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Major fault zones in the Austroalpine units of the Kreuzeck Mountains south of the Tauern Window (Eastern Alps, Austria)

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Abstract
The Kreuzeck Mountains are located between the Tauern Window in the north and the Southalpine unit in the south. They expose an Eoalpine (Cretaceous) nappe stack of Adria derived continental crust. The Koralpe–Wölz Nappe System in the footwall partly experienced Cretaceous eclogite-facies metamorphism, while the Drauzug-Gurktal Nappe System in the hanging wall remained at anchizonal to greenschist-facies conditions in Cretaceous time. From the Late Cretaceous onward the Austroalpine units in the Kreuzeck Mountains were affected by brittle/ductile shearing and brittle deformation. This contribution is based on mapping of the southeastern part of the Kreuzeck Mountains at the 1:10000 scale in combination with structural and petrological investigations and Rb–Sr biotite dating. The new data indicate that the boundary between the Koralpe–Wölz Nappe System and the overlying Drauzug-Gurktal Nappe System consists of three segments. It includes (1) the south dipping Wallner Normal Fault representing a more than 500 m wide shear zone responsible for the Cretaceous exhumation of the eclogite-bearing Polinik Complex to shallow crustal levels (2) the Oligocene to Miocene Ragga-Teuchl Fault and (3) the Großhalsgraben Fault. The latter is mechanically related to the Mölltal Fault and shows a dextral offset. The Drauzug-Gurktal Nappe System is from bottom to top composed of the Strieden, the Gaugen and the Goldeck complexes, which are transgressively overlain Permo-Triassic (meta)sediments. It is dissected by the steeply north dipping Lessnigbach Shear Zone with a dominant top to the south reverse sense of shear and the ENE–WSW trending, sub-vertical Blassnig Shear Zone showing sinistral kinematics. Both faults were active in the Late Cretaceous, but might have been initiated in the Late Jurassic.

Keywords Tectonics · Exhumation · Cretaceous normal fault · Shear Zone

1 Introduction

Even though the density of geological information in the Alps is generally high, there are some areas were essential stratigraphic, structural and petrological data are missing. One of these areas is in the Kreuzeck Mountains (Carinthia, Austria); especially the southern part is not well known. The area is part of the Austroalpine nappe stack located south of the Tauern Window exposing structurally deeper Penninic and Subpenninic units. The Tauern window has been the focus of investigations for a long time and several recent papers deal with the mechanism of its formation (e.g. Genser and Neubauer 1989; Scharf et al. 2013; Favaro et al. 2017; Rosenberg et al. 2017). There is general agreement that the window formed in the context of Miocene north-directed indentation of the Southalpine units into the orogenic wedge located north of the Periadriatic Fault. During this process the Subpenninic and Penninic units within the window were ductilely deformed and exhumed from underneath Austroalpine units, which remained under brittle conditions. Concerning the Austroalpine units south of the Tauern Window a number of Rb–Sr, Ar–Ar and fission track suggest heterogeneous cooling of different blocks between the Carboniferous and Miocene (e.g. Borsi et al. 1973; Hoke 1990; Schuster et al. 2001; Schulz et al. 2008; Wölfler et al. 2015a, b) However, the tectonic interpretation of the complex cooling history in

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the Kreuzeck Mountains requires a better knowledge of the geometry and the kinematics of the internal structure (Hoke 1990; Putiš et al. 2002).

The subdivision of the northern part of the Kreuzeck Mountains is based on the pioneering work by Hoke (1990). She discriminated between the Polinik Complex (for definition of “complex” see NACSN 2005) belonging to the Prijakt Nappe (Fig. 1b) characterized by Cretaceous amphibolite-facies metamorphism in the north and the Strieden Complex (Fig. 1b) that only suffered pre-Alpine amphibolite-facies metamorphism in the south. In the area investigated by Hoke (1990), the border between these complexes was defined by two steeply inclined Oligocene to Miocene fault zones referred to as Strugenkopf fault zone and Ragga-Teuchl fault zone by this author (Fig. 4 in Hoke 1990). These comprise the western segment of the

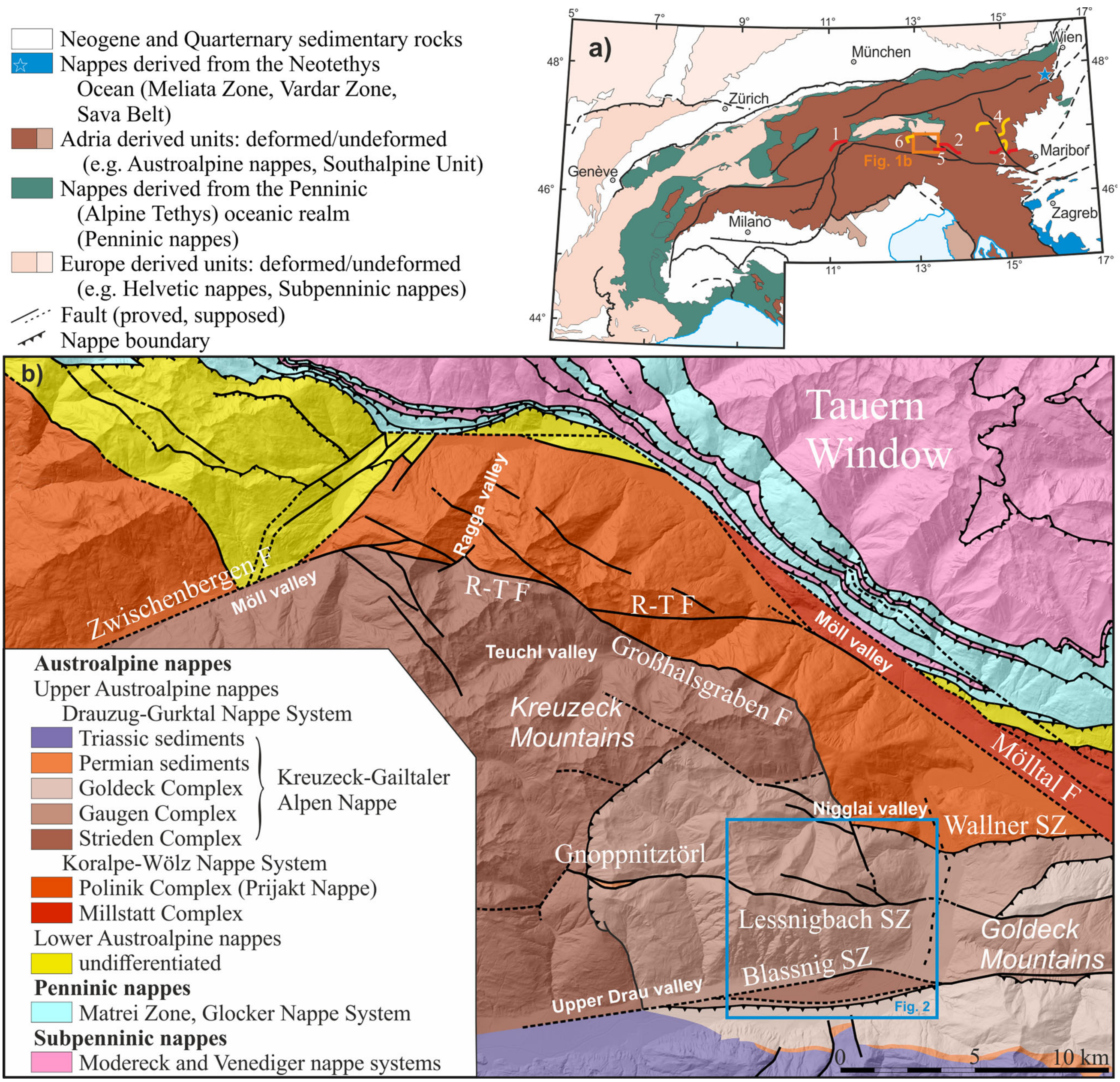

Fig. 1 Geological overview maps: **a** Paleogeographic origin of the main tectonic units of the Alps. Orange square marks the location of Fig. 1b. Red and yellow lines indicate normal faults on top and base of eclogite-bearing units, respectively (1: Schneeberg Normal Fault; 2: normal fault in the Radenthein area; 3: Plankogel detachment; 4: basal shear zone in northern part of Saualpe and Koralpe ridge; 5: Wallner Shear Zone; 6: basal shear zone in Schober Mountains). **b** Tectonic subdivision of the Kreuzeck Mountains and its surrounding. Square indicates location of Fig. 2. *F* fault, *SZ* shear zone, *R-T* Ragga-Teuchl). The signs for fault and nappe boundary in the legend of Fig. 1a are also valid for Fig. 1b

Ragga-Teuchl Fault as mapped in our Fig. 1, a term we use throughout the rest of this work. Hoinkes et al. (1999) extrapolated the boundary between the Polinik and Strieden complexes marking the so-called Southern border of Alpine Metamorphism further to the southeast and linked it with the Mölltal Fault. The latter also separates units with Cretaceous eclogite or amphibolite-facies metamorphism in the north from units with Alpine lower greenschist-facies metamorphism in the south. It is important to note that the extrapolated southeastern extension of the Southern border of Alpine Metamorphism is just the boundary between the Polinik and Strieden complexes, but not the eastern prolongation of the Ragga-Teuchl Fault (Fig. 1b). The latter continues eastward by cutting across the Polinik Complex (Schuster and Ilickovic 2015). The Austroalpine nappes characterized by a pressure dominated Eoalpine upper greenschist to eclogite-facies imprint are referred to as Koralpe–Wölz Nappe System (KWNS), while the structurally overlying nappes to the south exhibit a low grade Alpine metamorphic overprint and are grouped to the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems (DGNS); together they represent an Eoalpine upper plate (Schmid et al. 2004). This interpretation has been followed by many subsequent studies in the Kreuzeck Mountains (e.g. Scharf et al. 2013; Schmid et al. 2013; Wölfler et al. 2015a, b), all of which mapped the entire length of the boundary between KWNS and DGNS as Ragga-Teuchl Fault and associated this boundary with a dextral offset.

This contribution presents structural, petrological and geochronological data from the southeastern part of the Kreuzeck Mountains, with special focus on the major shear zones and faults. The analysis of the structural inventory indicates Late Cretaceous ductile and brittle deformation and additionally, exclusively brittle deformation of Oligocene–Miocene age related to the exhumation of the Tauern Window. The newly discovered Wallner Shear Zone is of special interest, since it represents a several hundreds of meters thick shear zone linked to a normal fault that accommodated the exhumation of the Cretaceous eclogites from (eclogite) amphibolite to lower greenschist-facies conditions. Hence, it represents an important segment of the Southern border of Alpine Metamorphism and may help to reconstruct the exhumation of the KWNS more precisely.

2 Geological setting

The Alpine orogen developed from the amalgamation of the European and Adriatic continent associated with subduction of the Neotethyan and Penninic oceans (Fig. 1a; e.g. Schmid et al. 2004). The tectonically lowermost units are derived from the former continental margin of Europe. They include the Helvetic nappes along the northern front of the orogenic belt and the Subpenninic nappes appearing within tectonic windows. The Penninic nappes above include remnants of the Penninic (Alpine Tethys) oceanic realm and continental fragments. Structurally, highest are the Austroalpine and the Southalpine units derived from the Adriatic continental margin, separated by the Periadriatic Fault from each other. Formation of the Cretaceous-age (Eoalpine) Austroalpine nappe stack began in the Early Cretaceous. Hence, it represents the oldest part of the southeast-dipping pro-wedge of the Alpine orogen. The Southalpine Unit formed during the Cenozoic as a north-dipping retro-wedge. Thin tectonic slices derived from the Neotethys Ocean occur within the Austroalpine nappe pile and are referred to as the Meliata Unit.

The Kreuzeck Mountains are mainly composed of Upper Austroalpine nappes. Two Upper Austroalpine nappe systems occur in the study area, namely the KWNS represented by the Prijakt Nappe in the northeast, and the DGNS comprising the Kreuzeck-Gailtaler Alpen Nappe in the southwest, subdivided into several subunits (Figs. 1b, 2). Within the working area, the Prijakt Nappe is built up by the Polinik Complex. The Kreuzeck-Gailtaler Alpen Nappe consists of several complexes that are, from bottom to top, the Strieden, Gaugen and Goldeck complexes (Figs. 1b, 2). Together they represent a tilted section across the Permian crust (Schuster et al. 2001). The topmost Goldeck Complex in the south of the investigated area is transgressively overlain by Permo-Mesozoic sediments (Schuster et al. 2006; Fig. 1b). The complex internal structure of the Kreuzeck-Gailtaler Alpen Nappe is the result of post-Permian Alpine tectonics, as for example shown by Permian metasediments, which appear in a negative flower structure at Gnoppnitztörl in the southern part of the central Kreuzeck Mountains (Schuster and Schuster 2003; Fig. 1b). According to the map compilation by Scharf et al. (2013) the boundary between the KWNS and DGNS nappe systems trends NW–SE between the Teuchl valley in the north and the Nigglai valley (Fig. 1b) in the south, where it turns into E–W direction and continues on the eastern side of the Upper Drau valley in the Goldeck Mountains. The E–W oriented segment, here referred to as Wallner Shear Zone, is mapped as a steeply dipping, cataclastic zone in the map by Pestal et al. (2006).

According to Hoinkes et al. (1999) the eclogites in the northern part of the Kreuzeck Mountains are of Cretaceous age. Ar–Ar muscovite ages and Rb–Sr biotite ages in the Polinik Complex are around 85 Ma (Wölfler et al. 2015a) and 80 Ma, respectively (Brewer 1969; Deutsch 1988). The zircon fission track ages yield Paleogene values (Wölfler et al. 2008), while apatite fission track ages yield Miocene values (Wölfler et al. 2015a, b). In the

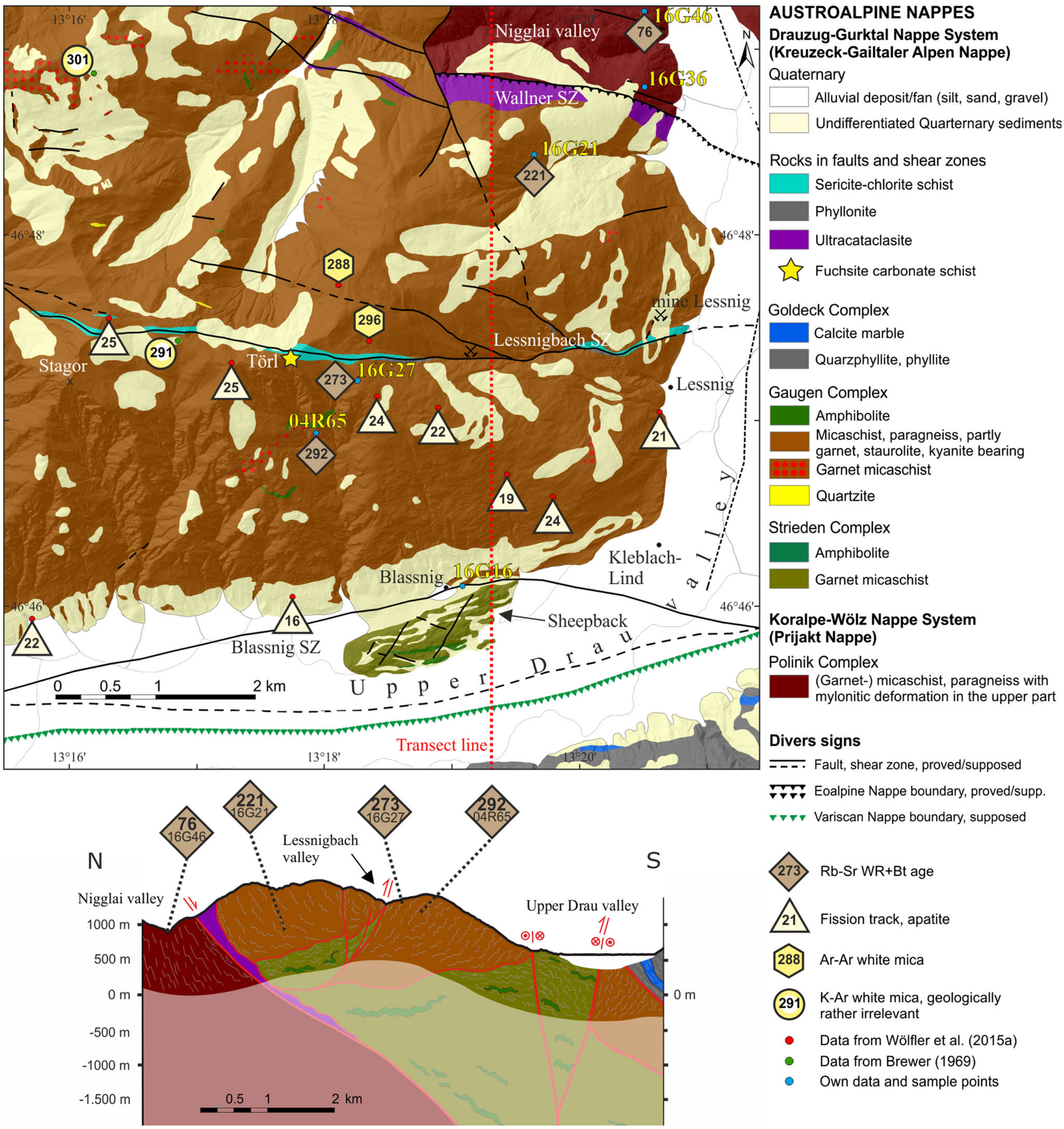

Fig. 2 Geological map (top) and transect (bottom) of the investigated area in the southeastern Kreuzeck Mountains. Important shear zones are labeled. Geochronological data on the map comprise literature data (Brewer 1969; Wölfler et al. 2015a) referred to in the text, together with Rb–Sr biotite ages carried out by this work. The sample numbers and accompanying exact coordinates of the Rb–Sr data as given in Tables 1 and 2 are listed in the transect (bottom). Localities of data from Brewer (1969) are approximations due to restricted information. The profile only shows own data. The less colorful part of the profile shows an interpretation at greater depth. Transect trace is depicted on the map (end points: 13°19′18″E, 46°45′4″N; 13°19′18″E, 46°49′4″N; WGS 84 datum). For details see text

Kreuzeck-Gailtaler Alpen Nappe the Variscan and Permian metamorphic imprints reach greenschist to amphibolite-facies conditions. Locally, in the structurally deepest parts exposed in the north, Permian anatexis was observed (Schuster 2001). A Cretaceous metamorphic overprint is restricted to lower greenschist-facies

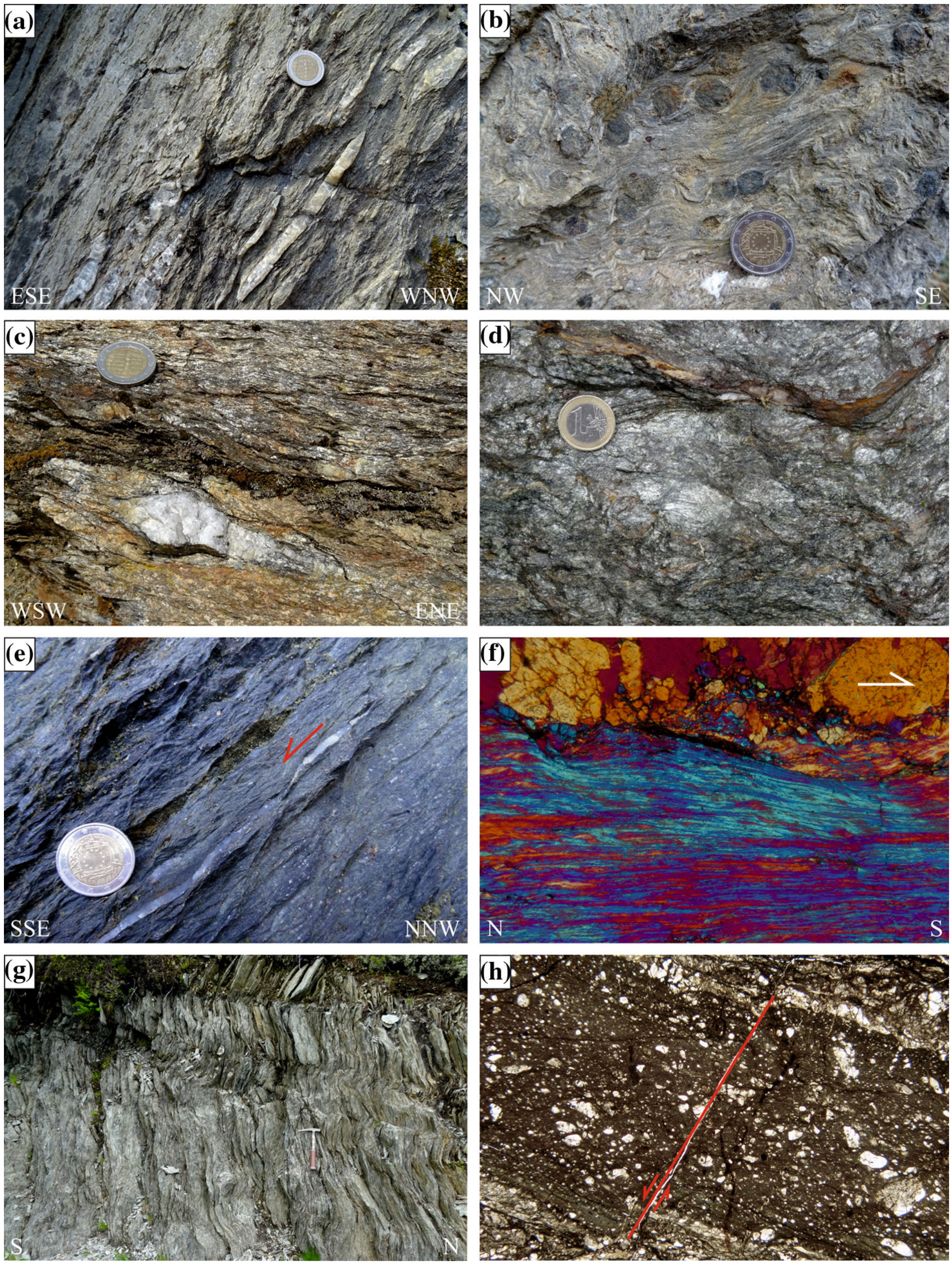

Fig. 3 **a** Paragneiss from the Polinik Complex with quartz-layers and < 1 cm sized garnet porphyroblasts. A slight SC-structure is developed even though the core of the Wallner Shear Zone is located about 1 km structurally above. **b** Folded micaschist from the Strieden Complex with garnet crystals of up to 1 cm in diameter. **c** Paragneiss with asymmetric elongated quartz-clast and shiny white mica from the Gaugen Complex. The brownish weathering color is typical for these rocks. **d** White mica-rich phyllite from the Goldeck Complex with brownish carbonate + quartz vein. Chlorite is responsible for the greenish color. **e** SC mylonite from the Wallner Shear Zone with translucent quartz veins showing top SSE normal faulting. **f** Thin section of quartz mylonite from the Wallner Shear Zone with cataclastically broken feldspar crystals in the upper part. Quartz shows evidences of strong crystal plastic deformation in combination with subgrain formation. The quartz mylonites record strong crystal preferred orientation as seen with sensitive tint plate (sample 16G36, width of the image: 7.5 mm). **g** Chlorite-sericite schist from the Lessnigbach Shear Zone. Overprinting kink folding is also observable. **h** Pseudotachylite from the Blassnig Shear Zone. The crystals are strongly grinded and quartz shows undulose extinction. A later brittle-ductile fault with a few mm displacement cuts across the pseudotachylite (sample 16G16, width of the image: 11.71 mm)

conditions, as Ar–Ar muscovite and Rb–Sr biotite ages are unaffected or only slightly rejuvenated during the Eoalpine event (Schuster et al. 2001; Griesmeier et al. 2017). Fission track data indicate exhumation to shallow depths in the Oligocene (Wölfler et al. 2015a).

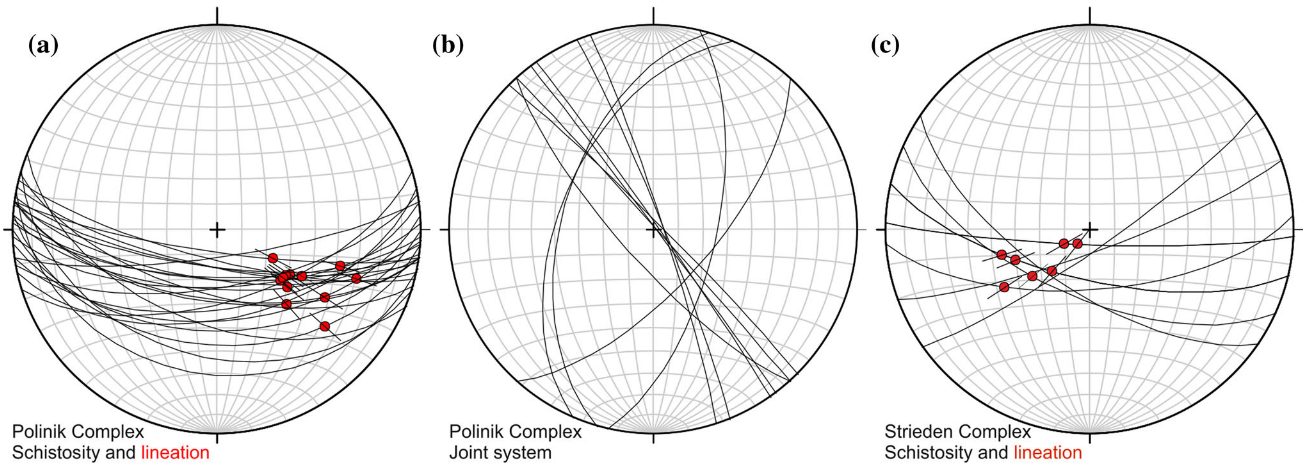

Fig. 4 Equal area, lower hemisphere stereoplots: **a** Dip of schistosity planes and the stretching lineation (red) from the Polinik Complex. **b** Orientation of two well developed joint systems from the Polinik Complex. Rocks are preferably fractured along the NNW-SSE striking joint system. **c** Dip of schistosity planes and the stretching lineation (red) from the Strieden Complex. Rocks are intensely folded by steeply SSW dipping folding axes

3 Samples and methods used for Rb–Sr isotopic analysis

Samples used for Rb–Sr isotopic analyses on biotite, listed in Tables 1 and 2, show the following characteristics (see Fig. 2 for their location in the tectonic map and transect). 16G46 from the Polinik Complex is a fine-grained paragneiss rich in mica. Occasionally, few millimeters sized garnet is abundant. The fine-grained paragneisses to micaschists 16G27, 16G32, 16G21 and 04R65 from the Gaugen Complex are rich in mica and contain frequent garnet up to 3 mm in diameter. In samples 16G32 and 16G21 kyanite and staurolite also occur. Further samples listed in Table 2 are described in the text and figure captions, respectively.

Mechanical and chemical separation for the Rb–Sr isotope analyses were performed at the Geological Survey of Austria (Geologische Bundesanstalt) in Vienna. Minerals were separated by standard methods of crushing, grinding, sieving and magnetic separations. Weights of samples used for dissolution were about 100 mg for whole rock powder and 200 mg for biotite. The chemical sample preparation follows the procedure described by Sölva et al. (2005). Element concentrations were determined by isotope dilution using mixed Rb–Sr spikes. Overall blank contributions were < 1 ng for Rb and Sr. Isotopic ratios were analysed at a ThermoFinnigan® Triton MC-TIMS at the Department of Lithospheric Research at the University of Vienna. Sr was run from Re double filaments, whereas Rb was evaporated from Ta-filaments. The NBS987 standard yielded $^{87}Sr/^{86}Sr = 0.710271 \pm 4$ (n = 40; 2σm standard deviation). Errors for the $^{87}Rb/^{86}Sr$ ratio are < 1%, based on iterative sample analysis and spike recalibration. Ages were calculated with the software ISOPLOT/Ex (Ludwig 2003). Ages are based on decay constants of 1.42×10^{-11} a^{-1} for ^{87}Rb. Figure 7 and Table 2 show the results of the measurements.

4 Results

4.1 General field observations

Mapping of the southeastern part of the Kreuzeck Mountains revealed that the E–W trending segment of the boundary between the Prijakt and Kreuzeck-Gailtaler Alpen Nappe is a several hundred meters wide south dipping shear zone referred to as Wallner Shear Zone (Fig. 2). Its footwall is represented by the Polinik Complex, mylonitized below the cataclasites; the hanging wall consists of the Gaugen Complex.

Further to the south the Gaugen Complex is dissected by internal faults and phyllonite zones, the most significant one being the E–W striking Lessnigbach Shear Zone (Fig. 2). Still further south the Gaugen Complex is bordered by the ENE–WSW striking Blassnig Shear Zone separating Gaugen from Strieden Complex. Additional faults are covered by Quaternary sediments of the Upper Drau valley. Their existence is indicated by the presence of the Goldeck Complex at the southern slopes of the valley.

4.2 Lithostratigraphic units

Only a brief summary of the lithological content of the individual lithostratigraphic units and the overall internal structure is given here. For more detailed lithological descriptions the reader is referred to Deutsch (1977), Hoke (1990), Schuster et al. (2006) and Griesmeier and Schuster

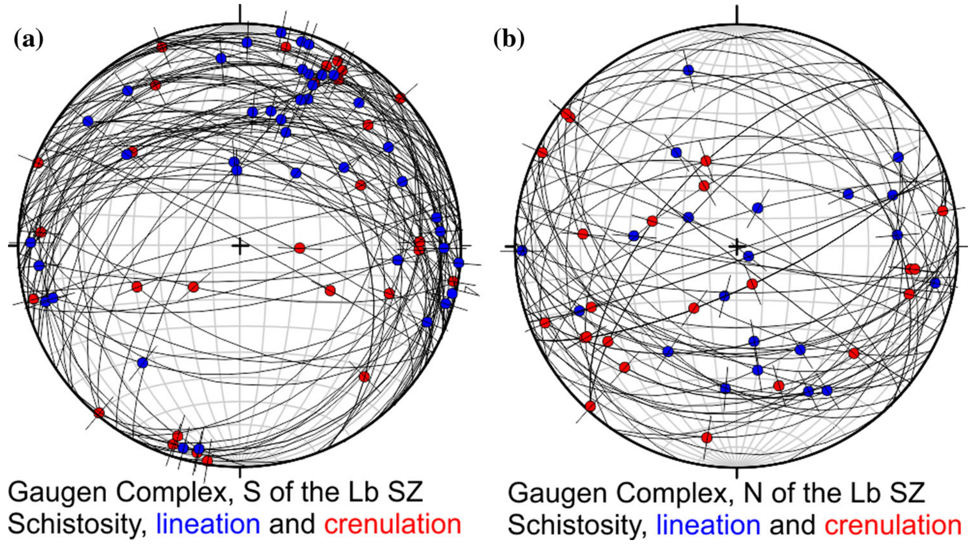

Fig. 5 Equal area, lower hemisphere stereoplots of structures from the Gaugen Complex. **a** Area south of the Lessnigbach Shear Zone, where a north-dip of the schistosity planes dominates. **b** Area north of the Lessnigbach Shear Zone, where a dip to the south is frequent. The stretching lineation is depicted in blue and crenulation axes in red in both plots

(2017). Locations of samples mentioned in the figure caption of Fig. 3 are listed in Table 1 and depicted together with age data in Fig. 2.

The *Polinik Complex (KWNS/Prijakt Nappe)* consists of monotonous paragneiss (Fig. 3a) with few intercalations of orthogneiss, amphibolite, deformed Permian pegmatite and Cretaceous eclogite. In the study area the paragneiss grades into micaschist and occasional garnet micaschist towards the structurally highest part of the complex. In the vicinity of the border to the hanging wall with the Gaugen Complex these rocks transform into mylonites and cataclasites with evidence of top to the south sense of shear accommodated by the Wallner Shear Zone that hence represents a normal fault (Fig. 3e, f).

The Eoalpine schistosity in rocks of the Polinik Complex consistently dips to the south at angles between 30° and 80°. The corresponding stretching lineations dip to the ESE with about 50° (Fig. 4a). Furthermore, a subvertical NNW-SSE striking joint system and a conjugate roughly N-S striking system are well developed (Fig. 4b). The paragneiss is preferably fractured along the NNW-SSE striking joints, which are quite prominent on the E-facing slopes of the Upper Drau valley.

The *Strieden Complex (DGNS/Kreuzeck-Gailtaler Alpen Nappe)* in general shows a variegated lithological composition with different types of metapelite and intercalations of orthogneiss, amphibolite, marble and quartzite, as well as deformed Permian pegmatite. However, in the study area (Fig. 2) greenish, chlorite rich garnet micaschist with

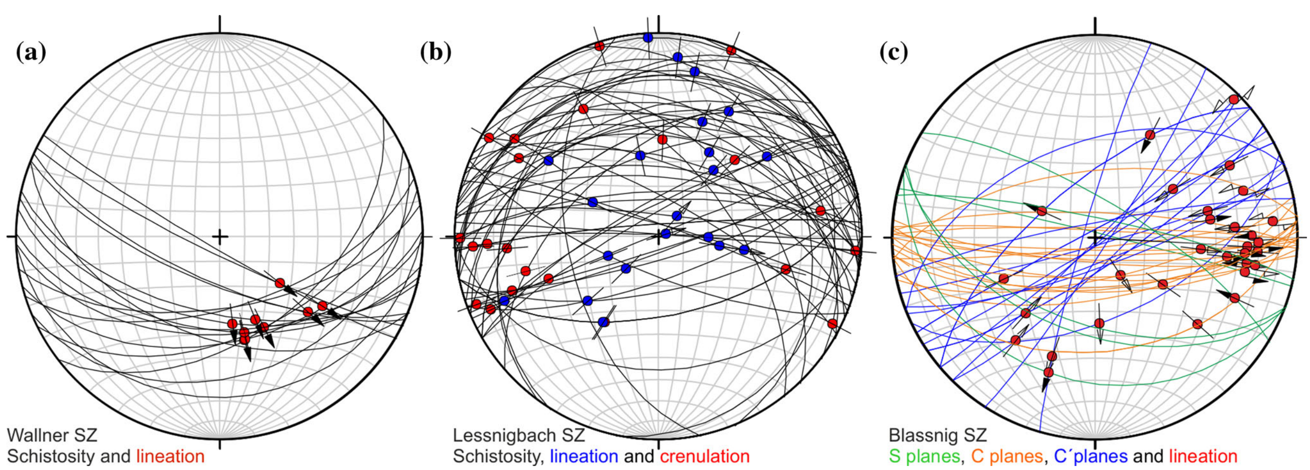

Fig. 6 Equal area, lower hemisphere stereoplots of major shear zones. **a** Dip of schistosity planes of the Wallner Shear Zone. The lineation shows normal faulting to the S–SE. **b** Dip of schistosity planes of the Lessnigbach Shear Zone. The stretching lineation is depicted in blue and the crenulation in red. **c** Dip of schistosity and harnish planes from the Blassnig Shear Zone. S, C and Ć planes can be distinguished (S: green, C: orange, Ć: blue). The lineation is dipping shallowly to the east and shows sinistral shear sense

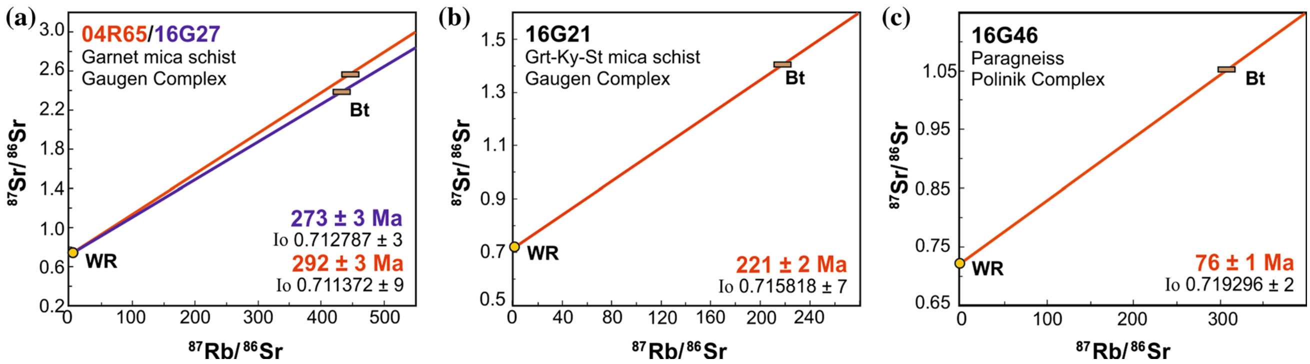

Fig. 7 Rb–Sr age diagrams calculated from whole rock and biotite analysis. Garnet micaschists from the Gaugen Complex (a) south of the Lessnigbach Shear Zone yield ages of 273 ± 3 Ma and 292 ± 3 Ma, whereas (b) for a garnet-kyanite-staurolite micaschist from north of the Lessnigbach Shear Zone an age of 221 ± 2 Ma was determined. A paragneiss from the Polinik Complex (c) yields an age of 76 ± 1 Ma

Table 1 Coordinates of the samples used for Rb-Sr biotite ages and of samples mentioned in Fig. 3 given in the WGS 84 datum

Sample	Latitude	Longitude	Alt. (m)	Lithology
16G04	46.816944	13.343119	640	Paragneiss
16G18	46.766604	13.317685	650	Grt mica schist
16G21	46.806723	13.326555	1290	Paragneiss
16G27	46.786413	13.303478	1920	Paragneiss
16G32	46.807068	13.310492	1730	Paragneiss
16G35	46.812640	13.339750	920	Mylonite
16G36	46.812806	13.340983	780	Quartzmylonite
16G46	46.819597	13.340946	780	Paragneiss
04R65	46.782280	13.298080	1500	Grt mica schist

The locations of these samples are also shown in Figure 2

up to 15 mm large garnet porphyroclasts and amphibolite are typical lithologies (Fig. 3b).

The overall dip direction of the pre-Alpine schistosity is SE to SSW with a dip angle of about 60° to 85° (Fig. 4c). Characteristically, the rocks were intensely folded during the Variscan event with fold axes moderately plunging toward SSW and with axial planes dipping steeply to the NW. In the area of the sheepback in the corner of the Upper Drau valley near Blassnig (Fig. 2) a conjugate ESE–WNW and NNE–SSW-striking fault system is well developed. This fault pattern is typical of the whole Kreuzeck-Gailtaler Alpen Nappe in the investigated area.

The most common lithology of the *Gaugen Complex (DGNS/Kreuzeck-Gailtaler Alpen Nappe)* is ochre colored paragneiss (Fig. 3c) with gradational transition to micaschist. Additionally, garnet micaschist, locally with staurolite and minor kyanite, and rare amphibolite and orthogneiss layers of < 10 m thickness occur.

Due to the polyphase deformation of the rocks, the dip direction of the schistosity of the Gaugen Complex is highly variable, but an overall E–W strike of the foliation can be observed. Schistosity planes in the area to the south of the Lessnigbach Shear Zone predominantly dip shallowly to the north (Fig. 5a), whereas those in the areas north of the shear zone mostly dip moderately to the south (Fig. 5b). Stretching lineations and crenulation/fold axes are highly variable, but often run parallel. To the south of the Lessnigbach Shear Zone a dip to the north and an E–W strike are dominating, whereas to the north no trend is observable. Due to multiple folding and nearly undetectable overprinting relationships, it is hardly possible to separate older from younger structures. Parallel oriented stretching lineation and crenulation could have been formed at the same time, most probably during the Variscan event.

The *Goldeck Complex (DGNS/Kreuzeck-Gailtaler Alpen Nappe)* consists of different types of phyllite with intercalations of marble, greenschist and quartzite (Deutsch 1977). The indicated lower greenschist-facies metamorphic imprint occurred during the Variscan event, as documented with K–Ar data measured on muscovite and muscovite rich whole rocks (Hoke 1990). The phyllites exhibit an intense synmetamorphic folding by E–W orientated axes (Deutsch 1977). The Goldeck Complex is overlain by un-

Table 2 Rb-Sr isotopic data on biotite and whole rock from the Kreuzeck Mountains

Sample	Material	Rb [ppm]	Sr [ppm]	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$\pm 2s_m$	Age (Ma)
04R65	WR	138.1	255.3	1.5664	0.717890	0.000004	
04R65	Bt	459.5	3.521	446.33	2.568383	0.000016	292.4 ± 2.9
16G21	WR	138.3	257.7	1.5552	0.720713	0.000003	
16G21	Bt	462.9	6.550	218.47	1.403461	0.000012	221.3 ± 2.2
16G27	WR	64.76	338.0	0.5548	0.714938	0.000004	
16G27	Bt	357.2	4.757	236.91	1.631271	0.000013	272.5 ± 2.7
16G46	WR	113.0	210.4	1.5565	0.720975	0.000004	
16G46	Bt	450.1	4.371	308.01	1.051678	0.000008	76.0 ± 0.8

Analytical techniques are described in the text. Ages are calculated from biotite and corresponding whole rock assuming an error of ± 1% on the $^{87}Rb/^{86}Sr$ ratio

metamorphosed Permo-Triassic sediments (Pestal 2006). The hole sequence forms a large-scale syncline with an E–W oriented axis, formed during Cretaceous deformation.

4.3 Major shear zones

4.3.1 Wallner Shear Zone

The Wallner Shear Zone represents the E–W trending, southeasternmost segment of the boundary between the KWNS in the footwall and the DGNS in the hanging wall (Fig. 1). Within a thickness of more than 500 m, the rocks are strongly affected by mylonitisation, phyllonitisation and cataclasis.

The shear zone develops out of blocky shattering, monotonous paragneiss of the Polinik Complex, which contains an increasing amount of phyllonitised and mica-enriched zones near the hanging wall. Quartz mylonites (Fig. 3e) and cataclasites occur close to the top of the footwall, at the southern slopes of the Nigglai valley. The exact boundary to the overlying Gaugen Complex is difficult to define, because the fault zone includes strongly deformed rocks of unclear provenance; they are probably derived from both the hanging wall and footwall. The latest stage of deformation is localized in phyllonitized paragneiss of the Gaugen Complex with well-developed SSĆ structures and within several meters thick ultracataclastic zones. These cataclasites are black and break into sharp fragments along variously oriented planes. Towards higher structural levels few millimeter thin layers of ultracataclasite decorate south dipping slickensides topped by a zone of protocataclastic and strongly jointed rocks. Generally, the shear zones and fault zones, including foliated mylonites and cataclastic zones moderately dip S to SW at angles varying between 40° and 60°. The mylonitic stretching lineation dips constantly towards S to SE revealing a sinistral strike slip component of the normal fault (Fig. 6a). This is clearly defined by kinematic indicators like mica fish, SCĆ structures as well as sigmoids (Fig. 3e).

Based on the deformation mechanisms of quartz and the associated mineral record investigated by optical microscopy, the shear zone was active under sub-greenschist to greenschist-facies conditions. In shear bands and C' planes biotite is partly replaced by chlorite, feldspar is affected by sericitisation and quartz shows low temperature bulging, undulose extinction and probably basal gliding. C′ planes are partly coated with iron oxide/hydroxide minerals. Garnet, if preserved, forms fractured porphyroclasts often showing rotation of the fractured parts. The quartz-rich mylonites are nearly pure quartzites with minor feldspar, carbonate and white mica. The quartz crystals show an elongated shape due to dislocation glide and climb (Fig. 3f). Mica-rich rocks are strongly folded. Feldspar is fractured and records no evidence of crystal plastic deformation suggesting temperatures below 400 °C (Passchier and Trouw 2005). Ultracataclasites and cataclasites are rich in iron oxide/hydroxide minerals. Fractured feldspar and quartz grains are rounded by rotation and comminution. Additionally, foliated cataclasites with SC type fabrics suggest a switch in deformation mechanisms from cataclastic flow to dissolution–precipitation creep.

4.3.2 Großhalsgraben Fault

In the western part of the area mapped in Fig. 2 the Wallner Shear Zone is cut by a NNW–ESE striking fault, which is not exposed, but can be traced by loose blocks of cataclasite and a highly disintegrated rock mass. According to the larger scale mapping (Fig. 1) this fault separates the Polinik Complex from both the Gaugen Complex and the Strieden Complex along its northern prolongation. Intersection with topography suggests a NNW–SSE striking and steeply west dipping fault zone. Based on the proposal of Hoke (1990), we refer to this structure as Großhalsgraben Fault.

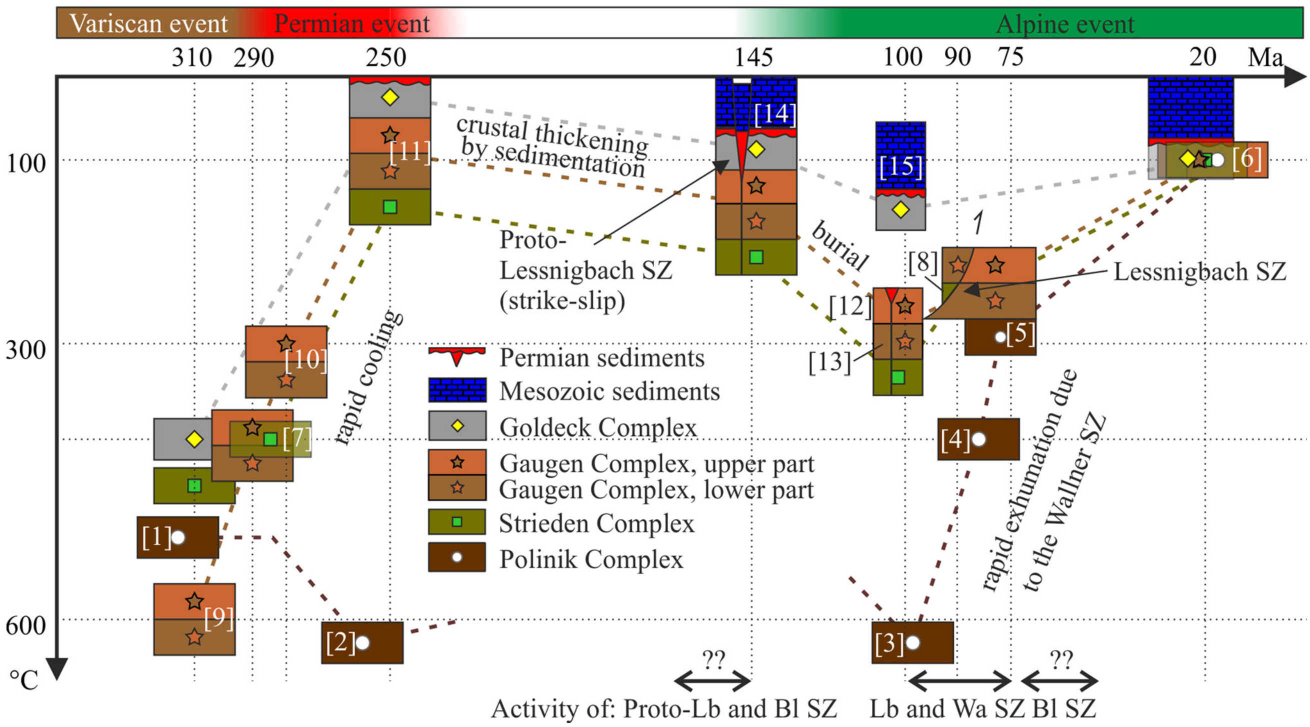

Fig. 8 Reconstructed T-t paths of the Polinik, Strieden, Gaugen and Goldeck complexes and proposed timing of activity of major shear zones during the Variscan, Permian and Alpine events. The age data are based on literature data (see text) and, in case of the Rb-Sr biotite data, on own data. The numbers in brackets refer to the detailed description in the text. It is assumed that the Gaugen Complex is split into two blocks divided by the Lessnigbach Shear Zone. The northern block resided at greater depth before exhumation along the Lessnigbach Shear Zone in the Late Cretaceous. The Proto-Lessnigbach Shear Zone represents a strike-slip shear zone that was probably active in the Late Jurassic. Permian sediments appear within this shear zone further west. The Polinik Complex was rapidly exhumed by the Wallner Shear Zone in the Late Cretaceous (*Lb* Lessnigbach, *Bl* Blassnig, *Wa* Wallner, *SZ* Shear Zone)

4.3.3 Lessnigbach Shear Zone

The subvertical to steeply north dipping Lessnigbach Shear Zone cuts across the Gaugen Complex dividing it in a northern and southern block. Within the shear zone the preexisting, predominantly north dipping schistosity of the paragneiss and micaschist of the Gaugen Complex is strongly overprinted by formation of a SCĆ fabric, whereby the C planes are steeply dipping to the N. The stretching lineation of the latter shows an overall N–S trend with strongly variable dipping angles and top to the south kinematics, suggesting differential exhumation of the northern block (Fig. 6b). In the topographically lower part of the fault zone (around 700 m altitude) the foliation is folded with rounded hinge areas, whereas in the topographically higher parts (around 2000 m altitude) kink-folds with sharp or partly broken hinge areas dominate (Fig. 3g). All fold axes and associated crenulation lineations are subhorizontal and roughly E–W striking (Fig. 6b). Axial surfaces are shallowly dipping to the west and south. Overprinting SCĆ fabrics and slickensides suggest a sinistral strike-slip displacement component.

In the field, the shear zone can be mapped over a structural thickness of roughly 200 m by the occurrence of strongly phyllonitised rocks of the Gaugen Complex. The rocks are strongly weathered, have an ochre color and nearly fall into crumbs, when taken out of the rock mass. Partly, the phyllonitised rocks are dark grey and disintegrate into sigmoidal shaped chips with shiny, silvery surface. Locally, few cm thin white quartz mylonites are observed as fractured cubes. The phyllonites mostly consist of quartz, feldspar and white mica. Under the optical microscope idiomorphic carbonate crystals and iron oxide/hydroxide pseudomorphs after carbonate crystals can be found in quartz rich layers.

Additionally, in the core of the Lessnigbach Shear Zone, green sericite-chlorite schist occurs (Fig. 3g). It is rich in mica and thin fractures along the predominant SCĆ structure. Commonly, few centimeters thick quartz veins are aligned along the schistosity. Further at the ridge (Törl; 2052 m altitude), a yellowish weathering carbonate schist with green fuchsite minerals crops out.

4.3.4 Blassnig Shear Zone

The Blassnig Shear Zone separates the Gaugen Complex in the north from the Strieden Complex in the south (Fig. 2). The outcrops near the village of Blassnig consist of micaschist of the Gaugen Complex affected by a penetrative SCĆ structure, ultracataclasite and locally pseudotachylite (Fig. 3h). The sheared rocks on the southern slopes of the Kreuzeck Mountains form the northern border of the Blassnig Shear Zone; the southern margin is not exposed. Because the sheepback south of Blassnig is not affected by the shear zone, a maximum shear zone thickness of 50 m can be assumed. The shear zone strikes roughly ENE–WSW with a nearly vertical dip (Fig. 6c). On C and Ć planes well developed slickensides with subhorizontal slickenlines indicate a sinistral strike-slip displacement. A minor vertical displacement component caused the differential exhumation of the southern block. Under the optical microscope undulose quartz, fractured feldspar and sericite can be observed in the ultracataclasites. Interestingly, sericite in the ultracataclasites shows a shape preferred orientation assuming shearing conditions in the brittle-ductile transition zone.

4.4 Geochronology

The activity of the individual faults with a dip-slip component is roughly reflected in the cooling history of hanging wall and footwall. To extend the data set available from the literature new Rb–Sr biotite ages from both sides of the Wallner Shear Zone and from several localities within the Gaugen Complex were determined. The biotite ages are interpreted as cooling ages with an assumed blocking temperature of 300 °C (Jäger et al. 1967; Thöni 1996) being aware of problems associated with this concept (e.g. Del Moro et al. 1982). The results are shown in Figs. 2, 7 and Table 2.

All investigated biotites show normal $^{87}Rb/^{86}Sr$ ratios in the range of 200-450 and Rb and Sr contents of 350–470 ppm and 3.5-6.6 ppm, respectively. The biotite ages were calculated with the corresponding whole rock values. Biotite from a paragneiss of the Polinik Complex (sample 16G46) collected north of the Nigglai valley yields 76.0 ± 0.8 Ma. Ages from micaschists of the Gaugen Complex are 221.3 ± 2.2 Ma (sample 16G21) in the block between the Wallner Shear Zone and the Lessnigbach Shear Zone and 272.5 ± 2.7 Ma (sample 16G27) and 292.4 ± 2.9 Ma (sample 04R65) to the south of the latter.

5 Discussion

In the following, the metamorphic history of the area is reviewed and, in combination with the geochronological data, the timing of the activity of the Wallner, Lessnigbach and Blassnig shear zones is discussed. The data are integrated in a T-t diagram for all units, shear zones and faults (Fig. 8). Numbers in square brackets refer to the numbers in Fig. 8.

5.1 T-t paths of the individual units

Little is known about the pre-Alpine metamorphic history of the *Polinik Complex,* but a Variscan metamorphic imprint at around 500 °C [1] is suggested by electron microprobe-dating on monazite (Krenn et al. 2012). At least in some parts Permian pegmatites [2] suggest amphibolite-facies metamorphic conditions (Schuster et al. 2006). Eclogite-facies conditions of 2.1 GPa and ~ 650 °C were reached during the Eoalpine event in the Cretaceous at about 100 Ma [3] (Hoke 1990; Linner et al. 1998; Konzett et al. 2011). However, eclogite bodies are only present in the northern part of the Kreuzeck Mountains, whereas in the investigated area amphibolite-facies conditions are indicated by the occurrence of garnet-bearing amphibolite. For the amphibolite-facies imprint Hoke (1990) determined conditions of 650 °C at > 6 kbar. K–Ar and Ar–Ar muscovite ages indicate cooling below 450–400 °C (Scharf et al. 2016) at about 85 Ma (Hoke 1990) [4], whereas Rb–Sr biotite ages from directly below the Wallner Shear Zone are 76–81 Ma (Deutsch 1988) [5]. Zircon fission track ages of 68–30 Ma indicate cooling to c. 240 °C (Wagner and Van den Haute 1992) and apatite fission track ages from the northern part of the Kreuzeck Mountains are in the range of 25–7 Ma [6], showing cooling to temperatures of 120–60 °C (Green et al. 1986) in Oligocene to Miocene times (Wölfler et al. 2008; Wölfler et al. 2015a). As already mentioned in the literature, this indicates fast exhumation of the Polinik Complex to shallow crustal levels in the Late Cretaceous, slow cooling in the Paleogene and final exhumation to the surface in the Miocene together with the neighboring units within the Tauern Window (Hoke 1990; Wölfler et al. 2015a).

In the *Strieden Complex* a strong regional zoning of the pre-Alpine imprints was interpreted as the result of folding of the whole Kreuzeck-Gailtaler Alpen Nappe during the Eoalpine event (Schuster et al. 2001). Variscan amphibolite-facies conditions are documented in the north, but in the south only Variscan greenschist-facies conditions have been found (Hoke 1990; Proyer et al. 2001). In the Permian a high-temperature low-pressure overprint caused local anataxis and upper amphibolite-facies conditions in the northern part and only greenschist-facies conditions in the south (Schuster et al. 2001). During the Eoalpine event only lower greenschist-facies conditions were reached, because Ar–Ar muscovite and most Rb–Sr biotite ages yield apparent pre-Alpine values. The Ar–Ar muscovite ages are in the range of 280-200 Ma [7] and interpreted to reflect cooling during and after Permian lithospheric extension (Schuster et al. 2001; Schuster and Faupl 2001). Zircon fission track ages are in the range of 107–64 Ma (Wölfler et al. 2015a), indicating a Late Cretaceous thermal overprint at high anchizonal conditions. Due to large scattering of these data, they are only taken as approximate values and a mean value is adopted for visualization in Fig. 8 [8].

For the *Gaugen Complex* Variscan amphibolite-facies conditions [9] were determined by Griesmeier et al. (2017). Ar–Ar and K–Ar muscovite ages of 296–288 Ma have been documented north of the Lessnigbach Shear Zone (Brewer 1969; Wölfler et al. 2015a) [7]. The Rb–Sr biotite ages from south of the Lessnigbach Shear Zone reported here are in the same range or slightly younger (292 Ma and 273 Ma) [10], indicating fast cooling in earliest Permian time. With respect to other Austroalpine units the earliest Permian cooling can be related to exhumation at the end of the Variscan orogenic event (Thöni 1999). The biotite age from north of the Lessnigbach Shear Zone is remarkably younger (221 Ma). It may reflect the time when this rock passed the closing temperature of biotite in the Triassic, or alternatively, it is due to Eoalpine rejuvenation of a Variscan cooling age. During the Permian, the Gaugen Complex must have stayed at a relatively shallow crustal level, beneath the Goldeck Complex [11], because of Permian metasediments trapped in the Lessnigbach Shear Zone at Gnoppnitztörl (Schuster & Schuster 2003). These metasediments include chloritoid-bearing, sericite-phyllites and quartz-phyllites indicating lowermost greenschist-facies conditions with temperatures of 300-350 °C. Prograde metamorphism of the sediments and available geochronological age data reveal the Eoalpine metamorphic conditions of the Gaugen Complex [12]. With respect to this overprint, the northward decreasing Rb–Sr biotite ages can be explained by slightly higher Eoalpine temperatures in the area north of the Lessnigbach Shear Zone causing a remarkable rejuvenation only there [13]. Apatite fission track ages of 25–16 Ma from the block to the south of the shear zone show cooling to near surface temperatures in the Oligocene to Miocene [6] (Wölfler et al. 2015a).

The lower greenschist-facies assemblage of the *Goldeck Complex* formed during the Variscan event, which is indicated by K–Ar muscovite ages in the range of 322-307 Ma (Brewer 1969) [5]. After that, it was exhumed to the surface and transgressed by Permian sediments. During the Triassic the crustal section was loaded by about 3000 m of carbonate-platform sediments [14]. During the Eoalpine event only anchizonal conditions were reached in the Goldeck Complex [15] (Niedermayr and Niedermayr 1984).

5.2 Timing of the activity of the faults

The *Wallner Shear Zone* separates the Polinik Complex of the Prijakt Nappe in the footwall from the Gaugen Complex of the Kreuzeck-Gailtaler Alpen Nappe in the hanging wall. As indicated by structures observed in the shear zone, it accommodated the exhumation of the Polinik Complex from upper to lowermost greenschist-facies conditions in contact to the Gaugen Complex. However, the schistosity of the Polinik Complex, which is oriented parallel to the schistosity of the Wallner Shear Zone and which formed under amphibolite-facies, is most probably responsible for the previous exhumation history of the high-pressure rocks. Based on the T-t path mentioned above (Fig. 8) we suggest differential exhumation between the metamorphic peak at c. 100 Ma and cooling below c. 300 °C at about 80 Ma (also Hoke 1990) in the order of 10–15 km. In summary, the observed structures in the Wallner Shear Zone record decreasing temperatures during displacement and localization of deformation towards the hanging wall. The latter, coupled with brittle deformation mechanisms overprinting brittle/ductile and ductile creep, is a typical feature observed in profiles across crustal scale normal faults (Reynolds and Lister 1987; Grasemann and Mancktelow 1993).

The Wallner Shear Zone represents an element of several other deep to mid crustal shear zones exhuming the Cretaceous eclogite-bearing units of the Koralpe–Wölz Nappe System between South Tyrol/Italy in the west and the southern Saualpe and Koralpe in Styria/Carinthia in the east. Figure 1a shows the shear zones at the base and at the top of the Cretaceous eclogite-bearing units with yellow and red lines, respectively. Coming from the west the north dipping Schneeberg Normal Fault (Sölva et al. 2005) exhumes the eclogite-bearing Texel Complex and the overlying Schneeberg Complex towards southeast. The hanging wall is formed by the Ötztal-Bundschuh Nappe System. This situation is very similar to the Radenthein area, where the eclogite-bearing Millstatt Complex and the overlying Radenthein Complex appear in the footwall of a north dipping shear zone and the Ötztal-Bundschuh Nappe System in the hanging wall (Schuster 2003). In contrast, the south dipping "Plankogel detachment" (Schorn and Stüwe 2016) at the southern slopes of the Saualpe and Koralpe exhumes eclogite-bearing units from below nappes of the Drauzug-Gurktal Nappe System. The footwall of the eclogite-bearing complexes is outcropping at the northern margin of the Saualpe and Koralpe ridges. Similarly, the

Wallner Shear Zone dips to the south and its hanging wall is formed by the Drauzug-Gurktal Nappe System. The base of the eclogite-bearing Polinik Complex is visible further in the northwest in the Schober Mountains (Fusseis and Grasemann 2000). Future reconstructions of the Alpine orogenic wedge during Paleogene and Cretaceous times will have to explain the observed distribution and orientation of such shear zones.

The *Großhalsgraben Fault* cutting off the Wallner Shear Zone to the west is more or less parallel to the N-S trending Upper Drau valley between Kleblach-Lind and Sachsenburg (Fig. 2). Hießleitner (1947) already suspected a horst and graben structure to be responsible for the orientation of the valley. During mining activities in the Sb-mine of Lessnig, he identified a fault responsible for the relative down throw of the eastern block. Towards the north, the Großhalsgraben Fault steepens and turns into WNW-ESE direction (Fig. 1b). There, it is parallel to the Miocene Mölltal Fault and cuts through the Oligocene–Miocene Ragga-Teuchl Fault (Hoke 1990) causing a dextral apparent strike-slip offset of several hundred meters in map view. Based on the orientation, cross cutting relationships and the brittle behavior, we suggest a Miocene age for the Großhalsgraben Fault, which accommodated dextral strike slip in the north and additionally E–W extension in the south.

Structural data indicate a top-to-the south reverse motion for the steeply north dipping *Lessnigbach Shear Zone* with a minor sinistral overprint. These structures formed under lowermost greenschist-facies conditions after the Eoalpine metamorphic peak at about 100 Ma. With respect to this temporal coincidence, it is likely that the Lessnigbach and Wallner shear zones were mechanically linked during exhumation of the Polinik Complex. During the exhumation process the block north of the Lessnigbach Shear Zone was decoupled from the southern block and might have experienced rotational exhumation for several hundred meters. This interpretation explains the younger, probably Eoalpine, rejuvenated Rb–Sr biotite age in the northern block. With respect to this interpretation, we draw a listric Lessnigbach Shear Zone in the section of Fig. 2. The occurrence of sericite-chlorite schist and fuchsite-bearing carbonate schist within the shear zone is of special interest, because these fault rocks did not develop from paragneiss and micaschist of the Gaugen Complex. Most probably, they represent exotic material squeezed into the shear zone during reverse faulting or during an earlier phase of movement (see cross section in Fig. 2). The carbonate schist most probably reflects additional metasomatic processes within the fault zone. Indications for a pre-Cretaceous initiation of the Lessnigbach Shear Zone are provided by Permian metasediments occurring in a negative flower structure at Gnoppnitztörl (Fig. 1) some kilometers further in the west (Schuster and Schuster 2003). This structure argues for an early phase of strike slip motion (Proto-Lessnigbach Shear Zone in Fig. 8) suggesting that it probably developed in a sinistral transpressional regime in the Late Jurassic (Schuster and Frank 1999).

The *Blassnig Shear Zone* represents an ENE–WSW trending, nearly vertical strike slip fault with a sinistral sense of shear and a minor south side up component. Fault rocks indicative for the brittle-ductile transition zone argue for lowermost greenschist-facies roughly around 300 °C or below during its activity. With respect to this temperature, an activity during cooling of the whole nappe stack in the Late Cretaceous is indicated by the Rb–Sr biotite and zircon fission track ages. It is important to note that there has to be another fault with a south side down component within the Upper Drau valley south of the sheepback formed by the Strieden Complex (Fig. 2). The latter is indicated by the Goldeck Complex appearing at the southern slopes of the Upper Drau valley (Pestal et al. 2006). As this fault runs subparallel to the Blassnig Shear Zone, but shows the opposite vertical displacement, we assume that the Strieden Complex forming the sheepback at Blassnig is located in the core of a positive flower structure. In analogy to the early phase of the Lessnigbach Shear Zone, the Blassnig Shear Zone may also have developed in a sinistral transpressional regime during the Late Jurassic (Schuster and Frank 1999). Alternatively, it may have initiated during extensional processes in latest Cretaceous times.

6 Conclusions

The boundary between the Prijakt Nappe (part of the KWNS) in the footwall and the Kreuzeck-Gailtaler Alpen Nappe (part of the DGNS) in the hanging wall consists of three segments, which are listed in sequence of the timing of their initiation. (1) The Wallner Shear Zone is an E–W striking, more than 500 m wide and moderately south dipping normal fault with a vertical offset of at least 15 km. It formed during the time span between the Eoalpine metamorphic peak at about 100 Ma and cooling below c. 300 °C at about 80 Ma. (2) The Ragga-Teuchl Fault represents an E–W trending and steeply dipping strike-slip fault, which was active in Oligocene to Miocene times with changing kinematics. (3) The Großhalsgraben Fault is offsetting the Ragga-Teuchl Fault and cutting off the Wallner Shear Zone. In the north, it is oriented WNW-ESE, subvertical and shows a dextral component, whereas towards the south it turns into a steeply WSW dipping brittle fault with a normal fault component. A relation to the Mölltal Fault and a Miocene activity at about 17 Ma could be expected.

The Kreuzeck-Gailtaler Alpen Nappe is built up, from bottom to top, by the Strieden, Gaugen and Goldeck complexes. It is dissected internally by several faults. The E–W trending and steeply north dipping Lessnigbach Shear Zone is up to 200 m wide and structural data indicate a top to the south reverse motion with a minor sinistral overprint. Structures indicate lowermost greenschist-facies conditions and a major activity after the Eoalpine metamorphic peak.

The Lessnigbach Shear Zone is most likely mechanically linked with antithetic kinematics in respect to the Wallner Shear Zone and therefore related to exhumation of the eclogite–bearing Polinik Complex. Late Cretaceous motion along the Lessnigbach Shear Zone is proved, but an initiation in Late Jurassic times seems possible. Further south, the Blassnig Shear Zone represents an ENE–WSW trending and nearly vertical strike slip fault with a dominant sinistral sense of shear and a minor south side up component. Deformation in the brittle-ductile transition zone suggests sub-greenschist to lowermost greenschist-facies conditions during its activity. For the timing Latest Cretaceous, or in analogy to the Lessnigbach Shear Zone, Late Jurassic motion seems likely.

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References

Borsi, S., Del Moro, A., Sassi, F. P., & Zirpoli, G. (1973). Metamorphic evolution of the Austridic rocks to the south of the Tauern Window (Eastern Alps): radiometric and geopetrologic data. *Memorie della Società Geologica Italiana, 12,* 549–571.

Brewer, M. S. (1969). Excess radiogenic argon in metamorphic micas from the Eastern Alps, Austria. *Earth and Planetary Science Letters, 6*(5), 321–331.

Del Moro, A., Puxeddu, M., Di Brozolo, F. R., & Villa, I. M. (1982). Rb-Sr and K-Ar ages on minerals at temperatures of 300–400 C from deep wells in the Larderello geothermal field (Italy). *Contributions to Mineralogy and Petrology, 81*(4), 340–349.

Deutsch, A. (1977). Geologie und Petrographie der mittleren Goldeckgruppe (Kärnten/Österreich). *Jahrbuch der Geologischen Bundesanstalt, 120*(2), 231–294.

Deutsch, A. (1988). Die frühalpidische Metamorphose in der Goldeck-Gruppe (Kärnten). Nachweis anhand von Rb-Sr-Altersbestimmungen und Gefügebeobachtungen. *Jahrbuch der Geologischen Bundesanstalt, 131*(4), 553–562.

Favaro, S., Handy, M. R., Scharf, A., & Schuster, R. (2017). Changing patterns of exhumation and denudation in front of an advancing crustal indenter, Tauern Window (Eastern Alps). *Tectonophysics, 36,* 1053–1071.

Fusseis, F., & Grasemann, B. (2000). Polyphase deformation of exhuming high-pressure rocks in the Schobergruppe, Austria. *Terra Nostra, 2000*(1), 44.

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

Grasemann, B., & Mancktelow, N. S. (1993). Two-dimensional thermal modelling of normal faulting: the Simplon Fault Zone, Central Alps, Switzerland. *Tectonophysics, 225*(3), 155–165.

Green, P. F., Duddy, I. R., Gleadow, A. J. W., Tingate, P. R., & Laslett, G. M. (1986). Thermal annealing of fission tracks in apatite 1. A qualitative description. *Chemical Geology, 59,* 237–253.

Griesmeier, G. E. U., & Schuster, R. (2017). Bericht 2016 über geologische Aufnahmen auf Blatt 181 Obervellach. *Jahrbuch der Geologischen Bundesanstalt, 157,* 369–373.

Griesmeier, G. E. U., Schuster, R., Grasemann, B., Huet, B. (2017). Variscan to Eoalpine tectono-metamorphic history of the Austroalpine Units south of the Tauern Window (Kreuzeck Mountains, Eastern Alps, Austria). ÉMILE Argand Conference—Workshop on Alpine Geological Studies, 13, p. 116; Zlatibor.

Hießleitner, G. (1947). Die geologischen Grundlagen des Antimonbergbaues in Österreich. *Verhandlungen der Geologischen Bundesanstalt, 1947,* 1–95.

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

Hoke, L. (1990). The Altkristallin of the Kreuzeck Mountains, SE Tauern Window, Eastern Alps; basement crust in a convergent plate boundary zone. *Jahrbuch der Geologischen Bundesanstalt, 133,* 5–87.

Jäger, E., Niggli, E., Wenk, E. (1967). Rb/Sr Altersbestimmungen an Glimmern der Zentralalpen. Beiträge zur geologischen Karte der Schweiz, NF 1344, Bern: 67.

Konzett, J., Krenn, K., Hauzenberger, C., Whitehouse, M., & Hoinkes, G. (2011). High-pressure tourmaline formation and fluid activity in Fe–Ti-rich eclogites from the Kreuzeck Mountains, Eastern Alps, Austria. *Journal of Petrology, 53*(1), 99–125.

Krenn, E., Schulz, B., & Finger, F. (2012). Three generations of monazite in Austroalpine basement rocks to the south of the Tauern Window—evidences for Variscan, Permian and Alpine metamorphism. *Swiss Journal of Geosciences, 105,* 1–18.

Linner, M., Richter, W., & Thöni, M. (1998). Frühalpidische Metamorphose- und Abkühlgeschichte der Eklogite im ostalpinen Kristallin südlich vom Tauernfenster (Schobergruppe). *Mitteilungen der Österreichischen Mineralogischen Gesellschaft, 143,* 334–335.

Ludwig, K. R. (2003). Isoplot/Ex version 3.0. A geochronological toolkit for Microsoft Excel. (70 pp.). Berkeley Geochronological Centre: Special Publication.

NACSN (North American Commission on Stratigraphic Nomenclature). (2005). North American Stratigraphic Code. *AAPG Bulletin, 89*(11), 1547–1591.

Niedermayr, E., & Niedermayr, G. (1984). Bericht 1981 über geologische Aufnahmen im Perm und Skyth auf Blatt 198 Weißbriach. *Verhandlungen der Geologischen Bundesanstalt, 1984,* 86–87.

Passchier, C. W., & Trouw, R. A. (2005). *Microtectonics* (366 pp.). Springer Science & Business Media.

Pestal, G., Rataj, W., Reitner, J., & Schuster, R. (2006). *Geologische Karte der Republik Österreich 1: 50.000, 182 Spittal an der Drau*. Wien: Geologische Bundesanstalt.

Proyer, A., Schuster, R., Hoinkes, G., & Faupl, P. (2001). Permo-Triassic metamorphic evolution of the Kreuzeck-Goldeck mountains (Carinthia, Austria). *Mittteilungen der Österreichischen Mineralogischen Gesellschaft, 146,* 240–242.

Putiš, M., Korikovsky, S. P., Unzog, W., & Olesen, N. O. (2002). HP rocks associated with mylonitoclasites: a result of polystage overprint of the Austro-Alpine basement (Kreuzeck Massif, Eastern Alps). *Slovak Geological. Magazine, 8*(1), 65–87.

Reynolds, S. J., & Lister, G. S. (1987). Structural aspects of fluid-rock interactions in detachment zones. *Geology, 15*(4), 362–366.

Rosenberg, C. L., Schneider, S., Scharf, A., Bertrand, A., Hammerschmidt, K., Rabaute, A., et al. (2017). Relating collisional kinematics to exhumation processes in the Eastern Alps. *Earth-Science Reviews, 176,* 311–344.

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

Scharf, A., Handy, M. R., Schmid, S. M., Favaro, S., Sudo, M., Schuster, R., et al. (2016). Grain-size effects on the closure temperature of white mica in a crustal-scale extensional shear zone—Implications of in situ 40 Ar/39 Ar laser-ablation of white mica for dating shearing and cooling (Tauern Window, Eastern Alps). *Tectonophysics, 674,* 210–226.

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

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

Schorn, S., & Stüwe, K. (2016). The Plankogel detachment of the Eastern Alps: petrological evidence for an orogen-scale extraction fault. *Journal of Metamorphic Geology, 34*(2), 147–166.

Schulz, B., Steenken, A., & Siegesmund, S. (2008). Geodynamics of an Alpine terrane—The Austroalpine basement to the south of the Tauern Window as a part of the Adriatic Plate. *Geological Society of London Special Publications, 298,* 5–43.

Schuster, R. (2003). Das eo-Alpine Ereignis in den Ostalpen: Plattentektonische Situation und interne Struktur des Ostalpinen Kristallins. *Arbeitstagung der Geologischen Bundesanstalt Blatt 148 Brenner, Blatt 175 Sterzing*, 141–159.

Schuster, R., & Faupl, P. (2001). Permo-Triassic sedimentary record and contemporaneous thermal basement evolution in the Drauzug-Goldeck-Kreuzeck area (Eastern Alps/Austria). Abstract Volume 5th Workshop on Alpine Geological Studies (Obergurgl/Austria). *Geologisch-Paläontologische Mitteilungen Innsbruck, 25,* 192–194.

Schuster, R., & Frank, W. (1999). Metamorphic evolution of the Austroalpine units east of the Tauern Window: indications for Jurassic strike slip tectonics. Mitteilungen der Geologie und Bergbaustudenten. *Österreich, 42,* 37–58.

Schuster, R., & Ilickovic, T. (2015). Analysis of Cretaceous to Miocene ductile and brittle fault systems in Austroalpine units to the southeast of the Tauern Window (Eastern Alps). Abstract Volume ÉMILE Argand Conference—EGU series, 12th Alpine Workshop 13-19 September 2015 Montgenèvre/Briançon—French Hautes-Alpes, 52–53.

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

Schuster, R., Scharbert, S., Frank, W., & Abart, R. (2001). Permo-Triassic extension and related HT/LP metamorphism in the Austroalpine – Southalpine realm. *Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten Österreichs, 44,* 111–141.

Schuster, R., & Schuster, K. (2003). Bericht 2001 über geologische Aufnahmen in der südlichen Kreuzeckgruppe auf Blatt 181 Obervellach. *Jahrbuch der Geologischen Bundesanstalt, 143*(3), 453–455.

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 (Italy/Austria). *Tectonophysics, 401,* 143–166.

Thöni, M. (1996). Isotopengeologie und Geochronologie – Einsatzmöglichkeiten in der Geologie. *Mitteilungen der Geologie und Bergbaustudenten. Österreich, 39*(40), 187–209.

Thöni, M. (1999). A review of geochronological data from the Eastern Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen, 79*(1), 209–230.

Wagner, G. A., & Van den Haute, P. (1992). *Fission-track dating*. Stuttgart: Enke.

Wölfler, A., Dekant, C., Danišík, M., Kurz, W., Dunkl, I., Putiš, M., et al. (2008). Late stage differential exhumation of crustal blocks in the central Eastern Alps: evidence from fission track and (U–Th)/He thermochronology. *Terra Nova, 20*(5), 378–384.

Wölfler, A., Dekant, C., Frisch, W., Danišik, M., & Frank, W. (2015a). Cretaceous to Miocene cooling of Austroalpine units southeast of the Tauern Window (Eastern Alps) constrained by multi-system thermochronometry. *Austrian Journal of Earth Sciences, 108*(1), 18–35.

Wölfler, A., Frisch, W., Fritz, H., Danišik, M., & Wölfler, A. (2015b). Ductile to brittle fault zone evolution in Austroalpine units to the southeast of the Tauern Window (Eastern Alps). *Swiss Journal of Geosciences, 108*(2–3), 239–251.