The Gurktal Nappe Complex and its frame

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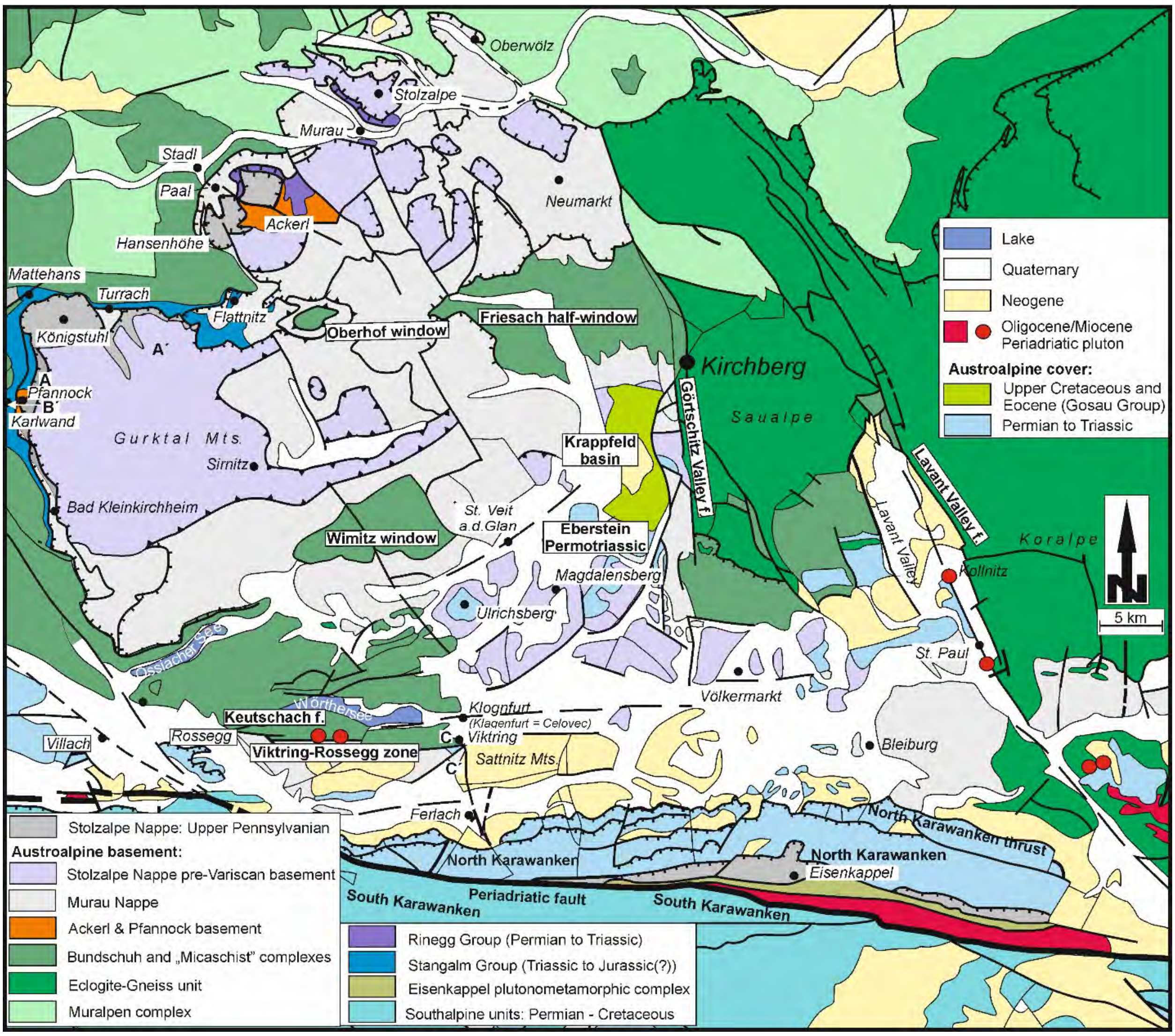
Abstract

The study reviews the composition and structure of the Gurktal Nappe Complex and its underlying frame, the Bundschuh Nappe (part of the Altkristallin basement) and Stangalm Mesozoic cover, mainly of the northern and northwestern parts. The Bundschuh basement is composed of a monotonous metasedimentary basement intruded by the acidic Bundschuh orthogneiss and granodioritic gneisses during Middle Ordovician times. The relatively thin Stangalm Group cover extends from Lower Triassic to Upper Jurassic and is interpreted to have been deposited on a rift shoulder. Basement and cover were variably metamorphosed during early Late Cretaceous (86–90 Ma). The overlying Gurktal Nappe Complex includes three major nappes, which are the Murau, Pfannock/Ackerl/Rinegg and Stolzalpe Nappes. The Murau Nappe, metamorphosed within upper greenschist facies during Cretaceous times, is composed of a Lower Paleozoic succession, which potentially extends to Lower Carboniferous. The overlying nappes include the Pfannock Nappe with an Upper Ordovician orthogneiss metamorphosed during Variscan processes and a thin uppermost Carboniferous to Rhaetian cover succession. The Ackerl Nappe consists of a Variscan nappe stack of paragneiss, overlain by less metamorphic micaschists covered by an Upper Permian to Anisian sedimentary succession. The Rinegg Nappe north and south of Murau includes a phyllonitic basement associated with an inverted succession of Permian to Anisian cover. The basement of the overlying Stolzalpe Nappe is dominated by mafic volcanic successions of Lower Ordovician to Lower/Middle Silurian age covered by a differentiated cover ranging from a carbonate facies extending from Middle Silurian to Lower Carboniferous (metalydite intercalations) to a clastic Silurian to Lower Devonian facies with thick sandstone packages, some Middle–Upper Devonian carbonates and a Carboniferous flysch. The Late Pennsylvanian to Permian cover (Stangnock and Werchzirm Formations) is often tectonically separated from the basement representing then separate tectonic slices. The less affected Permian to Upper Triassic cover is mostly preserved in the eastern central part and is in turn overlain by the Krappfeld Gosau basin fill, which represents a Late Cretaceous to Eocene collapse basin.

The synmetamorphic Alpine stacking of the Gurktal Nappe Complex occurred during Early Cretaceous to early Late Cretaceous pre-dating the deposition of Krappfeld Gosau sediments. Based on ductile field structures as thrusts and W-vergent folds and microfabrics, top-to-the WNW motion has been deduced. The stretching lineation of the ductile thrusts is plunging to the ESE. These fabrics are overprinted by a large-scale E-dipping ductile low-angle normal fault system. These fabrics indicate extension and thinning of the nappe stack. The strongest thinning is observed at the western boundary, where the Phyllonite zone as part of the Murau Nappe is strongly affected by this stage and metamorphic breaks are observed between the Stangalm Group and Murau Nappe and between the Murau Nappe and overlying Pfannock/Ackerl/Rinegg and Stolzalpe Nappes, respectively.

Introduction

In the discussion on the structure of the Eastern Alps, the Gurktal Nappe Complex plays a critical role since the discovery of Late Triassic fossils in limestones, later interpreted as the Kössen Formation (HOLDHAUS, 1921; TOLLMANN, 1959; KRISTAN-TOLLMANN & TOLLMANN, 1964), which are overlain by conglomerates of the Late Pennsylvanian Stangnock Formation (HOLDHAUS, 1922). This feature was taken to distinguish between an Upper Austroalpine nappe with a Lower Paleozoic phyllitic basement from an underlying amphibolite facies-grade basement and overlying Triassic sedimentary sequence considered to represent a separate tectonic unit (TOLLMANN, 1959, 1977; FLÜGEL, 1960), how classically tectonic nappes are defined based on stratigraphic reasoning (Text-Fig. 1). This interpretation resulted in a long-lasting controversy on the overall structure and scale of thrusting and some nomenclatoric confusion (CLAR, 1965, 1973; PISTOTNIK, 1980; FRANK, 1987; TOLLMANN, 1987; RATSCHBACHER & NEUBAUER, 1989; RATSCHBACHER et al., 1989; NEUBAUER et al., 2000; SCHMID et al., 2004). Later, it became clear that the structure of the Gurktal Nappe Complex is more complicated and this issue is still not fully resolved.



Text-Fig. 1: Geological overview map of the Gurktal Nappe Complex (modified and expanded from NEUBAUER et al., 2018). Note that the separation between the Murau Nappe and Stolzalpe Nappe is schematic and needs in details significant refinement because of the uncertain tectonic assignment of monotonous phyllites (e.g., PISTOTNIK, 1996; THIEDIG et al., 1999). A-A´ and B-B´ locate sections shown in Text-Fig. 11, Section C-C´ is shown in Text-Fig. 14.

Here, the results of new studies are reported and put into the frame of the overall structure of the northwestern and northern parts of the Gurktal Nappe Complex (Text-Fig. 1). First, we give an overview on the principal structural elements and then we summarize some details of recent studies, which are in various stages of publication. These recent studies are devoted to the lithostratigraphy and structures along the northern and northwestern margin of the Gurktal Nappe Complex and its underlying frame, particularly to the lithostratigraphy of the Mesozoic Stangalm Group. Most stratigraphic correlations of the Stangalm Group and of other Permomesozoic formations, except that on top of the Stolzalpe Nappe, are based on lithostratigraphic comparison. In basement rocks of the Stolzalpe Nappe, some new fossil localities (east of the Turracher Höhe) containing conodonts were found. Further U-Pb zircon and $^{40}Ar/^{39}Ar$ dating efforts of magmatism and detrital minerals are ongoing and some preliminary results are reported. We also compile hitherto not fully published $^{40}Ar/^{39}Ar$ white mica ages constraining the age of some stages of polymetamorphism.

Overview on structural units

The structural units underlying the Gurktal Nappe Complex and of its frame comprise, at the base, the Bundschuh basement complex (SCHUSTER & FRANK, 1999), a pre-Alpine basement and the primarily overlying Mesozoic Stangalm Group (tectonically termed as “Melitzen-Scholle” by TOLLMANN, 1975). The Stangalm Group can be traced along the northwestern margins between south of Bad Kleinkirchheim and west of Murau, respectively southwest of Murau (Text-Fig. 1). The Gurktal Nappe Complex comprises basement-cover units metamorphosed in mainly low-grade to very low-grade metamorphic conditions, and cover formations. These consist of (1) the Murau Nappe in a lower tectonic position, and (2) in three separated areas, the Pfannock, Ackerl and Rinegg Nappes. All three nappes consist of a metamorphic basement and a Permian–Triassic cover. The Rinegg unit around Murau, intercalated between Murau and Stolzalpe Nappes, is here introduced as a new structural unit with mainly a Permian to Middle Triassic cover and remnants of a phyllitic basement. The cover of this unit is overturned excluding a primary connection with the underlying Murau Nappe. In the same tectonic position above the Murau Nappe, the Pfannock Nappe with the Pfannock orthogneiss and a thin Upper Pennsylvanian to Upper Triassic cover is a separate unit along the western margin of the Gurktal Nappe Complex. Ironically, this unit includes the classical Eisentalhöhe fossil locality of HOLDHAUS (1921) and is now located within the Gurktal Nappe Complex. Finally, also in the same position above the Murau Nappe, the Ackerl Nappe includes a Variscan basement overlain by Permomesozoic cover (NEUBAUER, 1980b). (3) The Stolzalpe Nappe consists of an Ordovician to Carboniferous succession with abundant mafic volcanics and in part thick packages of sandstones and is primarily overlain by Pennsylvanian to Permian molasse-type deposits (Stangnock and Werchzirm Formations) and, on the eastern and central parts, by Permian to Upper Triassic successions (Eberstein/Krappfeld Triassic). These are again overlain, following an erosional and angular unconformity, by the Upper Cretaceous to Eocene Krappfeld Gosau (RIEHL-HERWIRSCH & WASCHER, 1972). In the following, we describe details of all these units with the main aspect on the lithostratigraphic succession including some new results.

Bundschuh basement

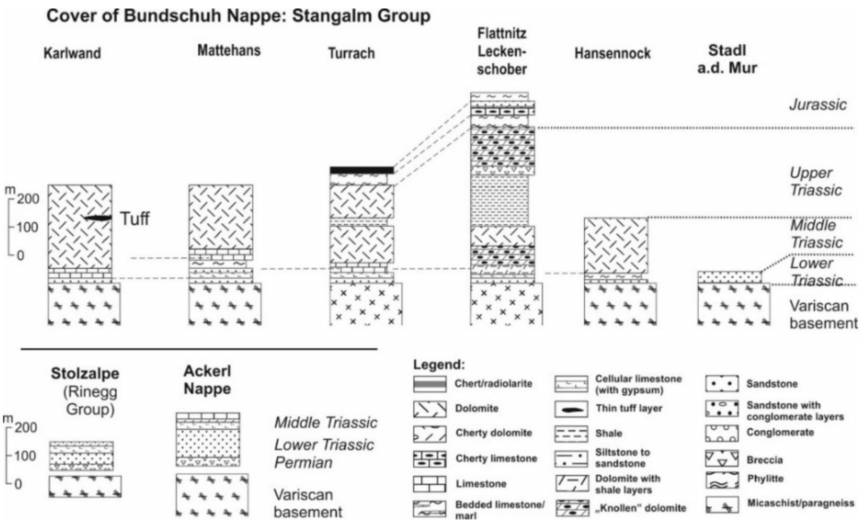
The Bundschuh basement consists of monotonous paragneiss and micaschists intruded by the Bundschuh orthogneiss and a number of fine-grained granodioritic gneisses. The age of the Bundschuh orthogneiss is late Middle Ordovician according to U-Pb zircon ages (462.5 ± 6.5 Ma; GENSER & LIU, unpubl. data, see NEUBAUER & GENSER, 2018). Previous Rb-Sr whole rock investigations resulted in sets of subparallel isochrons with model ages between 371 and 397 Ma and high initial $^{87}Sr/^{86}Sr$ ratios between 0.721 and 0.739 (FRIMMEL, 1988). Petrography, initial Sr isotopic values and geochemistry indicate a syn-collisional origin of the orthogneiss (FRIMMEL, 1988). Nothing is known from paragneiss and micaschist host rocks, their sedimentation age must predate late Middle Ordovician. A post-Variscan angular unconformity below the Lower Triassic Stangalm Quartzites (PISTOTNIK, 1976) proves the preservation of style and orientation of Variscan structures formed within amphibolite facies conditions in the Bundschuh basement unit, which includes two stages of Variscan ductile deformation (NEUBAUER & GENSER, 2018).
Rocks of the Bundschuh Nappe basement show two stages of metamorphism, Variscan and Cretaceous, well exemplified on two-stage garnet. In the southwestern part, KOROKNAI et al.

(1999) found P-T conditions of ca. 10 kbar and 580–630° C for the Cretaceous metamorphism. In the northwestern part, THEINER (1987) reported a Variscan metamorphic overprint on the Bundschuh basement complex at ca. 600–640° C and, in nearby localities, Alpine temperatures ranging from 500 to 520° C. Consequently, the Alpine metamorphic overprint decreases towards north.

Previous geochronological data constraining the age of the metamorphic event(s) of the investigated tectonic units were published by FRIMMEL (1986a, b), SCHIMANA (1986) and SCHUSTER & FRANK (1999). K-Ar data record an Alpine age in the Radenthein and Bundschuh (Priedröf) Nappes mostly in the range of 70–110 Ma. Rb-Sr white mica ages of the Bundschuh orthogneiss from the Innerkrems area range between 305 ± 12 and 119 ± 1 Ma (THEINER, 1987). Rb-Sr muscovite ages from the Bundschuh orthogneiss indicate an early Variscan metamorphic event (350–354 Ma). The Bundschuh orthogneiss was deformed intensely during Cretaceous metamorphism and Rb-Sr mineral ages (muscovite, feldspar) were variably reset to 119 to 91 Ma (FRIMMEL, 1986a, b). Altogether, according to these few geochronological data, the Bundschuh was strongly affected by Cretaceous metamorphism, while pre-Alpine metamorphism is restricted to the northern part of Bundschuh basement.

Stangalm Group

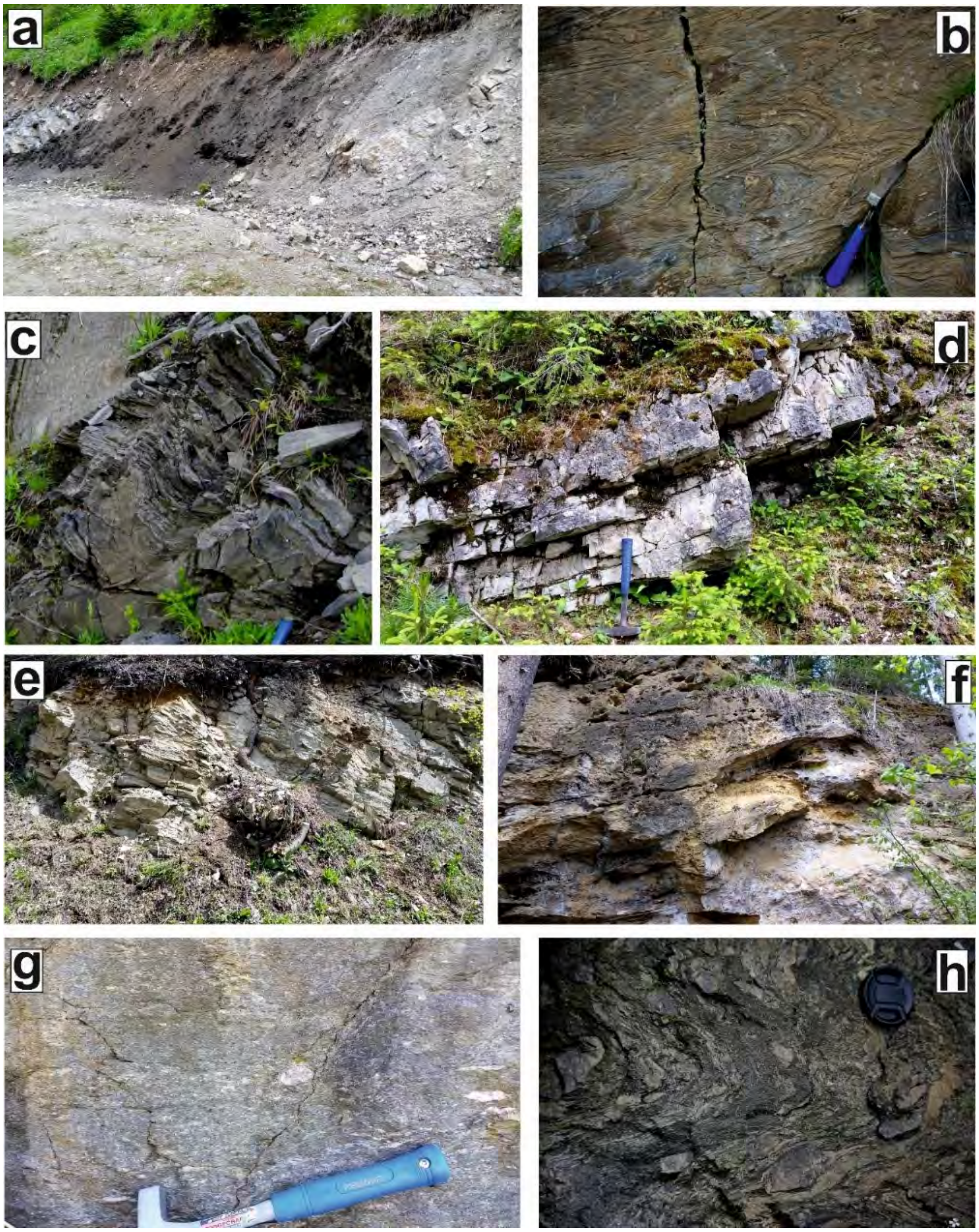
We describe the sections from the Stangalm Group from Southwest to Northeast (Text-Fig. 2). For the southwestern part of the Stangalm Group, the siliciclastic base, a light-greenish quartzite is very rare, maximum ca. 10 meters thick, but it is connected by an unconformity with the underlying amphibolite-grade basement (PISTOTNIK, 1976; KRAINER, 1984). This unit is overlain by a yellowish ca. 10 meters thick cellular limestone (rauhwacke in the local literature), rare sulfide-ore bearing carbonate quartzite and marbles (REDLICH, 1931) and several tens of meters thick greyish and dark foliated calcite marble (Text-Fig. 3b). With a thickness of ca. 300–400 meters at the northwestern corner of the Gurktal Nappe Complex, light-colored recrystallized, poorly bedded and/or foliated Wetterstein-type dolomites follow (PISTOTNIK, 1974; GOSEN, 1989), which represent the main rock body of the Stangalm Group. Based on lithostratigraphy, peculiarities of the Stangalm Group include (Text-Figs. 2, 3 for some peculiarities): only a thin siliciclastic Permian base, if any, and thin Lower Triassic quartzites, black phyllites, black calc-schists and related synsedimentary ore mineralizations of Anisian age, relatively thin Middle and Upper Triassic dolomites separated by Carnian siliciclastic beds, the latter showing extreme thickness variations interpreted to result from a synsedimentary normal faulting and Jurassic cherty limestones and thin Upper Jurassic cherts (BECK-MANNAGETTA in ANDERLE et al., 1964). Special attention is given to the thick Carnian siltstones and fine-grained sandstones of the Flattnitz area, there originally mapped as Bockbühel-Schiefer (STOWASSER, 1956), which can be traced, with interruptions, to the west of Turrach (Text-Fig. 3a). Cherty calcite and dolomite marbles can be mapped in several sections between Flattnitz and Turrach (already found in one section by BECK-MANNAGETTA in ANDERLE et al., 1964). These are correlated with Upper Jurassic



Text-Fig. 2: The Mesozoic cover, the Stangalm Group on the Bundschuh basement. Same legend is also used for Text-Figures 6 and 9.

radiolarites implying a more complete Triassic-Jurassic section (Text-Fig. 2). The eastern most occurrence of a rock, a Verrucano-type meta-conglomerate of the Stangalm Group underneath the Murau Nappe was recently found west of Murau.

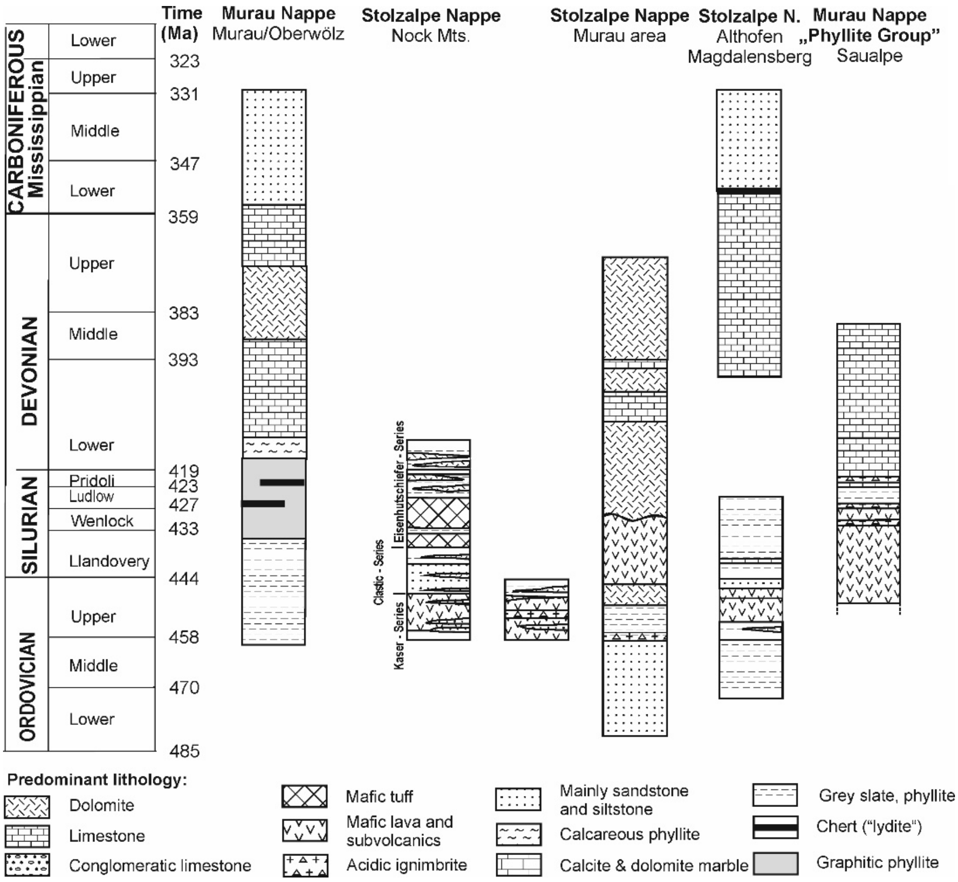
In the Nock road section, approx. 450° C was obtained for peak conditions of metamorphism. A previous muscovite K-Ar age of the Stangalm Mesozoic cover rocks is about 70 Ma (SCHIMANA, 1986). Recent $^{40}Ar/^{39}Ar$ white mica plateau ages are at 89.0 ± 0.6 Ma and 96.2 ± 0.4 Ma proofing the age of Early Alpine metamorphism (NEUBAUER & GENSER, 2018; STAUBER et al., 2018).



Text-Fig. 3: Representative lithologies of the Stangalm and Rinegg Groups. (a) Black phylites (Carnian level) intercalaed within dolomites (west of Turrach). (b) Foliated and folded dark-colored calcite marble (Anisian?) (west of Flattnitz). (c) Fine-grained sandstones within the Carnian Bockbühel Formation (west of Flattnitz). (d) Cherty dolomite respectively calcite marble (southwest of Turrach). (a) to (d) are from the Stangalm Group. (e) Green sandstone beds intercalated within greenish slates (Bundsandstein-type level). (f) Cellular limestone (or rauhwacke). (e) and (f) are from the Rinegg Group (Stolzalpe). (g) Quartz conglomerate. (h) Polymictic conglomerate. (g) and (f) belong to the Upper Carboniferous Stangnock Formation. Both examples are from west of Flattnitz.

Murau Nappe

The Murau Nappe is widespread within the Gurktal Nappe Complex and includes also the main body of various monotonous phyllites between Murau area in the north and Rossegg and Viktring areas in the south. The lithostratigraphy of the Murau Nappe has been not yet been systematically studied except the Phyllite Group in the southern Saualpe area. The best studied area is in the surroundings of Murau (Text-Fig. 4). There, the Murau Nappe basement comprises several informal units, which include monotonous greyish quartz-phyllites and phyllites, which could be considered as the base (potentially of mainly Ordovician age). The greyish phyllites are overlain by black graphitic phyllites (black phyllites), which include a number of intercalations including thin greenschist, metalydite (black chert) and very thin dolomite lenses. From the metalydites, HERITSCH & THURNER (1932) reported graptolites, which were obviously lost (JAEGER, 1969). EBNER et al. (1977) and NEUBAUER (1980a) reported Late Silurian to Early Devonian conodonts from a dolomite lens within black phyllites from the area west of Murau. In the overlying unit, carbonatic phyllite is also often graphitic and represents the transition zone to the Murau marble, a calcitic marble, with rare dolomite lenses. The Grebenzen marble seems to be an equivalent as well as such of the Adelsberg north of Neumarkt. The Murau and Grebenzen marbles are considered as Devonian. Mostly Emsian and Middle Devonian conodonts are reported from the Grebenzen (BUCHROITHNER, 1978; SCHÖNLAUB, 1979) and a rich Early Devonian conodont fauna from the Adelsberg NW Neumarkt (NEUBAUER, 1980d). NIEDERL (1980) found Devonian conodonts in the Oberwölz region. In the Murau area, the Murau marble is overlain by epidote- and chlorite-phyllite, which includes prasinite lenses and abundant quartzitic layers (Text-Fig. 5a), intercalated by phyllites (THURNER, 1958a, b). This unit could be considered as Carboniferous flysch (see also NEUBAUER, 1980c).

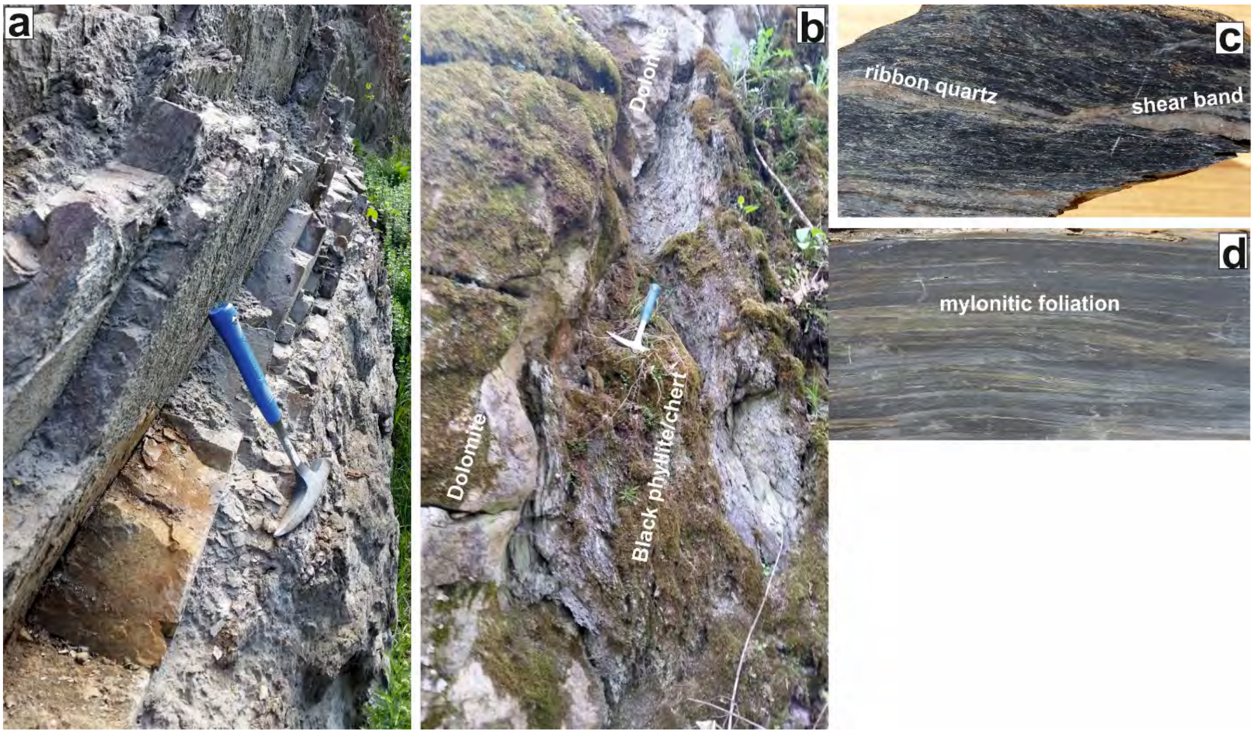


Text-Fig. 4: Simplified lithostratigraphic sections of the Murau and Stolzalpe Nappe basement. Time-scale is after OGG et al. (2016).

The Murau Nappe is metamorphosed in upper grenschist facies metamorphyic conditions. Only a few T estimates and are 460–500° C, respectively ca. 550° C (KOROKNAI et al., 1999). HEJL (1984) published a single K-Ar white mica age of 89.9 ± 7.1 Ma and Rb-Sr white mica age of 86.9 Ma from the Murau area. The Murau Nappe is potentially polymetamorphic, testified by not fully reset pre-Alpine $^{40}Ar/^{39}Ar$ white mica age of 240.3 ± 0.5 Ma in the Phyllonite zone, although mainly $^{40}Ar/^{39}Ar$ white mica ages in the range of 85–90 Ma are found (87.1 ± 0.5 Ma: STAUBER et al., 2018; 85.78 ± 0.33 Ma and further unpublished ages from the area east of Bad Kleinkirchheim ranging between 80 and 88 Ma). Consequently, the unit is fully overprinted by Late Cretaceous greenschist facies metamorphism. Furthermore, WIESINGER et al. (2006) reported white mica ages of 123.5 ± 0.9 Ma and 261.7 ± 1.4 Ma from Saualpe Phyllite unit, resp. Lower Magdalensberg unit showing polymetamorphism.

Pfannock Nappe

The Pfannock Nappe consists of an orthogneiss with a penetrative foliation, which is covered by an uppermost Pennsylvanian to Raetian sedimentary succession (KRAINER, 1984). The Pfannock gneiss has a U-Pb zircon age of ca. 440 Ma (GENSER & LIU, in prep.). This testifies that the Pfannock orthogneiss is ca. 20 Myrs younger than the Bundschuh orthogneiss. The white mica $^{40}Ar/^{39}Ar$ ages are Variscan, at around 310–320 Ma (GENSER, unpubl. data). These ages also indicate that the Pfannock gneiss escaped early Alpine metamorphism and cannot directly be

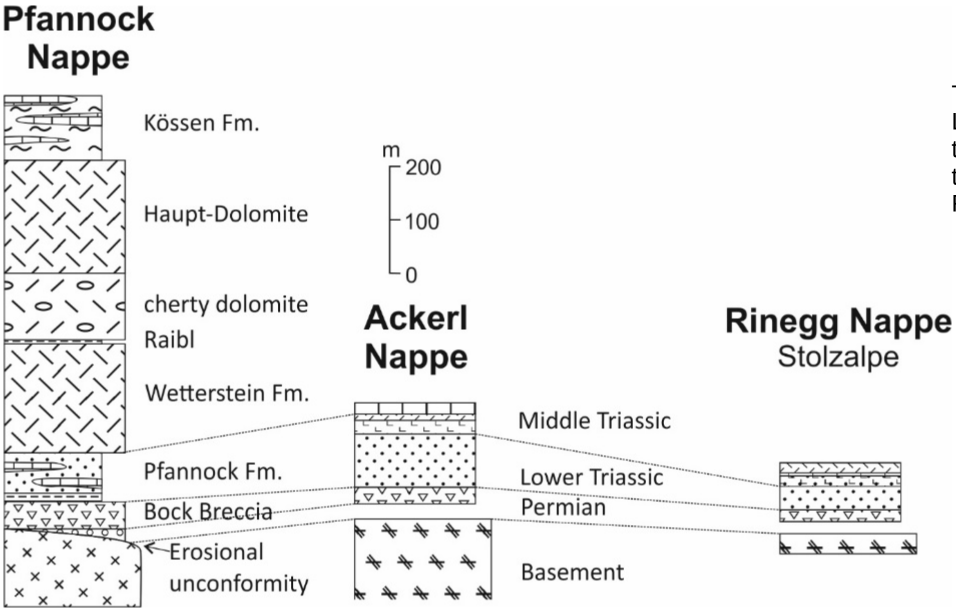


Text-Fig. 5: (a) Potential Carboniferous flysch of the Murau Nappe (parking place along the federal road at the SE edge of Stolzalpe). (b) Black siliceous phyllite/metachert (Kaindorf SW Murau). This level is interpreted as Mississippian in comparison with other Austroalpine and Southalpine Paleozoic successions (e.g. SCHÖNLAUB, 1979). (c) Mylonitic phyllite from the stratigraphic base of the Rinegg Nappe. Length of sample: ca. 5 cm. (d) Mylonitic tuff from the tectonic base of the Stolzalpe Nappe. Length of sample: ca. 6 cm.

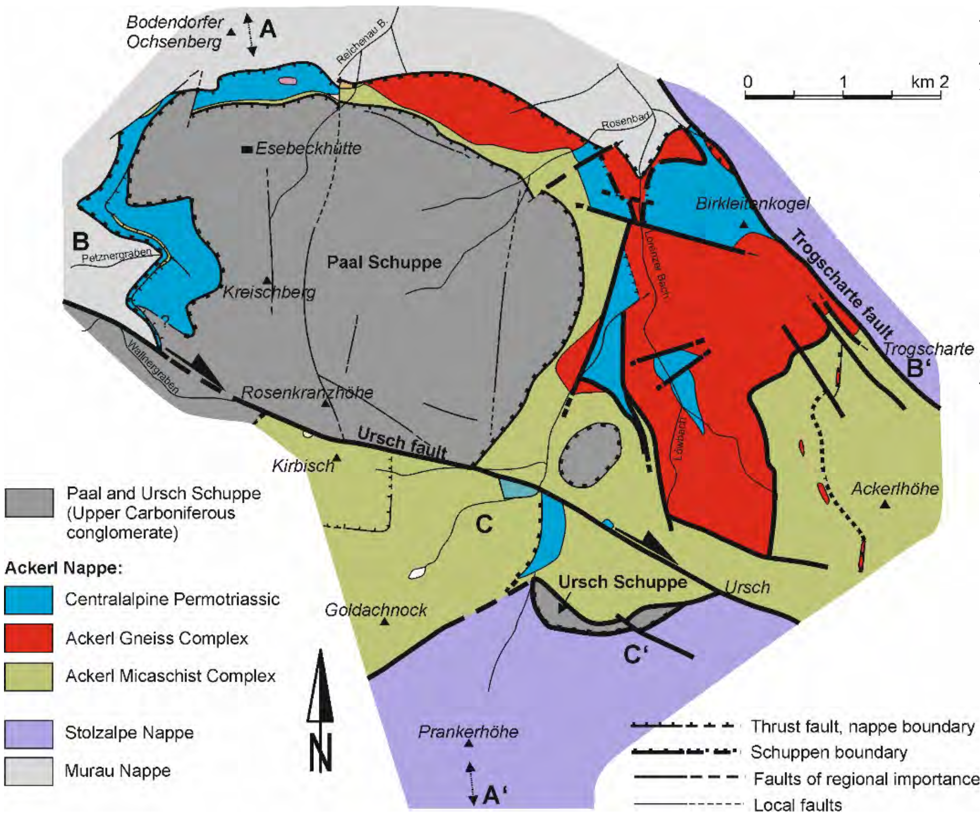
correlated in terms of the Alpine structure, therefore not with the Bundschuh orthogneiss.
The cover succession has been described in TOLLMANN (1975, 1977), PISTOTNIK (1980, 1996), KRAINER (1984, 1987) and SYLVESTER (1989a, b). It comprises a thin Upper Pennsylvanian conglomerate to siltstone layer, the purple Permian Bock Breccia, Werfen Formation, the Anisian Pfannock Formation with mixed sandstones and carbonate and a carbonate section ranging from Wetterstein Dolomite to the classical Rhaetian Kössen Formation (PISTOTNIK, 1996) (Text-Fig. 6).

Ackerl Nappe

The Ackerl Nappe is a basement-cover nappe with a partly amphibolite-grade and upper greenschist facies basement with gneisses and micaschists, which are associated with fossil-free Permian of lowermost Anisian carbonates (NEUBAUER, 1980b) (Text-Fig. 6). However, an unequivocal primary sedimentary contact between basement and cover was not found up to now. The basement is distinguished into an underlying Ackerl Micaschist unit and an overlying Ackerl Gneiss unit (Text-Fig. 7). The Ackerl Micaschist unit is relatively monotonous in composition comprising mica- and chlorite-rich micaschists with some plagioclase and rare garnet and is of lower metamorphic grade, within upper greenschist facies than the overlying Ackerl Gneiss unit.

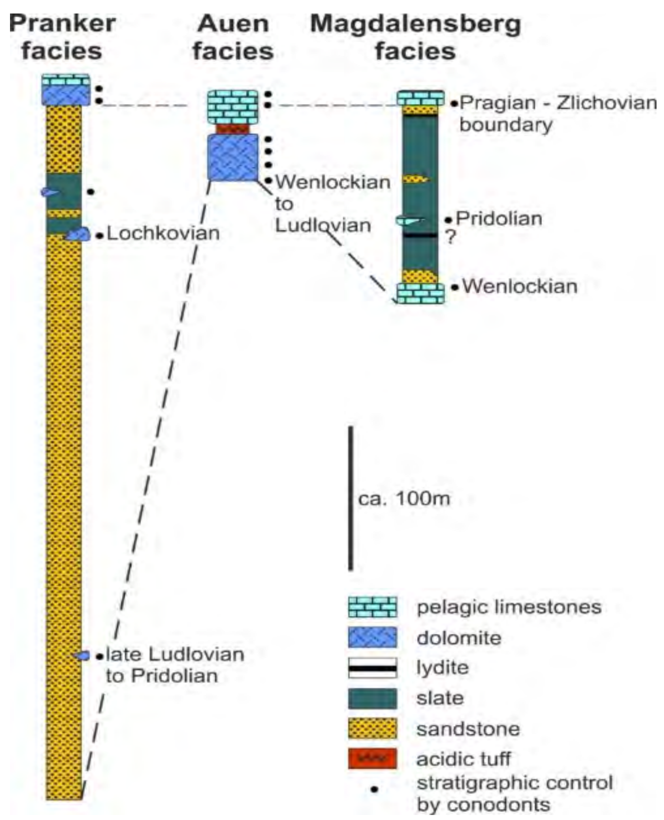


Text-Fig. 6: Lithostratigraphy of Permian to Mesozoic cover units of the Pfannock, Ackerl and Rinegg Nappes.



Text-Fig. 7: Map of the Ackerl Nappe area with strong late stage imbrication during Cretaceous nappe stacking and subsequent overprint by E-vergent normal faulting and dextral strike-slip faults (e.g., Ursch fault). Modified after Neubauer (1980b). A-A´ (section extends also outside of the map), B-B´ and C-C´locate sections shown in Text-Fig. 13.

The Ackerl Gneiss unit includes a sometimes staurolite-bearing paragneiss with a metablastic fabric and very rare amphibolite, aplite and pegmatite. Both Ackerl Gneiss and Ackerl Micaschist units show a Variscan metamorphism expressed by $^{40}Ar/^{39}Ar$ white mica ages with staircase patterns between 309 and 320 Ma, including a plateau age of ca. 309.2 ± 3.1 Ma (error



Text-Fig. 8: Paleozoic facies differentiation within the basement of the Stolzalpe Nappe.

recalculated with J-value; NEUBAUER & DALLMEYER, 1994). A low-temperature overprint is younger than ca. 200 Ma, meaning that the Early Alpine temperature reached ca. 300–350° C. The overlying cover section starts with a purple, 5–30 meter thick Alpine Verrucano Formation, which is overlain by a maximum 100 meter thick light-greenish and rarely purple, well bedded quartz-arenitic sandstone (from the type Lantschfeld or Semmering Formation). Overlying yellowish cellular limestones (rauwacke) and subordinate sandy limestones are 20–25 meter thick. These are followed by crinoid-bearing dolomites (dolopelmicrite) and locally thin dark foliated limestones (NEUBAUER, 1980b). These carbonates represent the Anisian stratigraphic level.

Rinegg Nappe

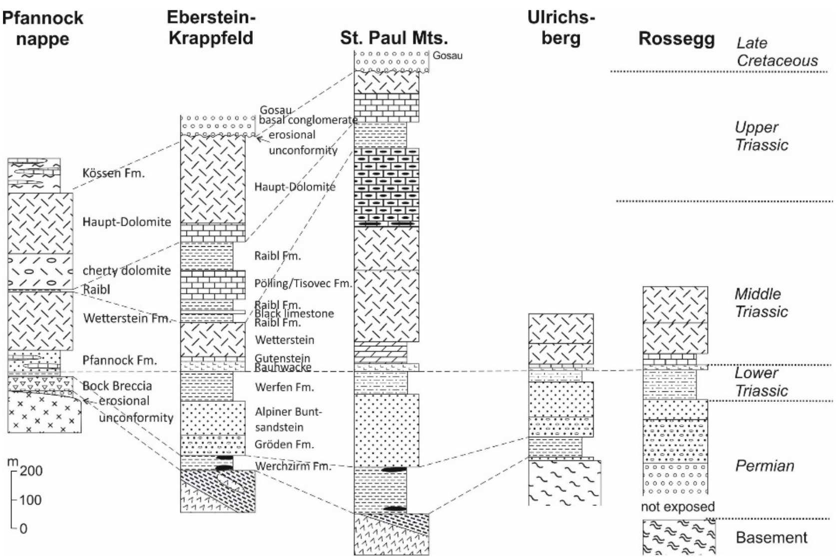
The Rinegg Nappe is a tectonic entity introduced here for the first time but the Triassic age was already recognized and mapped by THURNER (1935, 1958a, b). It separates the Lower Paleozoic successions of the underlying Murau Nappe from the overlying Stolzalpe Nappe and comprises a rare basement with phyllitic phyllonites (Text-Fig. 5c) exposed close to the Frauenalpe hospital. It is underlain by a sequence of several formations (see Text-Figs. 3e, f for some representative lithologies): Alpine Verrucano Formation, Bundsandstein, rauhwacke and sandy cellular limestone, rare graphitic marbles and graphitic-calcareous phyllites. The entire Permian to Triassic cover sequence is reversed.

Stolzalpe Nappe

The Stolzalpe Nappe with its Ordovician to Carboniferous very low-grade to low-grade metamorphic basement strata represents the unit at top of the Gurktal Nappe Complex. For terminology of various Lower Paleozoic formations, see also HUBMANN et al. (2014). The basement is associated with upper Pennsylvanian to Permian molasse-type formations (Stangnock and Werchzirm Formations) at the western margin and is locally overlain by Permian to Triassic unmetamorphic Permian to Triassic formations of the Eberstein and St. Paul Mts. at the southeastern margin of the Gurktal Nappe Complex.

The Stolzalpe Nappe basement (Text-Fig. 4) includes thick successions of clastic material (“clastic series”) at the base, mafic volcanics in the Ordovician (NEUBAUER & PISTOTNIK, 1984), locally an Upper Ordovician rhyolite level (Auen porphyry; NEUBAUER, 1980a) and an alkaline mafic diabase-keratophyre association of Early to Middle Silurian age, which is widespread in the Stolzalpe Nappe (GIESE, 1988; LOESCHKE, 1989; SCHNEPF, 1989; ANTONITSCH & NEUBAUER, 1992). As a whole, the age range of volcanism is uncertain and it remains unclear, whether three volcanic levels with distinct ages as proposed by GIESE (1988) and LOESCHKE (1989) (Text-Fig. 4, Nock Mts. Section) can be fully separated. Based on new mapping, some doubts were cast recently by HUET (2017). Recent unpublished $^{40}Ar/^{39}Ar$ dating results on magmatic amphibole of ca. 480 Ma from a diorite stock (Enge Gurk SW Sirnitz; Text-Fig. 1) argue for an Early Ordovician

age, conodonts from a dolomite associated with mafic tuff for a Middle–Late Ordovician level (NEUBAUER & PISTOTNIK, 1984). In the section east of Turracher Höhe, several thin conodont-bearing dolomite levels were identified.
According to the study of facies of the units overlying the Silurian volcanics, the overlying unit is differentiated, and three facies realms have been recognized (NEUBAUER & SASSI, 1993) during Upper Silurian to Lower Devonian (Text-Fig. 8): (1) a thin carbonate facies, which extends likely do the lower Carboniferous testified by recently detected black cherts and siliceous slates (Kaindorf west of Murau; Text-Fig. 5b), (2) a Silurian–Lower Devonian sandstone facies and (3) a shale and lydite (chert) facies. This sequence testifies a pelagic carbonate facies, a sort of delta front deposits and a basinal facies. In the Krappfeld region, the carbonate facies extends to Upper Devonian and carbonates are overlain there by a Mississippian lydite and siliciclastic flysch (SCHÖNLAUB, 1979; HUBMANN et al., 2014).
Following the Variscan orogeny in early Pennsylvanian, the molasse-type Stangnock Formation was deposited (Text-Figs. 3g, h). It consists of basal breccias, in part coarse-grained, boulder-sized conglomerates, abundant quartz conglomerate, shales/slates and some anthracite seams (KRAINER, 1989, 1993 and references therein) and their Late Pennsylvanian age is based on plant fossils (FRITZ et al., 1990). The Stangnock Formation is overlain by fanglomerates of the Werchzirm Formation. Both formations are dominated by nearby sources and short transport. These units are mainly sourced from amphibolite-grade siliciclastic metamorphic terrains. The conglomerates bear many orthogneisses, e.g. from either Pfannock or Bundschuh orthogneiss (e.g. FRANK, 1987). However, such orthogneisses are also exposed near the southern margin of the underlying basement (e.g. Villach orthogneiss). Meter-sized coral-bearing limestone clasts argue for a close connection with limestones of the Carboniferous of Nötsch (SCHLÖSER et al., 1990), which is exposed underneath the Drauzug with still unclear relationships to the overlying Dobratsch unit.
The Eberstein Permian to Triassic formations of the Krappfeld region were extensively investigated in terms of their lithostratigraphy and fossil content (Text-Fig. 9). The lithostratigraphy includes several 100 meter thick Permian to Lower Triassic terrestrial clastic red beds, thick "Permoskythian" Gröden-type sandstones and marine fossils bearing siltstones of the Werfen Formation, which grade into Middle to Upper Triassic shallow marine carbonates, Carnian Raibl Formation and peculiar Haupt-Dolomite (RIEHL-HERWIRSCH & WASCHER, 1972; DULLO & LEIN, 1982; WOLTER et al., 1982; APPOLD & PESCH, 1984; LEIN, 1989).



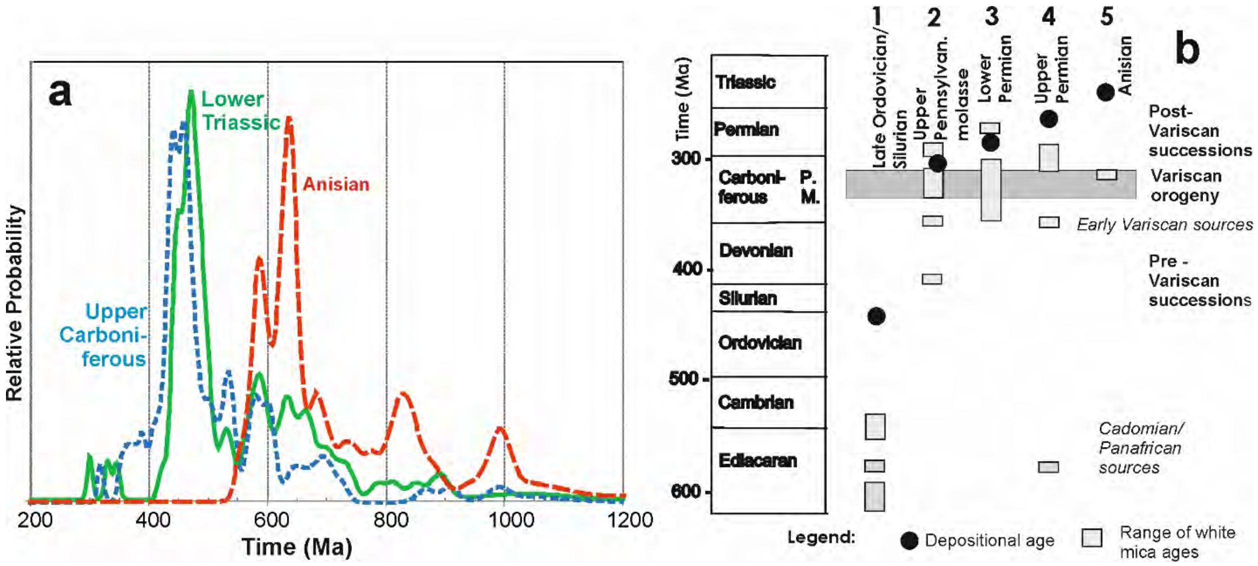
Text-Fig. 9: Lithostratigraphy of the cover units on the Stolzalpe Nappe in the central and southeastern Gurktal Nappe Complex. The Permotriassic Pfannock cover is shown for comparison.

After a phase of erosion cutting the section down to an Upper Triassic level, the Krappfeld Gosau was deposited since ca. Santonian. This unit starts with terrestrial basal breccia, which grade into shallow water and then deeper marine deposits, turbidites and olistostromes indicating rapid subsidence. In this part of the section, abundant fragments of the Stolzalpe Nappe basement

appear as clasts indicating significant local relief and denudation. Subsidence analysis revealed that the rapid tectonic subsidence of this basin is coeval with exhumation of metamorphic units (WILLINGSHOFER et al., 1999). Seemingly conformable marine Paleocene and Eocene strata complete the section.
Except the unmetamorphic Eberstein Permotriassic in the Krappfeld region, based on vitrinite reflection studies and conodont alteration index, the metamorphism within the Stolzalpe Nappe is very low-grade to just low-grade (GOSEN et al., 1987; NEUBAUER & FRIEDL, 1997; RANTITSCH & RUSSEGGER, 2000).

Paleogeographic considerations and provenance

The paleogeographic origin of various nappes of the Gurktal Nappe stack is not clarified yet. Consequently, detrital zircons from few cover rocks were studied and detrital white mica from both the less affected basement and post-Variscan cover were studied.
Three sandstone samples of Upper Carboniferous to Middle Triassic levels from post-Variscan cover successions of the Gurktal Nappe Complex of the Eastern Alps demonstrate a low importance of Variscan detrital zircons for that paleogeographic element. In two of them (Stangnock Formation from the Königstuhl area and a Permian–Lower Triassic sandstone from the Ackerl Nappe), the main input mainly came from Silurian–Ordovician and Cambrian (430–510 Ma) and Panafrican (570–650 Ma) magmatic units supplemented by small proportions of age populations of ca. 850 and ca. 1030 Ma (Text-Fig. 10a), and of ca. 2.0 and 2.65 Ga (not shown in Text-Fig. 10a). These patterns contrast with that of distant upper Carboniferous to Anisian to Carnian places like in in West Carpathians or Southern Alps, which are dominated by Variscan ages (KOHÚT et al., 2018; ARBOIT et al., 2019 and references therein). This pattern seems, therefore, unique within the Alpine-Carpathian orogenic belt. The data also reveal that the main stage of crustal growth of this Austroalpine segment occurred during Late Neoproterozoic to Silurian times.



Text-Fig. 10: (a) Some results of detrital zircons from Upper Pennsylvanian to Anisian sandstones of the Gurktal Nappe Complex. Note, the time line is cut at 1200 Ma. Carboniferous sample is from the Königstuhl area (blue), Permianskythian sample from Ackerl Nappe area (green), and the Anisian sample is from the Pfannock Formation (orange, Pfannock area). (b) Overview on results of $^{40}Ar/^{39}Ar$ dating of detrital white mica from Lower Paleozoic to Permian successions of northern and western Gurktal Nappe Complex. Column 1: Golzeck Formation (Middle to Late Ordovician?); column 2: Upper Carboniferous molasse (Königstuhl and Paal areas); column 3: Lower Permian (Paal/Kreischberg area); 4: Upper Permian (Bock Breccia, Nock area); 5: Pfannock Formation (Nock area). M.: Mississippian, P.: Pennsylvanian.

In contrast, the sandstone sample from the Pfannock Formation (Anisian) of the Pfannock Nappe show a major peak at ca. 640 Ma and the youngest grain is at 551.8 ± 8.1 Ma (Text-Fig. 10a). Many grains are between 700 and 880 Ma (Cryogenian to Tonian) complemented by smaller populations at 1000, 2000 and 2550 Ma.

The $^{40}Ar/^{39}Ar$ ages of detrital white mica from pre-Variscan Late Ordovician/Silurian and post-Variscan Upper Pennsylvanian to Middle Triassic sandstone successions of the Gurktal Nappe Complex of the Eastern Alps have been studied, too, in order to reveal paleogeographic relationships of these units and late to post-Variscan tectonic processes of the Austroalpine mega-unit in the Eastern Alps (Text-Fig. 10b; NEUBAUER et al., 2007 and references therein). Single grains of a sample from an Upper(?) Ordovician/Lower Silurian sandstone of the Golzeck Formation (south of Murau) show ages ranging from 497 to 614 Ma, possibly with two age clusters (ca. 600 and 540 to 520 Ma: Cryogenian and Cambrian). These ages are interpreted to record two stages of cooling or two sectors with different ages of a Cadomian orogen exposed in the hinterland. The ages are consistent with previously reported multi-grain ages from the Carnic Alps and Greywacke Zone of the Eastern Alps (NEUBAUER et al., 2007 for references) indicating a similar paleogeographic origin of all these units.

Both multi-grain concentrates and single white mica grains of nine samples of post-Variscan Upper Pennsylvanian (Stangnock Formation in Paal and Turrach areas) and Permian molasse sandstones (Werchzirm and Bock Breccia Formations) and Permian to Lower/Middle Triassic sandstones of a rift environment ("Permosythian" Quartzite, and Anisian Pfannock Formation) include uniform late Variscan ages, mainly ranging from 300 to 320 Ma. No significant variation of age patterns was detected within these late Carboniferous to Middle Triassic sandstones. As these 320–300 Ma ages also occur in the Westfalian C/D to Stefanian Stangnock Formation conglomerates, these suggest very rapid cooling from mid-crustal levels, typical for temperatures of ca. 425º C (Ar retention temperature of white mica) and associated exhumation to the surface and denudation within a few million years. As no older ages occur in the Pennsylvanian to Middle Triassic sandstones, we assume that the Cadomian terranes lost any major importance at the surface exposure level, which was dominated by rejuvenated Variscan metamorphic crust. This also suggests that erosion of upper brittle sectors of the Variscan orogenic wedge with old ages was nearly completed at the time of deposition of molasse deposits. Furthermore, sparse previously reported Rb-Sr ages of ca. 390 Ma from the Bundschuh basement of the Middle Austroalpine Nappe complex seemingly exclude a primary source-deposition relationship between the Bundschuh basement and Pennsylvanian Stangnock Formation. It appears that the Ackerl Nappe basement of the Gurktal Nappe Complex with its 309–320 Ma and similar metamorphic complexes could represent the source for these molasse-type formations. Consequently, the Variscan orogeny seemingly resulted in throughout rejuvenation of older crust and denudation of all upper brittle crust above the ca. 425º C-level prior to deposition of molasse-type sediments.

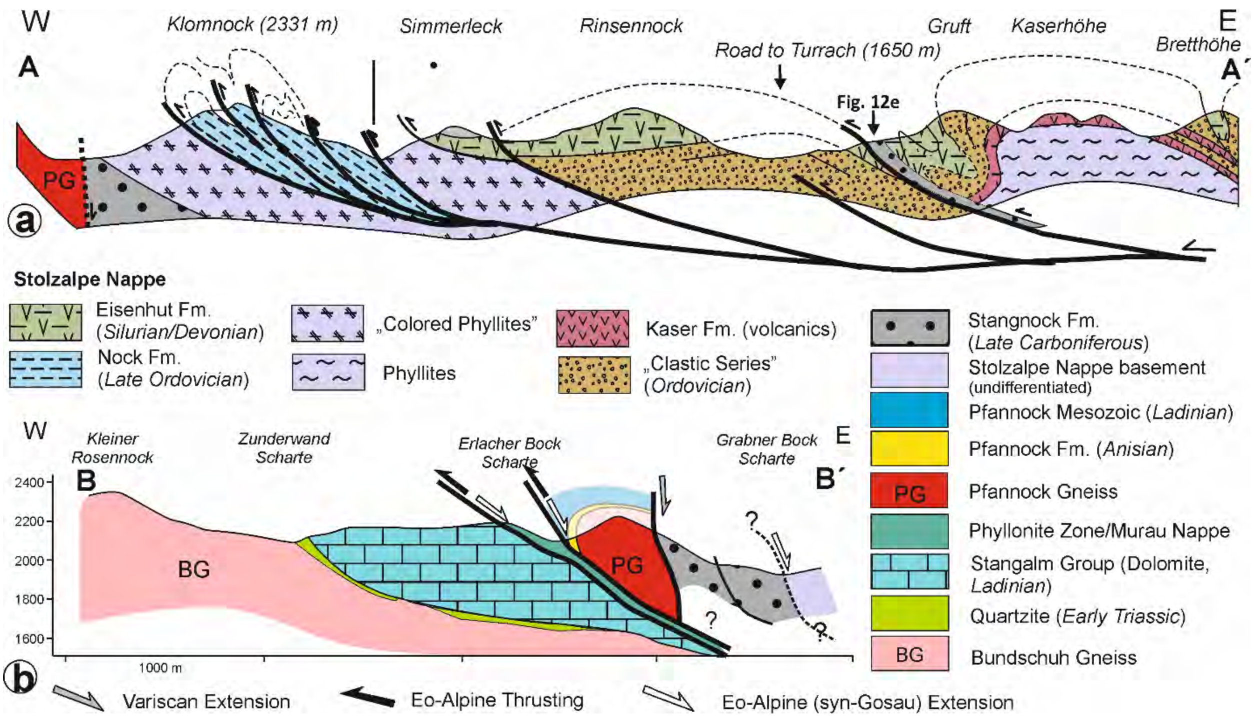
Structural evolution

The Bundschuh basement and all nappes of the Gurktal Nappe Complex are fully affected by the Variscan orogeny during early Pennsylvanian. Evidence for that is the two-stage Variscan ductile deformation in the Bundschuh basement below the angular unconformity at the base of the Stangalm Group and Variscan (NEUBAUER & GENSER, 2018) $^{40}Ar/^{39}Ar$ white mica ages in the Pfannock and Ackerl basement including the nappe stacking of the Ackerl Gneiss unit over the Ackerl Micaschist unit. The most convincing evidence is that the detrital $^{40}Ar/^{39}Ar$ white mica ages in post-Variscan molasse-type sedimentary units are dominated by a Variscan upper greenschist (because of the grainsize of dated minerals > 0.25 mm) to amphibolite facies grade metamorphic basement.

The Alpine tectonic cycle starts with a differentiation between the Stangalm Group, which lacks a thick Permian to Lower Triassic sedimentary succession and which is characterized by a thin carbonate succession. We interpret this unit as deposits on a rift shoulder, which was uplifted during the Permian. In contrast, the cover of Pfannock, Ackerl and Rinegg Nappes includes thicker Permian to Lower Triassic siliciclastic sediments and these units could be transitional to the much thicker siliciclastic successions on top of the Stolzalpe Nappe. We suppose therefore that these potentially represent graben infillings (SYLVESTER, 1989a, b).

The stacking of the Gurktal Nappe Complex occurred during Early Cretaceous to early Late Cretaceous pre-dating the deposition of the Krappfeld Gosau basin fill. This phase was associated

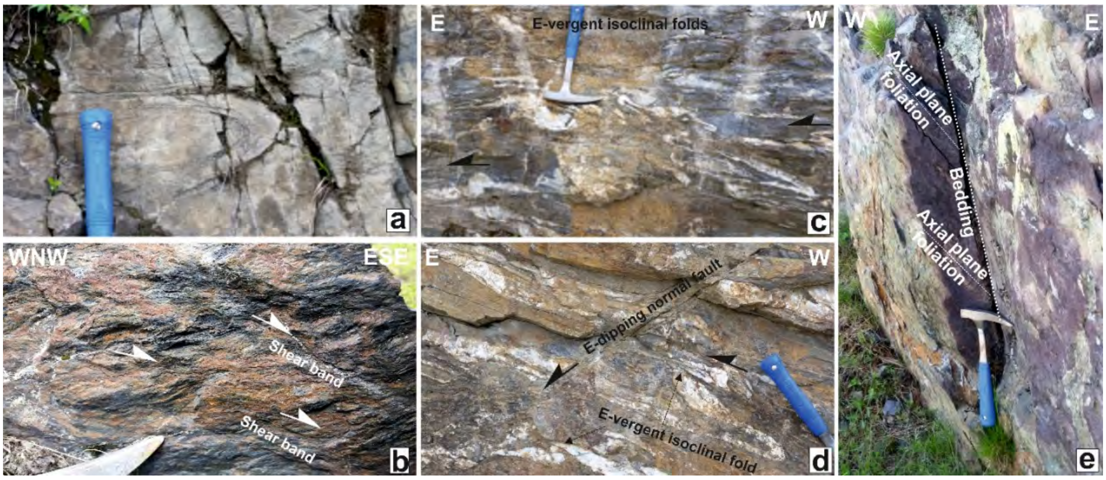
either with a severe phase of erosion down-cutting the sedimentary succession of the Eberstein-Krappfeld Permotriassic or with an earlier Jurassic phase of non-deposition.
Nappe stacking and internal shortening started during early Late Cretaceous (Alpine deformation stage D_1). Based on field structures, top to the WNW motion has been deduced (NEUBAUER, 1987; RATSCHBACHER & NEUBAUER, 1989; RATSCHBACHER et al., 1989). Sections and field examples of folds related to deformation stage D_1 are shown in Text-Figures 5d, 11, 12 and 13. The sense of motion is based on map-scale structures like W-vergent and overturned km-scaled folds, E-dipping thrusts and microfabrics of mylonitic rocks along thrust shear zones, which are largely synmetamorphic with early Alpine greenschist facies metamorphism. The stretching lineation is plunging to the ESE, the shear sense is dominantly top WNW. However, it must be noted that locally the opposite transport direction can be observed, e.g. in the Ackerl Nappe area. There, top-E thrusting and E-vergent folding sections (sections B-B´ and C-C´ in Text-Fig. 13) can be observed. This peculiarity can be tentatively interpreted as back-thrusting or retrowedge formation. Furthermore, in many areas, separation of the Stolzalpe Nappe basement from the Upper Carboniferous cover can be observed, e.g. the Paal Schuppe from the Stolzalpe Nappe sensu stricto except the Ursch Schuppe (e.g. section A-A´ in Text-Fig. 13). In several cases, the Upper Pennsylvanian cover is overturned (Text-Fig. 12e) and underlying the Lower Paleozoic Stolzalpe Nappe senso stricto. These relationships can be followed between Turrach and Flattnitz, or along the western margin of the Stolzalpe Nappe (Text-Fig. 11a). Because of some primary relationships, we argue that separated units should be discussed as separate schuppen of the overall Stolzalpe Nappe.



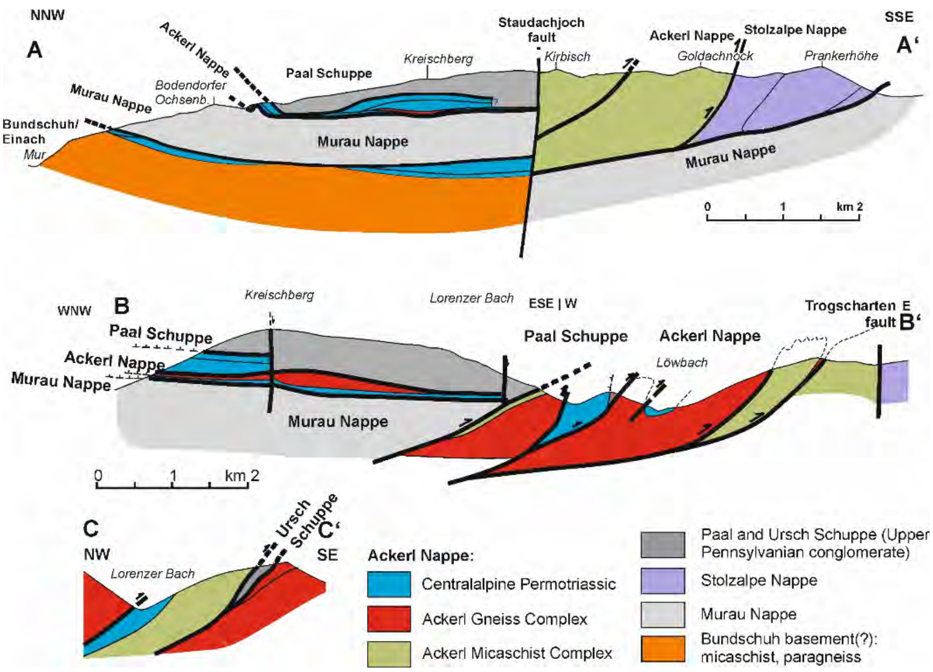
Text-Fig. 11: Two sections showing details of the structure of the western part of the Gurktal Nappe Complex. (a) E–W section across Turracher Höhe showing W-vergent fold structures within the Stolzalpe Nappe. The section shows evidence for Cretaceous age of W-vergent folding within the Stolzalpe Nappe. Section modified after LOESCHKE (1989) and HUET (2017). (b) W–E section across the western boundary of the Gurktal Nappe Complex showing the structural setting of the Pfannock Nappe (modified after KURZ et al., 2013). For locations of sections, see Text-Fig. 1.

These fabrics are overprinted by ductile low-angle normal faults gradually changing into semiductile and brittle E-dipping normal faults with a sense of motion ESE (e.g. NEUBAUER, 1987; RATSCHBACHER et al., 1989; STOCK, 1992), here assigned to deformation stage D_2. Examples of field structures are shown in Text-Figures 12b–12d. The main fault is in the hanging wall of the Murau Nappe and this is related to a significant break of the Early Cretaceous metamorphic profile. The fabrics indicate extension and thinning of the entire nappe stack. The strongest

thinning is observed along the western boundary, within the strongly thinned Phyllonite zone, which is part of the Murau Nappe.
The entire Gurktal Nappe Complex was gently folded along gently E-plunging km-scaled open folds, likely during Late Oligocene times (NEUBAUER et al., 2018 and references therein) (deformation stage D_3). This resulted in updoming of anticlines exposing now the Bundschuh and equivalent basement rocks, e.g. in the Wimitz and Oberhof windows.
The eastern part of the Stolzalpe Nappe was always at the surface as in the Krappfeld basin area discontinuous basin sediments were deposited (KOROKNAI et al., 1999; WILLINGSHOFER et al., 1999; NEUBAUER & GENSER, 2018 and references therein). In the western part, the final cooling and exhumation of the previously buried Bundschuh Nappe was also affected by thinning and retrogression along top-ESE shear zones (e.g. RATSCHBACHER et al., 1989, 1990; NEUBAUER & GENSER, 2018). Later, exhumation was erosional and occurred during Oligocene and Miocene times (HEJL, 1997) and is related to eastward tilting of the entire Gurktal Nappe Complex related to the activity of the Katschberg normal fault and thinning of the entire area between Tauern window and the Pannonian basin.



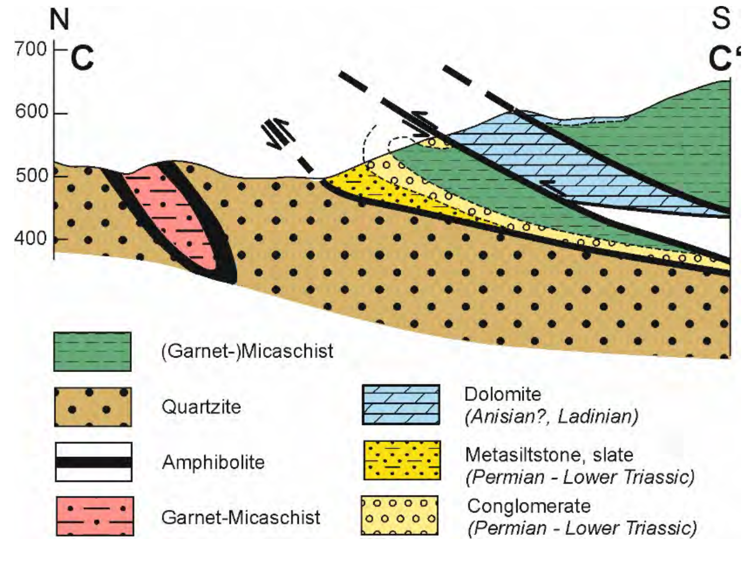
Text-Fig. 12: Representative field structures showing the structural evolutionary history of the Gurktal Nappe Complex. (a) Isoclinal fold in calcite marble (Stangalm Group) related to vertical ductile thinning of the Stangalm Group Mesozoic. (b) Semiductile top-ESE shearing of the Murau Nappe (Phyllonite zone). Nockalm road south of Eisentalhöhe. (c) E-vergent overturned folds in the Murau marble. (d) E-dipping brittle high-angle normal fault and E-vergent overturned folds. (c) and (d) are at Murau railway station. (e) Example of the overturned limb with axial plane formation of a fold within the Stangnock Formation east of Turracher Höhe. For location, see Text-Figure 11a.



Text-Fig. 13: Some sections showing details of the structure of the Ackerl Nappe area and of the Paal Schuppe. Sections imply separation of the Paal Schuppe from the Stolzalpe Nappe sensu stricto except the Ursch Schuppe (e.g. section A-A´) and top-E thrusting and E-vergent folding. Sections modified and reinterpreted after NEUBAUER (1980b). For location of sections, see Text-Figure 7.

Where is the southern edge of the Gurktal Nappe Complex?

Most authors agree that the Gurktal Nappe Complex extends to a fault zone in the south, which is marked as Viktring-Rossegg zone in Text-Figure 1 (GOSEN et al., 1985; NEUBAUER, 1987; GOSEN, 1989). The Murau Nappe extends far to the south, without intercalations of Mesozoic sediments, showing therefore rather a basement-to-basement contact with retrogressive, greenschist facies grade zones in between. A simple thrust relationship can be seen and an amphibolite- to upper greenschist facies-grade metamorphic basement is exposed, which is fully rejuvenated by Cretaceous metamorphism as a white mica $^{40}Ar/^{39}Ar$ plateau age of 90.7 ± 1.6 Ma testifies (NEUBAUER et al., 2018). Along the Viktring-Rossegg zone, the Viktring Permotriassic rocks override this basement with a thrust contact (Text-Fig. 14) and even a Lower Paleozoic very low-grade unit is exposed along the Viktring-Rossegg zone, too (but not shown in Text-Fig. 14) (SCHÜNEMANN et al., 1982; CLAASSEN et al., 1982).

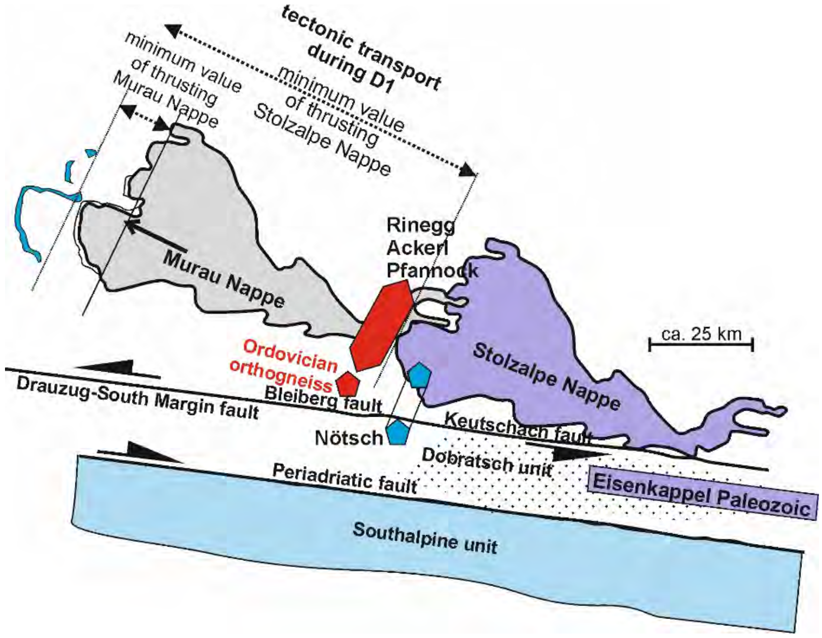


Text-Fig. 14: Simplified section of the Viktring Permomesozoic area. Modified after SCHÜNEMANN et al. (1982). For location, see Text-Fig. 1.

The Viktring-Rossegg zone is overthrusted by a monometamorphic upper greenschist facies phyllite unit of hitherto unknown relationships (SCHÜNEMANN et al., 1982 for description; GOSEN, 1989). With these relationships in mind, the Gurktal Nappe Complex was transported over a relatively large distance to WNW (Text-Fig. 15) although a later back-motion to the ESE is well documented. These relationships also imply that the root zone is likely along or south the Viktring-Rossegg zone and this would mean that a broad zone is needed south of the Viktring-Rossegg zone (see also NEUBAUER, 1987; GOSEN, 1989).

Discussion and Conclusions

The Gurktal Nappe Complex shows pronounced paleogeographic relationship, which needs revision of existing models. The Bundschuh basement with its Middle Ordovician intrusions virtually shows an entirely different evolution than the Murau and Stolzalpe Nappes. It represents a pre-Middle Ordovician basement unit intruded by a Middle Ordovician S-type granite. In contrast, the Murau and Stolzalpe Nappe basements show sedimentary, respectively volcano-sedimentary successions, which exhibit close relationship, based on detritus, with northern Gondwana (NEUBAUER et al., 2007). Whether or not a major suture separates Bundschuh and Gurktal Nappe basement is unknown.



Text-Fig. 15. Simplified tectonic restoration of the top WNW nappe transport during the shortening/thrusting deformation stage D1. Restoration is taking into account the duplication of tectonic (Murau and Stolzalpe nappes. Note that subsequent D_2 thinning and extension are not balanced.

The Ordovician to Mississippian evolution can be discussed by several stages: In the Ordovician, accretion of continental crust to, and amalgamation with, Gondwana occurred (e.g. NEUBAUER & SASSI, 1993). On the other hand, the Ordovician succession represents likely a continental margin above a subduction zone. Later, during Early to Middle Silurian, alkaline volcanism represents within-plate magmatism and interestingly is sometimes overlain by thin carbonates. Potentially, a passive continental margin was formed during Early Devonian (mainly based on evidence of the Murau Nappe basement including the shallow-water Murau and Grebenzen marbles). This also implies a location between equator and ca. 30°-latitude as testified by a thick carbonate platform in the Murau Nappe basement, whereas the Stolzalpe Nappe basement is part of a more distal passive margin. During Carboniferous, collision occurred and both Murau and Stolzalpe Nappe basement represent a lower plate position with deposition of flysch on it. The Variscan orogeny resulted in burial, amphibolite- to greenschist grade metamorphism, synmetamorphic nappe stacking (e.g. Ackerl Gneiss unit over Ackerl Micaschist unit) and subsequent erosion. The intramontane molasse (Stangnock Formation) was deposited on the northern margin of the Stolzalpe Nappe basement. The coral-bearing Lower Carboniferous limestone boulders of the Stangnock Formation suggest a close relationship to similar units of the Nötsch (and Veitsch) units (Text-Fig. 15). A further potential correlation is between the Late Ordovician Pfannock gneiss and small orthogneiss bodies with a similar age north of the Wörthersee.

The Alpine cycle started with Permian rifting, expressed in thick successions at the top of the Stolzalpe Nappe. We interpret the Lower Triassic strata of the Stangalm Group to reflect extension of the rifting stage, which also enhanced synsedimentary Early Anisian iron mineralization was potentially related to normal faults. A second stage of extension occurred during Early Carnian, when siltstone and sandstone of the Bockbühel Formation were deposited. The variable and eastward increasing thickness of the Bockbühel Formation argues for a syndepositional graben formation.

The Pennsylvanian to Triassic cover successions of the Gurktal Nappe Complex seem dissimilar to the Drauzug unit and resemble rather to the westernmost and even eastern Northern Calcareous Alps. The new data makes it necessary to reconsider currently popular paleogeographic and tectonic models of the Austroalpine domain. The Gurktal Nappe Complex is an early Late Cretaceous nappe stack transported to WNW and has its root in the area of the Viktring-Rossegg zone and its eastward extension. Structure and paleogeography are not similar to the Drauzug. We suggest that the eastward tectonic and paleogeographic extension including the Middle-Late Triassic Pb-Zn mineralizations of the Drauzug unit sensu stricto is in the North Karawanken thrust sheet overlying there the southern margin of the Gurktal Nappe Complex and a poorly characterized metamorphic basement unit (garnet-micaschists in Text-Figure 14).

Acknowledgements

1978, the first author finished his Doctoral Thesis in the northern part of the Gurktal Nappe Complex, around the Ackerl Nappe area west of Murau and major portions of the thesis were never published. However, coming into age, the interest on the Gurktal area came back and several bachelor thesis mapping courses had the margins of the Gurktal Nappe Complex and many new data (structural studies, biostratigraphy, geochemistry, dating results) were created in addition, many more as exposed in this short review-type paper. The authors want to thank all participants of the mapping courses and the Geological Survey of Austria, particularly CHRISTOPH IGLSEDER, for the opportunity to contribute to the Arbeitstagung 2019. Many thanks to GERIT GRIESMEIER for careful reading and correcting the text.

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