern. TRANSALP Coll., Munich, 17.

Hermanns, R. L., Blikra, L.H., Naumann, M., Nilsen, B., Panthi, K.K., Stromeyer, D. & Longva, O. (2006): Examples of multiple rockslope collapses from Köfels (Ötz valley, Austria) and western Norway. – Eng. Geol., 83, 94-108.

Heuberger, H. (1966): Gletschergeschichtliche Untersuchungen in den Zentralalpen zwischen Sellrain und Ötztal, Wiss. – Alpenvereinshefte, 20, 1-126.

Heuberger, H. (1975): Das Ötztal. Bergstürze und alte Gletscherstände, kulturgeographische Gliederung. – Innsbr. Geograph. Stud., 2, 213-249.

Hoinkes, G. (1973): Die Anatexis des Winnebachgranits (Ötztaler Alpen, Österreich) am Beispiel eines Aufschlusses. – Tschermaks Mineral. Petrogr. Mitt., 20, 225-239

Hoinkes, G., Kostner, A. & Thöni, M. (1991): Petrologic constraints for Eo-Alpine eclogite facies metamorphism in the Austroalpine Ötztal Basement. – Mineral. Petrol., 43, 237-254.

Hoinkes, G. & Thöni, M. (1993): Evolution of the Ötztal-Stubai, Scarl-Campo and Ulten basement units. – In: Raumer, J. F. v. & Neubauer, F. (eds.) Pre-Mesozoic Geology in the Alps, Springer Verlag, Heidelberg, pp. 485-494.

Hoinkes, G., Thöni, M., Bernhard, F., Kaindl, R., Lichem, C., Schweigl, J., Tropper, P. & Cosca, M. (1997): Metagranitoids and associated metasediments as indicators for the pre-Alpine magmatic and metamorphic evolution of the Western Austroalpine Ötztal Basement (Kaunertal, Tirol). – Schweiz. Mineral. Petrogr. Mitt., 77, 299-314.

Hoinkes, G., Koller, F., Rantitsch, G., Dachs, E., Höck, V., Neubauer, F. & Schuster, R. (1999): Alpine metamorphism of the Eastern Alps. – Schweiz. Mineral. Petrogr. Mitt., 79, 155-181.

Hoinkes, G., Koller, F., Demeny, A., Schuster, R., Miller, C., Thöni, M., Kurz, W., Krenn, K., Walter, F. (2010) Metamorphism in the Eastern Alps. – IMA 2010 Field Trip Guide AT1, Acta Mineralogica Petrographica, 1, 1-47.

Hoschek, G., Kirchner, E.C., Mostler, H. & Schramm, J.M. (1980): Metamorphism in the Austroalpine units between Innsbruck and Salzburg (Austria) – a synopsis. – Mitt. Österr. Geol. Ges., 71/72, 335-341.

Holland, T. J. B. (1979): High water activities in the generation of high pressure kyanite eclogites in the Tauern Window, Austria. – J. Geol., 87, 1-27.

Holland, T.J.B. & Ray, N.J. (1985): Glaucophane and pyroxene breakdown reactions in the Pennine units of the Eastern Alps. – J. Metam. Geol., 3,417-438.

Holland, T.J.B. & Richardson, S.W. (1979): Amphibole zonation in metabasites as a guide to the evolution of metamorphic conditions. – Contrib. Mineral. Petrol., 70, 143-148.

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

Ivy-Ochs, S., Heuberger, H., Kubik, P. W., Kerschner, H., Bonani, G., Frank, M. & Schlüchter, C. (1998): The age of the Köfels event. Relative, 14C and cosmogenic isotope dating of an early Holocene landslide in the Central Alps (Tyrol, Austria), – Zeitschr. Gletscherkd. Glazialgeol., 34, 57-68.

Klier, R. (2005): Das Tarntal Mesozoikum: Petrologie und Geologie einer enigmatischen Einheit in den Ostalpen. – Unpubl. Ms. Thesis, University of Innsbruck, 99 pp.

Klötzli-Chowanetz, E., Klötzli, U. & Koller, F. (1997): Lower Ordovician migmatisation in the Ötztal crystalline basement (Eastern Alps, Austria): linking U-Pb and Pb-Pb dating with zircon morphology. – Schweiz. Mineral. Petrogr. Mitt., 77, 315-324.

Kolenprat, B. (1998): Bericht 1997 über geologische Aufnahmen im Altkristallin und Unterostalpin im Raum Glungezer auf Blatt 148 Brenner. – Jb. Geol. BA, 141, 292.

Kolenprat, B., Rockenschaub, M. & Frank, W. (1999): The tectonometamorphic evolution of Austroalpine units in the Brenner Area (Tirol, Austria)-structural and tectonic implications. – Tüb. Geowiss. Arb., Ser. A, 52, 116-117.

Konzett, J. & Hoinkes, G. (1991): High pressure metamorphism in the Austroalpine Schneeberg Complex and adjacent Ötztal basement rocks. – Terra Abstr., 3, 88.

Konzett, J. & Hoinkes, G. (1996): Paragonite-hornblende assemblages and petrological significance: an example from the Austroalpine Schneeberg Complex, Southern Tyrol, Italy. – J. Metam. Geol., 14, 85-101.

Kralik, M., Krumm, H. & Schramm, J. M. (1987): Low Grade and Very Low Grade Metamorphism in the Northern Calcareous Alps and in the Greywacke Zone: Illite Crystallinity Data and Isotopic Ages.– In: Flügel, H. W. & Faupl, P. (eds.): Geodynamics of the Eastern Alps. Deuticke, Vienna, pp. 164-178.

Miller, C. (1974): On the metamorphism of the eclogites and high-grade blueschists from the Penninic Terrane of the Tauern Window, Austria. Schweiz. – Mineral. Petrogr. Mitt., 54, 371-384.

Miller, C. (1977): Chemismus und phasenpetrologische Untersuchungen der Gesteine aus der Eklogitzone des Tauernfensters, Österreich. – Tschermaks Mineral. Petrogr. Mitt., 24, 221-277.

Miller, C. (1986): Alpine high-pressure metamorphism in the Eastern Alps. – Schweiz. Mineral. Petrogr. Mitt., 66, 139-144.

Miller, C. (1987): Die Eklogite des Tauemfensters. – Field Guide, Tauerntagung, Mittersill, 10 pp.

Miller, C. & Thöni, M. (1995): Origin of eclogites from the Austroalpine Otztal basement (Tirol, Austria): geochemistry and Sm-Nd vs. Rb-Sr isotope systematics. – Chem. Geol., 122, 199-225.

Mostler, H. (1973): Alter und Genese ostalpiner Spatmagnesite unter besonderer Berücksichtigung der Magnesitlagerstätten im Westabschnitt der Nördlichen Grauwakkenzone (Tirol, Salzburg). – Veröff. Univ. Innsbruck, 86, 237-266.

Neubauer, F., Hoinkes, G., Sassi, F. P., Handler, R., Höck, V., Koller, F. & Frank, W. (1999): Pre-Alpine metamorphism in the Eastern Alps. – Schweiz. Mineral. Petrogr. Mitt., 79, 41-62.

Oberhänsli, R., Bousquet, R., Engi, M., Goffé, B., Gosso, G., Handy, M., Koller, F., Lardeaux, J.-M., Polino, R., Rossi, P., Schuster, R., Schwartz, S., Spalla, I. E., Agard, P., Babist, J., Berger, A., Bertle, R., Bucher, K., Burri, T., Heitzmann, P., Hoinkes, G., Jolivet, L., Keller, L., Linner, M., Lombardo, B., Martinotti, G., Michard, A., Pestal, G., Proyer, A., Rantisch, G., Rosenberg, C., Schramm, J., Sölva, H., Thoeni, M. & Zucali, M. (2004): Metamorphic structure of the Alps 1:1'000000. – Paris, CGMW.

Piber, A. (2005): Tectonometamorphic evolution of the Austro-Alpine nappes in the northern Zillertal-Area, Eastern Alps. – Unpublished Ph.D Thesis, University of Innsbruck, 268 pp.

Piber, A., Tropper, P. & Mirwald, P.W. (2008): The metamorphic evolution of the Patscherkofel Crystalline Complex (Tyrol, Eastern Alps, Austria). – Austr. Jour. Earth Sci., 101, 27-35.

Piber, A. & Tropper, P. (2007): Muscovite-chlorite-quartz thermobarometry of the Permian metamorphic overprint of the central part of the western Innsbruck Quartzphyllite Complex (Tyrol, Austria). – Mitt. Österr. Mineral. Ges., 153, 291-300.

Piber, A. & Tropper, P. (2005): The polymetamorphic evolution of the Austroalpine Innsbruck Quartzphyllite Complex. – Mitt. Österr. Mineral. Ges., 151.

Pomella, H., Fügenschuh, B. & Stipp, M. (2008): The Giudicarie Fault System at the transition between Southern and Eastern Alps (Northern Italy) A new structural analysis. – Abstr. Vol., 6. Swiss Geosci. Meet., 55.

Purtscheller, F. (1969): Petrographische Untersuchungen an Alumosilikatgneisen des Ötztales-Stubaier Altkristallins. – Tschermaks Mineral. Petrogr. Mitt., 13, 35-54.

Raith, M., Mehrens, Ch. & Thöle, W. (1980): Gliederung, tektonischer Bau und metamorphe Entwicklung der penninischen Serien im südlichen Venediger-Gebiet, Osttirol. – Jb. Geol. BA, 123, 1-37.

Ring, U. & Richter, C. (1994): The Variscan structural and metamorphic evolution of the eastern Southalpine basement. – J. Geol. Soc. Lond., 151, 755-766.

Rockenschaub, M. (1998): Bericht 1997 über geologische Aufnahmen in der Quarzphyllitzone und im Tauernfenster auf Blatt 148 Brenner. – Jb.Geol. BA, 141, 295.

Rockenschaub, M., Kolenprat, B. & Frank, W. (1999): The tectonometamorphic evolution of Austroalpine units in the Brenner area (Tirol, Austria)-new geochronological implications. – Tüb. Geowiss. Arb., 52, 118-119.

Roth, R. (1983): Petrographie und Tektonik der mittelostalpinen Kellerjochgneis-Decke und angrenzender Gebiete zwischen Schwaz und Märzengrund (Tirol.). – Unpublished PhD Thesis, University of Münster, 196 pp.

Rottura, A., Bargossi, G. M.,Caggianelli, A., Del Moro, A., Visona, D. & Tranne, C.A. (1998): Origin and significance of the Permian high-K alkaline magmatism in the central-eastern Southern Alps, Italy. – Lithos, 45, 329-348.

Sassi, F.P. & Spiess, R. (1993): The South Alpine metamorphic basement in the Eastern Alps. – In: Raumer, J. F. v. & Neubauer, F. (Eds): Pre-Mesozoic Geology in the Alps, Springer, Heidelberg, pp. 599-607.

Sassi, F. P. & Spiess, R. (1992): Further Data on pre-Alpine metamorphic pressure conditions of the Austridic phyllitic complexes in the Eastern Alps. – In: Carmignagi, L. and Sassi, F. P. (eds.), Contributions to Geology of Italy with special regard to the Paleozoic basements. IGCP Mo. 276, Newsletter 5, 297-307.

Schmid, S.M., Fügenschuh, B., Kissling, E. & Schuster, R. (2004): Tectonic map and overall architecture of the Alpine orogen. – Eclog. Geol. Hel., 97/1, 93-117.

Schmidegg, O. (1964): Die Ötztaler Schubmasse und ihre Umgebung. – Verh. Geol. BA, 1957/1, 76-77.

Schmidlechner, M., Neubauer, F. & Handler, R. (2006): Extent and age of metamorphism of the central Grauwacken Zone, Eastern Alps: a Ar-Ar study. – Pangeo 2006, Innsbr. Univ. Press, 314-315.

Schuster, R., Koller, F., Höck, V., Hoinkes, G. & Bousquet, R. (2004): Explanatory notes to the map: metamorphic structure of the Alps, metamorphic evolution of the Eastern Alps. – Mitt. Österr. Miner. Ges., 149, 175-199.

Schuster, R., Scharbert, S., Abart, R. & Frank, W. (2001): Permo-Triassic extension and related HAT/LP metamorphism in the Austroalpine – Southalpine realm. – Mitt. Ges. Geol. Bergbaustud. Öster., 45, 112-141.

Schweigl, J. (1993): Kristallingeologische Untersuchungen in den Nauderer Bergen (Westliche Ötztaler Alpen, Tirol). – Unpubl. Masters Thesis, University of Vienna, 87 pp.

Schweigl, J. (1995): Neue geochronologische und isotopengeologische Daten zur voralpidischen Entwicklungsgeschichte im Ötztalkristallin (Ostalpen). – Jb. Geol. BA., 138/1, 131-149.

Selverstone, J. (1993): Micro- to macroscale interactions between deformational and metamorphic processes, Tauern Window, Eastern Alps. – Schweiz. Mineral. Petrogr. Mitt. 73, 229-239.

Selverstone, J., Franz, G., Thomas, S. & Getty, S. (1992): Fluid variability in 2GPA eclogites as an indicator of fluid behaviour during subduction. – Contrib. Mineral. Petrol. 112, 341-357.

Söllner, F. (1982): Zur Altersstellung des Winnebach-Migmatits im Ötztal (Ostalpen). – Verh. Geol. BA., 2, 95-106.

Söllner, F. & Schmidt, K. (1981): Rb/Sr- und U/Pb-Datierungen am Winnebach-Migmatit (Ötztaler Alpen, Österreich). – Fortschr. Mineral., 59, 1, 188.

Sölva, H., Grasemann, B., Thöni, M., Thiede, R. & Habler, G. (2005): The Schneeberg Normal Fault Zone: normal faulting associated with Cretaceous SE-directed extrusion in the Eastern Alps. – Tectonophysics, 401, 143-166.

Sölva, H., Thöni, M., Graseman, B. & Linner, M. (2001): Emplacement of eo-Alpine high-pressure rocks in the Austroalpine Ötztal complex (Texel group, Italy/Austria). – Geodinam. Act., 14, 345-360.

Spear, F.S. & Franz, G. (1986): P-T evolution of metasediments from the Eclogite Zone, south-central Tauern Window, Austria.– Lithos, 19, 219-234.

Spiess, R. (1995): The Passeier-Jaufen Line: a tectonic boundary between Variscan and eo-Alpine Meran-Mauls basement. – Schweiz. Mineral. Petrogr. Mitt., 75, 413-425.

Thöni, M. (1981): Degree and evolution of the Alpine metamorphism in the Austroalpine unit west of the Hohe Tauern in the light of K/Ar and Rb/Sr age determinations on micas. – Jb. Geol. BA., 124, 111-174.

Thöni, M. (1986): The Rb-Sr thin slab isochron method – an unreliable geochronologic method for dating geologic events in polymetamorphic terrains? – Mem. Sci. Geol., 38, 283-352.

Thöni, M. (1999): A review of geochronological data from the Eastern Alps. – Schweiz. Mineral. Petrogr. Mitt., 79, 209-230.

Thöny, W.F. (2008): Permian contact metamorphism in the Southalpine: U-Pb and U-Th-Pb geochronology of plutons and contact metamorphism. – Unpubl. Ph.D. Thesis, University of Innsbruck, 200 pp.

Thöny, W.F., Tropper, P., Schennach, F., Krenn, E., Finger, F., Kaindl, R., Bernhard, F. & Hoinkes, G. (2008): The metamorphic evolution of migmatites from the Ötztal Complex (Tyrol, Austria) and constraints on the timing of the pre-Variscan high-T event in the Eastern Alps. – Swiss J. Geosci., 101, 111-126.

Tropper, P. & Hoinkes, G. (1996): Thermobarometry in Al_2SiO_5-bearing metapelites in the western Austroalpine Ötztal-basement. – Mineral. Petrol, 58, 145-170.

Viola, G., Odonneb, F. & Mancktelow, N.S. (2004): Analogue modelling of reverse fault reactivation in strike-slip and transpressive regimes: application to the Giudicarie fault system, Italian Eastern Alps. – J. Struct. Geol., 36, 401-418.

Wyhlidal, S., Thöny, W.F., Tropper, P., Kaindl, R., Hauzenberger, C. & Mair, V. (2012): Petrology of contact metamorphic metapelites from the southern rim of the Permian Brixen Granodiorite (South Tyrol, Italy). – Mineralogy and Petrology, 106, 173–191.

Zimmermann, R., Hammerschmidt, K. & Franz, G. (1994): Eocene high pressure metamorphism in the Penninic units of the Tauem Window (Eastern Alps). Evidence from ^{40}Ar-^{39}Ar dating and petrological investigations. – Contrib. Mineral. Petrol. 117, 175-186.

Zwingmann, H. & Mancktelow, N.S. (2004): Timing of Alpine fault gouges. – Earth Planet. Sci. Lett., 223, 415-423.

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