Structural Development of Austroalpine Units: the Radstadt- to Tennen Mts. Section, Eastern Alps

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1. Introduction

The structure of the Eastern Alps is still in debate, and many controversial models still exists. This particularly applies to models concerning the internal structure of the Austroalpine nappe complex (e.g., Slapansky and Frank, 1987; Exner, 1996). New methods like geochronological and structural studies provide new insights (e.g., Liu et al., 2001). In order to better understand structural relationships between Penninic units at the northeastern-most edge of the Tauern window, the internal structure of the Austroalpine nappe complex and that of the uppermost Austroalpine units in southern Northern Calcareous Alps, the area between Obertauern and ca. Flachauwinkel in the southern Enns Valley in the south and the southern margin of the Tennengebirge in the north has been mapped. Mapping included specifically the official geological map 1:50,000, sheet Radstadt, and present work continues in the adjacent western area (sheet Bischofshofen). The project included a number of master theses (Lackner, 2003; Schmidlechner, 2005; Schreiner, 2008; Ebner, 2008; Windberger, 2010).
The proposed interpretations and models are preliminary, and some new observations still need final assessment, which is planned to perform during following months.
For an overview of the region, see also Braunstingl et al. (2005, 2009), Slapansky and Frank (1987) and Tollmann (1977)

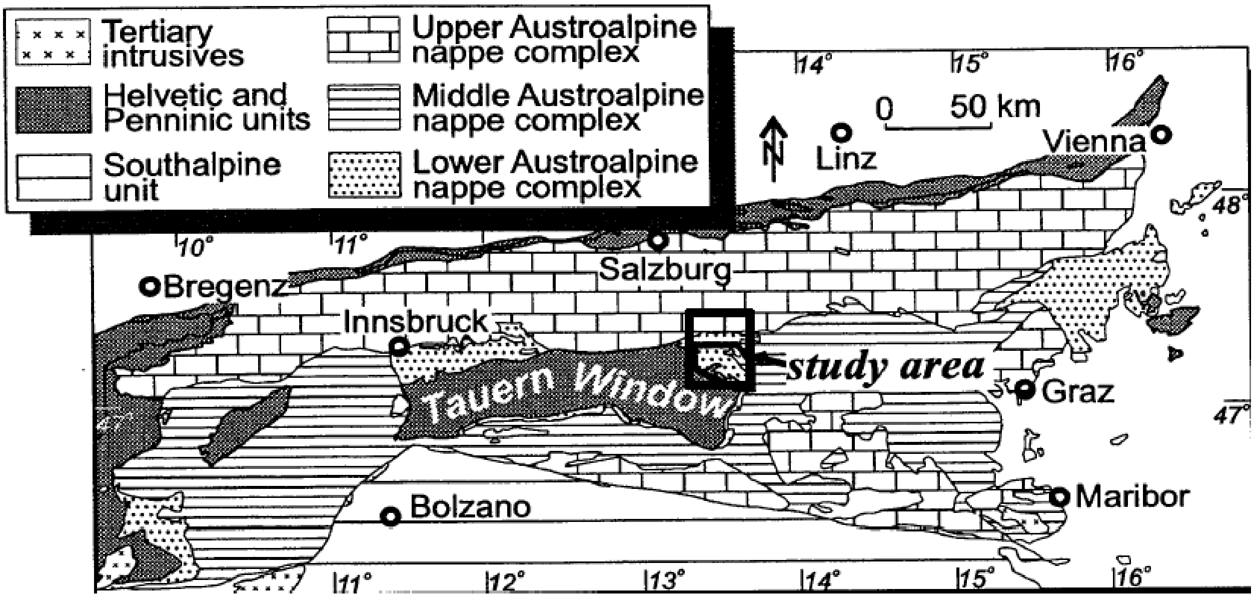

Fig. 1. The Radstadt Mts.-Tennengebirge area within the Eastern Alps (modified from Liu et al., 2001).

2. Overview of tectonic units

The general strike in the study area is ca. E-W, with the exception of an ESE-WNW strike in the SW in lowermost tectonic units. In general, all units dip to the north although large-scale folding resulted in local S-dipping. From base to top, the following tectonic units can be distinguished:

(1) Matrei zone of Penninic units of the Tauern window,
(2) Lower Austroalpine cover units, particularly the Quartzphyllite nappe, which is the northernmost part of the “Main nappe group”,
(3) Seekarspitz metamorphic complex,
(4) Metamorphic Koppen complex, which is considered to represent the western lateral extension of the Schladming basement massif,
(5) Wagrain Phyllite,
(6) Greywacke zone,
(7) Werfen imbricate zone, and
(8) Middle-Upper Triassic portions of Tirolic and Juvavic nappes of the Northern Calcareous Alps.
(9) The structure is further complicated by the presence of major Oligocene-Neogene faults, including the Salzach-Enns fault (Mostler, 1964; Wang and Neubauer, 1978) also called SEMP (Salzach-Enns-Mariazell-Puchberg fault: Ratschbacher et al., 1991) and the Mandling fault (Hirschberg, 1965), which is considered to represent the North Enns Valley fault further east (Keil and Neubauer, 2011.

Along the northern block of the Mandling fault, and to the west, after the merging of the Mandling with the SEMP fault, the Miocene Wagrain basin is exposed. The area between the Salzach-Enns-Mariazell-Puchberg Mandling faults is occupied by the Mandling wedge (Hirschberg, 1965) with Triassic units derived from Northern Calcareous Alps (e.g., Mandl, 2000).

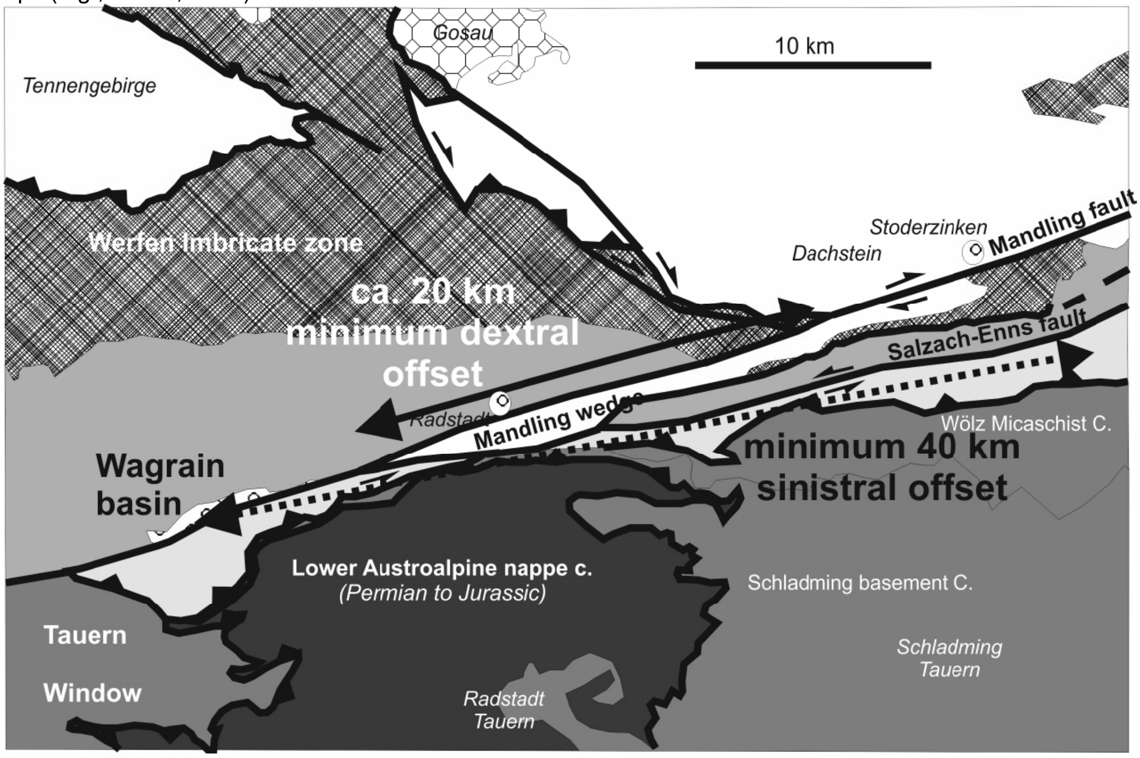

Fig. 2. Simplified tectonic overview of the Radstadt Mts.-Tennengebirge area.

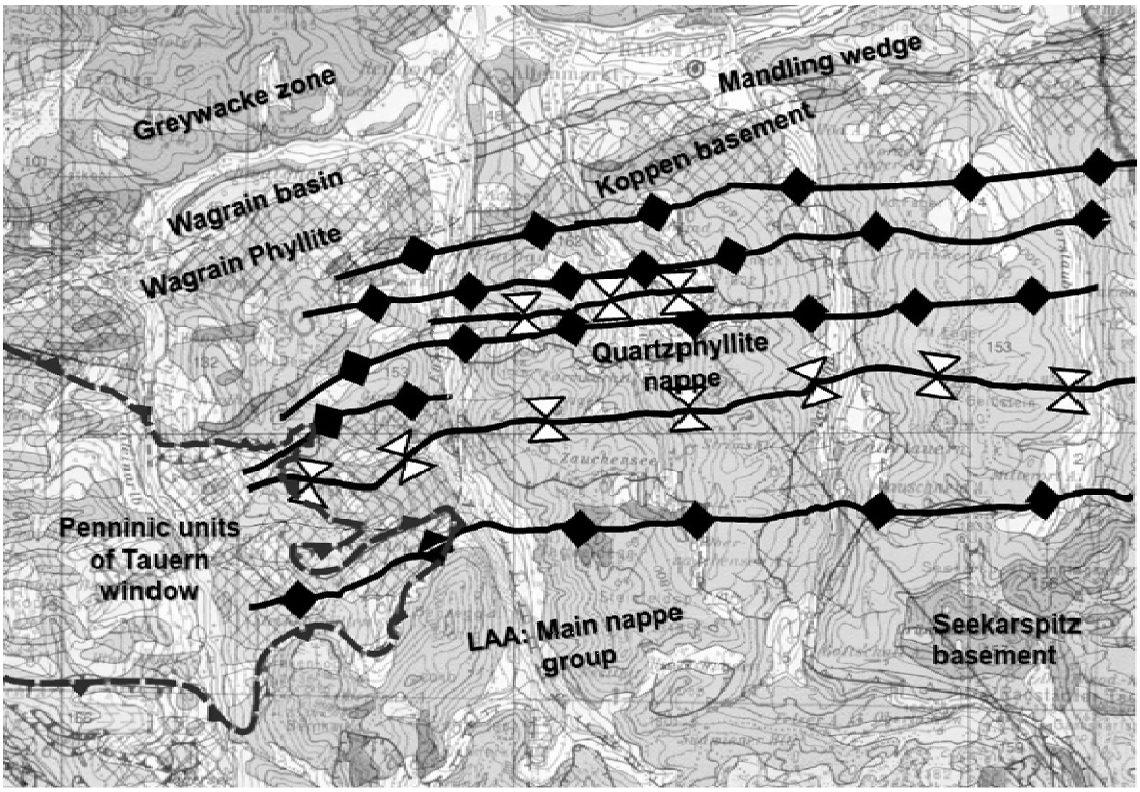

Fig. 3. Simplified tectonic overview of the Radstadt Mountains area with fold structures (base map from .

3. Stratigraphic overview

In this chapter, formations and their lithologies are shortly characterized.

Penninic units of the Tauern window

The Penninic units at the NE edge of the Tauern window. Main constituents are phyllites, quartz-rich phyllites and carbonaceous schists of the Bündnerschiefer Group and Matrei Group. In addition, Exner (1996) describes lamellae of relictic strongly sheared pre-Alpine rocks, which along or near the upper boundary of Tauern window. These include the various orthogneisses, chlorite-rich phyllonites, plagioclase-rich gneisses of the Moseregg and Seekopf lamellae. They likely represent sheared rocks aligned along the tectonic boundary.

Seekarspitz metamorphic complex

The Seekarspitz metamorphic complex is a western extension of the Schladming basement (Slapansky and Frank, 1987). It comprises a succession of lens-shaped metamorphic rocks initially metamorphosed within amphibolite metamorphic conditions, which were variably retrogressed and sheared within subsequent greenschist facies conditions. Rocks include amphibolites, fine-grained plagioclase-rich orthogneiss, paragneisses, rare mica-gneisses, mylonitic greenschists and phyllonites. The ages of the protoliths are uncertain and all the rocks are affected by Variscan amphibolite facies metamorphic conditions and subsequent retrogression (pre-Alpine and Alpine). The age of amphibolite-grade metamorphism is Variscan (Ar-Ar ages of coarse white mica: ca. 300 and ca. 250 Ma; Schreiner, 2008), and two stages of Alpine overprint have been proven in several outcrops by Ar-Ar dating. Fine-grained white mica gives ages at ca. 80–85 Ma, and a low-temperature overprint at ca. 50–60 Ma (Schreiner, 2008).

Metamorphic Koppen complex

The polymetamorphic Koppen complex, first postulated and extensively described by Exner (1996) includes a succession of strongly sheared polymetamorphic rocks. A wide range of retrogressed amphibolites dominate, paragneiss and sheared pegmatites are rare. In all samples of retrogressed amphibolites, two stages of metamorphism can be found: (1) a first stage of metamorphism, which reached amphibolite facies conditions, and (2) a subsequent retrogressive greenschist facies grade metamorphism, which was associated with extensive ductile shearing. Metamorphic conditions of the second stage were similar to that of the underlying Radstadt Quartzphyllite and overlying Wagrain Phyllite. No geochronological ages from the metamorphic Koppen complex are available up to now, and some work is in progress.

Lower Austroalpine cover units, particularly the Quartzphyllite nappe

The Quartzphyllite nappe comprise a mostly inverted sedimentary slightly metamorphosed succession (Fig. 4), which include an up to 1000 m thick Alpine Verrucano Fm. (Permian), Lantschfeld Quartzite (Lower Triassic), Reichenhall Rauhwacke (Anisian), a succession of calcitic marbles, thick dolomite with slate and metasandstone intercalations in its stratigraphically lower parts, phyllites, calcschists of Carnian age, stratigraphically overlain by dolomite and massive and well bedded limestones/calcitic marbles of Raetian age Rossner, 1979). Among these stratigraphic units, the Alpine Verrucano Fm. is most widespread in the central part of the study area and exhibits a pronounced facies differentiation. It comprises metaconglomerate, quartzphyllites with some intercalations of acidic metatuffs and greenschists in stratigraphically lower levels, and pure grayish-purple phyllites in some levels in western areas, which gradually shift into quartz-rich quartzphyllites and arenitic metasandstones in the east (Hellerschmidt-Alber, 2008). The Alpine Verrucano Fm. is considered to represent the infilling of a rift basin, which formed in terrestrial conditions.

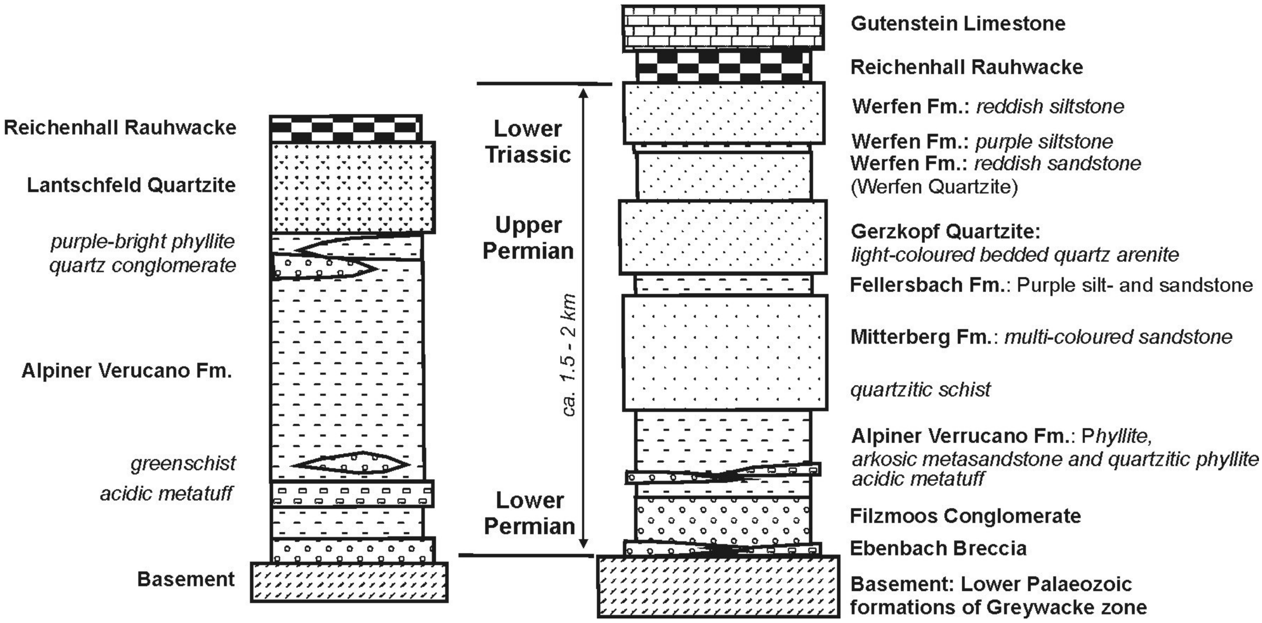

Fig. 4. Lithostratigraphic Permian to lowermost Middle Triassic section of the Lower Austroalpine Quartzphyllite unit (left column) and the base of the Northern Calcareous Alps (right column).

Wagrain Phyllite

The Wagrain Phyllite is a unit, which used to be considered to be part of the Radstädter Quartzphyllite prior to the discovery of the metamorphic Koppen complex. The Wagrain Phyllite is a succession of gray and dark phyllite, which often grades into black phyllites and includes thin lenses of iron-bearing dolomite, greenschists, calcareous phyllites and quartzites. Schönlaub (1975) reports conodonts and foraminifera from a location to the west of the study area. These indicate an approximate age at the Silurian/Devonian boundary. Exner (1996) already equates the Wagrain Phyllite unit with the Greywacke zone north of the SEMP/Mandling fault system.

Greywacke zone

The Greywacke zone comprises a mainly phyllitic basement with a vast amount of gray phyllite (type Wildschönau phyllite/slate), intercalations of two types of acidic metatuffs, greenschists, meta-lydite (dark chert), thin calcareous phyllite, black graphitic phyllite, thin calcitic marbles and iron-dolomite. The two types of acidic metatuffs include greenish Blasseneck-Porphyroid type rocks (Radstadt city wall) and albite-rich metatuffs. A thick iron-dolomite is exposed at Brand-Mandling in the Enns Valley, and is likely a separate tectonic unit tectonically overlying the thick phyllite succession. No stratigraphic age is known from the phyllite succession. The lithological composition resembles that of the Glemmtal unit further west or that of a newly defined phyllite-dominated unit in the Dienten-Mühlbach-Bischofshofen area (Fig. 5; see also Dum et al., in press).

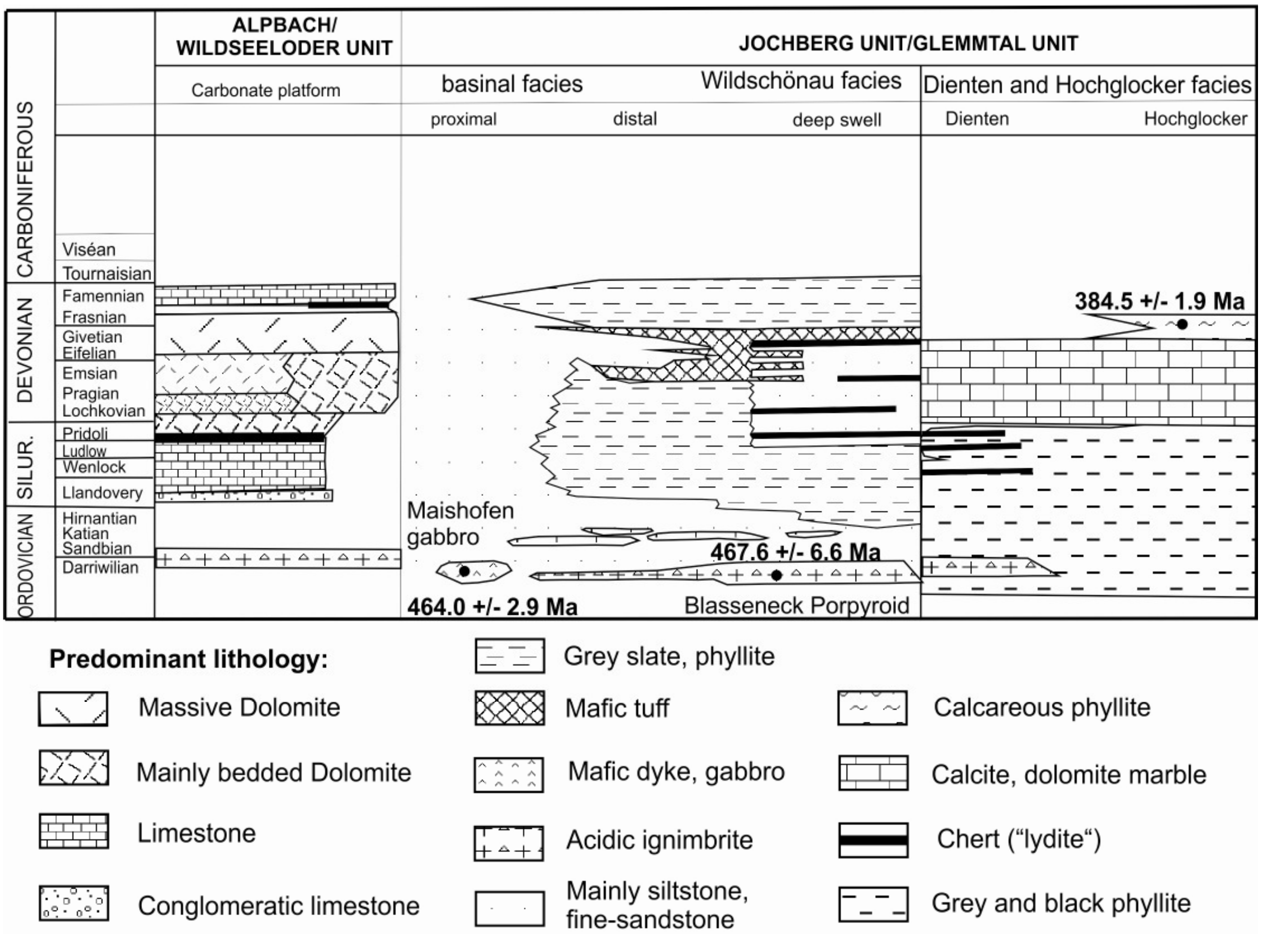

Fig. 5. Simplified stratigraphic section of the western Greywacke zone (after Dum et al., in press). Published and new U-Pb zircon ages are given. The Radstadt area has similarities to the distal Wildschönau facies and the lower portions of the Hochglocker facies, respectively.

Werfen imbricate zone

The Werfen Imbricate zone of the central southern Northern Calcareous Alps is still a not fully resolved issue. The Werfen Imbricate zone contains several major tectonic nappes with mainly Permian to Middle Triassic formations, which are cut along their hangingwall margins. Remnants of the Haselgebirge Formation are common on top of the uppermost nappe of the Werfen Imbricate zone. The Permian to Lower Triassic sections of the nappes are dominated by siltstones and subordinate fine-grained, thin-bedded sandstones. In purple fine-grained sandstones considered to represent part of the Fellersbach Formation a shell fauna (molluscs) with a number of distinct species was detected. A hitherto unknown, several tens of meters thick formation of greyish siltstones with intercalated thin-bedded sandstones is directly overlain by thin-bedded greyish to beige Werfen Limestone. This new formation also yielded a mollusc fauna in tempestitic sandstones. We interpret this as an offshore facies below the storm-wave base deposited in a local off-shore depression. The uppermost nappe of the Werfen Imbricate zone comprises abundant Hallstatt facies-type limestones, which were not found in lower nappes.

Mandling wedge

The Mandling wedge forms a wedge-shaped body exposed between the SEMP and Mandling faults. It is nearly exclusively composed of small remnants of the Lower Triassic Werfen Fm. and thick Middle to Upper Triassic carbonate formations, including Wetterstein/Ramsau dolomite and Dachstein Fm. reef limestones (Hirschberg, 1965).

Base of Northern Calcareous Alps including Werfen imbricate zone

The Permian (?) to Lower Triassic siliciclastic successions of the central southern section of the Tirolic units of the Northern Calcareous Alps along the southern margin of the Tennengebirge exhibit a spatially variable sequence of formations, which are separated by a low-angle normal fault (Halm fault). A halfgraben-type infilling includes a ca. 1.5 – 2 km thick sequence (Fig. 4, right column) starting with the Filzmoos Conglomerate containing coarse polymict breccia and quartz conglomerate, thick Alpine Verrucano, and thick quartz arenite at the top. This sequence is interpreted to represent the transition from a desert climate to shallow marine barrier sandstones during prograding extension within a synrift geodynamic setting. Overlying siliciclastic sediments are interpreted to indicate changes between terrestrial and marine environments until a full marine environment was established in upper parts of the Lower Triassic. The siliciclastic base of the Northern Calcareous Alps can be interpreted as a rift succession indicating syn-depositional extension.

Middle-Upper Triassic portions of Tirolic and Juvavic nappes of the Northern Calcareous Alps

Thick Middle-Upper Triassic shallow-water carbonate successions build up the southern slopes of the Tennen and Dachstein blocks. Main constituents are Gutenstein and Ramsau/Wetterstein dolomites and limestones and the Dachstein reef limestones (for details, see Tollmann, 1985; Mandl, 1998, 2000; Mandl in Scheidleder et al., 2001). Towards SW, the shallow water carbonates grade into pelagic limestones, particularly along the ridge to the west of the Dachstein massif (Schlager, 1967; Mandl, 2000).

Miocene Wagrain basin

The Neogene (ca. Karpatian to Lower Badenian) Wagrain basin formed within a halfgraben, close to the north-eastern edge of the exhuming and uplifting Neogene Tauern metamorphic core complex, along the ENE-trending, ca. orogen-parallel sinistral-transtensional Salzach-Enns and Mandling fault systems of the Eastern Alps (Figs 6, 7). Based on a pronounced color change from thin basal reddish, hematite-rich conglomerates to gray-brownish clastics, the basin infill records a climate change from a subtropical to humid climate. The change is used as a proxy for the dating of the basin as a similar regional climate shift has been reported, e. g., from the Styrian basin. The lithofacies evolution of the Wagrain basin fill shows initial rapid subsidence and infilling by massive, coarse-grained conglomerates and subsequent mica-rich immature sandstones deposited in a prodelta environment of a lake.

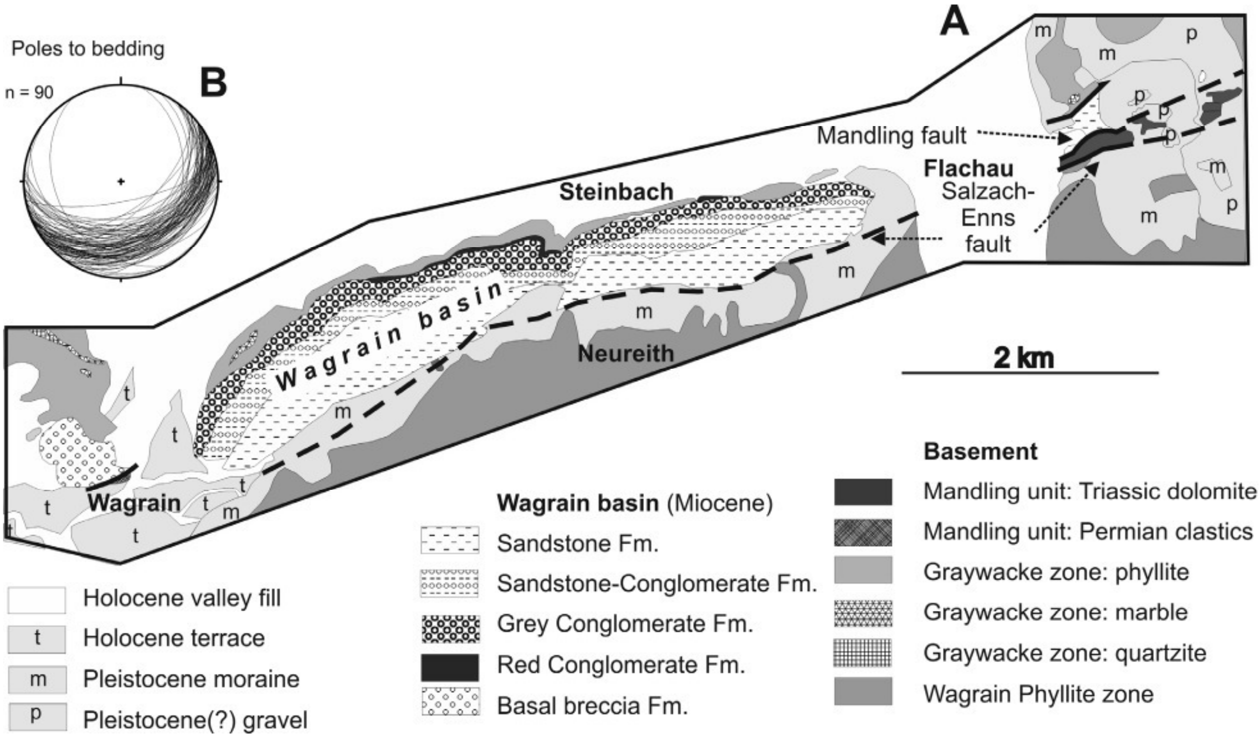

Fig. 6. Geological map of the Wagrain basin.

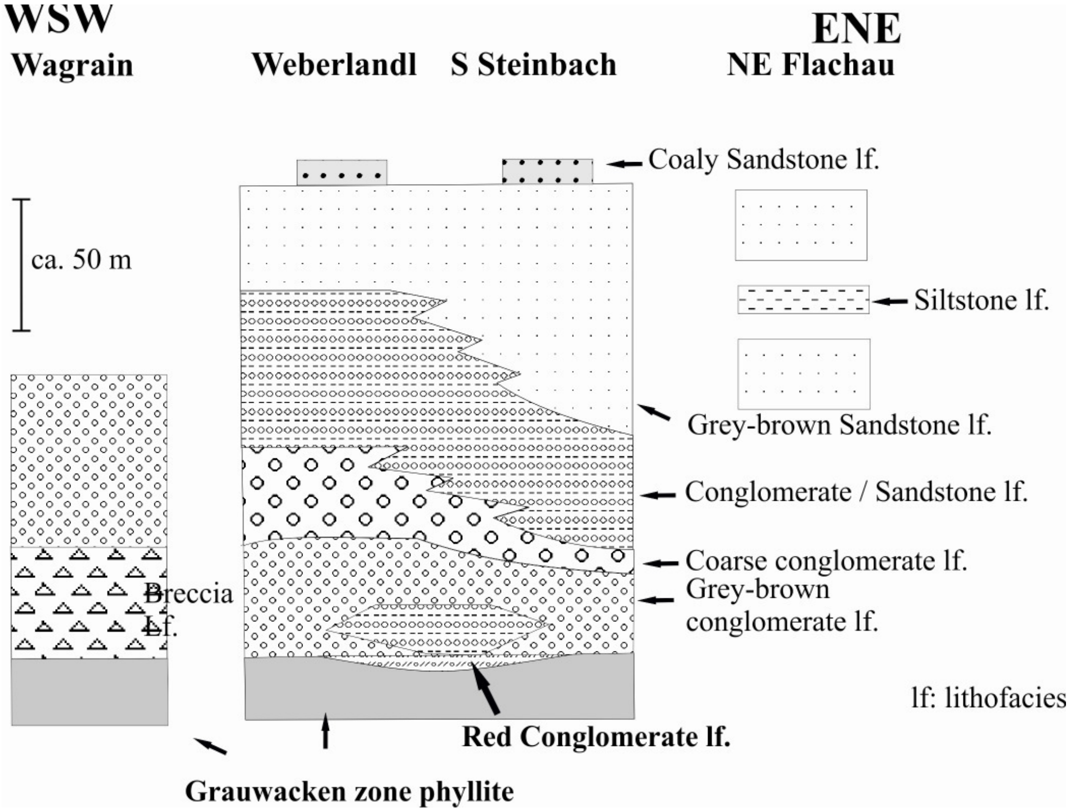

Fig. 7. Ca. ENE–WSW oriented lithofacies section of the Wagrain basin displaying vertical and lateral variations of lithofacies types. Horizontal and vertical sections are not to scale.

Conditions and age of Alpine metamorphic overprint

As has been known for a long time, that the age and conditions of the Alpine metamorphic overprint vary between the Penninic units and the Austroalpine units. Uppermost portions of Penninic units within the northeastern Tauern window are metamorphosed within upper grenschist facies conditions during Eocene-Oligocene times. In general, the conditions of metamorphism are greenschist facies conditions in Lower Austroalpine units, and seem to slightly increase, at least the grain size of newly formed minerals like quartz, white mica and chlorite, towards to the top boundary within the Quartzphyllite nappe. The metamorphic Koppen complex is strongly sheared within upper greenschist facies conditions. The Wagrain Phyllite unit and Greywacke zone are fully recrystallized within greenschist facies conditions, and some variation is visible as the largest grain sizes occur in central parts of the section.

The structural base of the NCA is also metamorphosed within greenschist facies conditions (e.g., Schramm, 1980; Brückl and Schramm, 1982), and sharply decreases towards the hangingwall. A conspicuous break in metamorphism is observed in the Rettenstein section, where greenschist facies metamorphic rocks (> 350 °C) of the basal NCA are overlain by Lower and Upper Juvavic nappes, which are within diagenetic conditions (< 200 °C). This implies a metamorphic break, which is likely associated with a ductile low-angle normal fault (e.g., the Rettenstein extensional allochthon).

Previous geochronological ages are mainly from Hejl (1984). Because of the overall greenschist facies conditions of the Alpine metamorphic overprint, the $^{40}Ar/^{39}Ar$ technique applied to newly-grown white mica is appropriate due to the Ar retention temperature of ca. 425 ± 25 °C (Harrison et al., 2009). Liu et al. (2001) reported a number of white mica ages (10-20 grains, single grains) from the southern margin of the study area. The most important age is ca. 50–54 Ma for the base of Lower Austroalpine nappe complex. The authors interpreted this age as the time of thrusting of the Austroalpine nappe complex over Penninic units. Frank and Schlager (2005) reported conventional $^{40}Ar/^{39}Ar$ white mica ages from the Eben Valley W of Filzmoos, mostly from basal units of the NCA. Their ages range between 101 and 123 Ma.

New unpublished $^{40}Ar/^{39}Ar$ white mica ages are as follows: Large white mica grains of the Seekarspitz basement complex gave a plateau age at ca. 300 Ma (Schreiner, 2008). Fine-grained white mica of a second generation gave a plateau and integrated ages ranging from 80 to 90 Ma, and are thermally disturbed at ca. 50-55 Ma. White mica from the Alpine Verrucano generally gave ages clustering around 80 Ma and displaying a thermal overprint between 50 and 60 Ma.

$^{40}Ar/^{39}Ar$ patterns of syntectonic white mica from the Greywacke zone display a plateau with an eo-Alpine age at ca. 100 Ma (98–102 Ma; Schmidlechner et al., 2006). Some samples show a staircase argon release pattern and a younger, second Cretaceous-aged heat pulse at ca. 70 Ma reaching ca. 300 °C.

4. Structures and structural evolution

Structures of Quartzphyllite nappe

A detailed structural study of the Quartzphyllite nappe and its basal plate boundary to the underlying Penninic units in the NW Radstadt Mountains of the Eastern Alps enable the recognition of a number of important structural events, which were previously unknown, particularly a post-thrust folding and shortening of the Lower Austroalpine/Penninic nappe boundary.

The Lower Austroalpine nappe complex of the Radstadt Mountains in characterized by largely inverted nappes, among which the Quartzphyllite nappe comprises a thick, inverted succession of Permian Alpine Verrucano, thick Lantschfeld Quartzite (Lower Triassic) and a Middle-Upper Triassic succession of carbonates. The Quartzphyllite nappe is thrusted over Penninic tectonic units of the NE edge of the Tauern window during the Eocene as suggested by dating of ductile fabrics of the Hochfeind nappe in the SE (Liu et al., 2001). Rock successions of the Quartzphyllite nappe are characterized by a dominant foliation and a ca. WNW-trending stretching lineation formed during deformation stage D_1, which formed during nappe transport towards the WNW as already described by Becker (1993) during Late Cretaceous ($^{40}Ar/^{38}Ar$ white ages are ca. 78–80 Ma). Isoclinal km-scaled folds and local internal thrust splays are connected with D_1 deformation. These fabrics are overprinted by ductile fabrics at the base of the Quartzphyllite nappe (D_2). In the interior of the Quartzphyllite nappe, the foliation S_1 is overprinted by km-meter-scaled open N-vergent, asymmetric D_3 folds, which also affect the D_2 thrust boundary of the Penninic to Lower Austroalpine nappe complex (Fig. 8). D_3 folds trend ENE to E and gently plunge to the E/ENE with amplitudes of ca. 1 – 2 km. On the outcrop-scale, D_3 folds are often connected with a steeply S-/SSE-dipping axial surface foliation (Schwan and Rossner, 1987). The microfabrics of these S_3 planes reveals their rather cataclastic origin, and no recrystallization of these fabrics occurred. Therefore, the D_3 postdate the D_2 thrust at ca. 50–54 Ma, and indicate a late stage shortening of Lower Austroalpine units, which was previously not recognized.

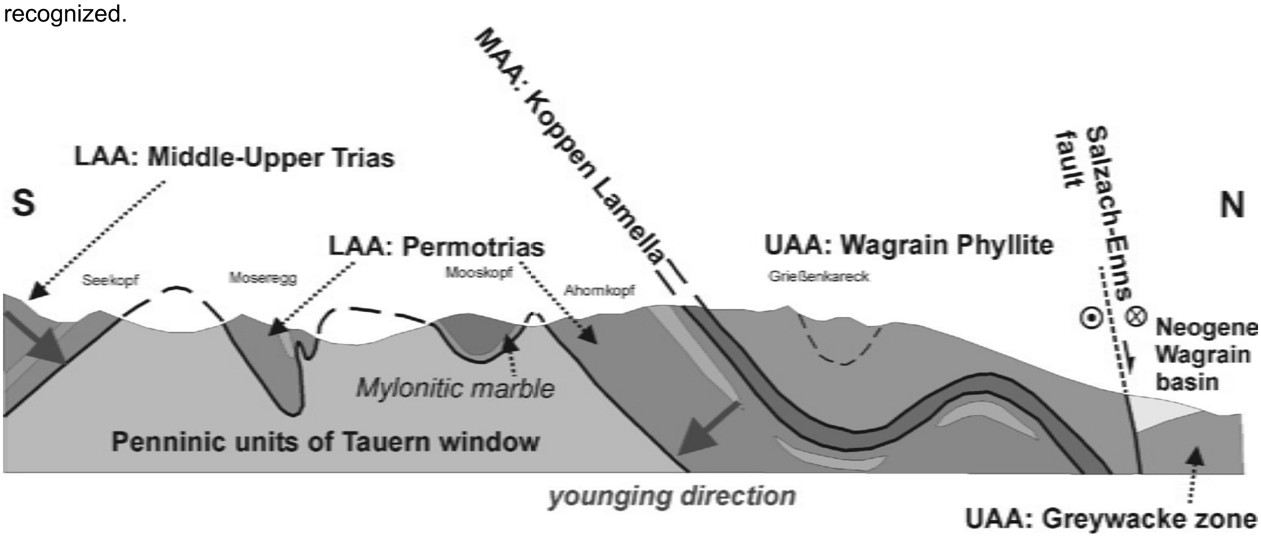

Fig. 8. The N-S section W of Enns Valley show the D3 fold structures of the Penninic/Austroalpine boundary. LAA – Lower Austroalpine units, MAA – Middle Austroalpine units. UAA – Upper Austroalpine units.

Structural evolution of the Greywacke zone

The Greywacke zone shows a two-stage tectonic evolution during the Alpine orogeny. The dominant penetrative foliation S1 formed during peak conditions of metamorphism (ca. 98-102 Ma; Schmidlechner et al., 2006). The foliation often contains a stretching lineation, which trends E-W. On the outcrop-scale, the foliation is often folded during a deformation stage D_2 forming open folds F_2 and subvertical axial plane foliation S_2.

Structural evolution of the Werfen Imbricate zone

The Werfen Imbricate zone (Grubinger, 1953; Rossner, 1972, 1977; Brückl and Schramm, 1982) comprises several major tectonic nappes with mainly Permian to Middle Triassic formations, which are cut along their hangingwall margins, and remnants of the Haselgebirge formation are common on top of the uppermost nappe of the Werfen Imbricate zone.

The siliciclastic Permian to Lower Triassic formations show abundant E-W trending folds with axial plane foliation and, therefore, evidence for N-S shortening during Cretaceous very-low grade conditions of metamorphism. However, the stratigraphic relationships of thrust ramps of nappes show evidence for ca. E-W transport as an important mechanism for the formation of the Werfen Imbricate zone. The thrust surfaces were later reactivated by Cenozoic strike-slip faults and back-thrusts. Consequently, the present-day structure of the Werfen Imbricate zone is the result of superimposed deformation stages.

Structural evolution of the southern Tirolic units
Furthermore, the main body of the overlying Tirolic Tennengebirge nappe comprises spectacular evidence for synsedimentary pre-Dachstein Formation block tilting, and upper portions of Middle to lowermost Upper Triassic formations were eroded before deposition of the Dachstein Formation.

Brittle fault systems
Two different sets of steep faults with predominant strike-slip displacement are found in the study area. Two segments of N-trending strike-slip faults are known. An apparent dextral N-trending fault lies parallel to the Kleinarl Valley south of the SEMP fault. The offset along this fault can be explained by dextral displacement or eastern block down or by a combination of these two displacements. The sinistral N-trending Halm fault is exposed north of the Mandling fault and displaces carbonates of the lowermost imbricate within the Werfen Imbricate zone to the south. This fault implies ca. NNW-SSE strike-slip compression and this event must predate the activation of the SEMP fault. The ENE-trending SEMP fault (Ratschbacher et al., 1991) was operative during Late Oligocene-Miocene lateral extrusion and also associated with the uplift of the Niedere Tauern block (Ratschbacher et al., 1991; Reinecker, 1999; Hejl, 1997, 1998; Keil and Neubauer, 2009). The Mandling/North Enns Valley fault was operative during inversion of the extrusional system and ca. 20 km dextral Middle-Late Miocene displacement can be postulated (Fig. 2; see also Keil and Neubauer, 2011 and their interpretation for the Enns Valley further east).

Formation and inversion of the Wagrain basin and development of the Enns Valley
The Neogene (ca. Karpatian to Lower Badenian) Wagrain basin formed within a halfgraben (Fig. 9), close to the north-eastern edge of the exhuming and uplifting Neogene Tauern metamorphic core complex, along the ENE-trending, ca. orogen-parallel sinistral-transtensional Salzach-Enns and Mandling fault systems of the Eastern Alps. Transtension is also shown by the south-dipping basal unconformity of the Wagrain basin fill and of the underlying Greywacke zone (Fig. 9). The lithofacies evolution of the Wagrain basin fill shows initial rapid subsidence and infilling by massive, coarse-grained conglomerates and subsequent mica-rich immature sandstones deposited in a prodelta environment of a lake. The conglomerates were mainly shed from a polymetamorphic, medium-grade metamorphic basement similar to the Middle Austroalpine Altkristallin basement complex, which is not exposed in the present surroundings of the basin. Provenance studies particularly suggest the Schladming/ Bösenstein and Wölz Micaschist complexes as possible sources. Provenance analysis contrasts recent models for the Neogene evolution of the Eastern Alps, which assume a phyllitic source for similar conglomerates exposed further north and northeast. Paleostress tensor orientations, gathered from faults within the Wagrain basin fill, allow us to distinguish pre-basin and post-depositional palaeostress tensors on a regional scale. This data is consistent with palaeostress development along the Salzach-Enns fault, which also confines the Tauern metamorphic core complex, and shows an evolution from sinistral transtensional to sinistral transpressional to post-depositional dextral transpression.

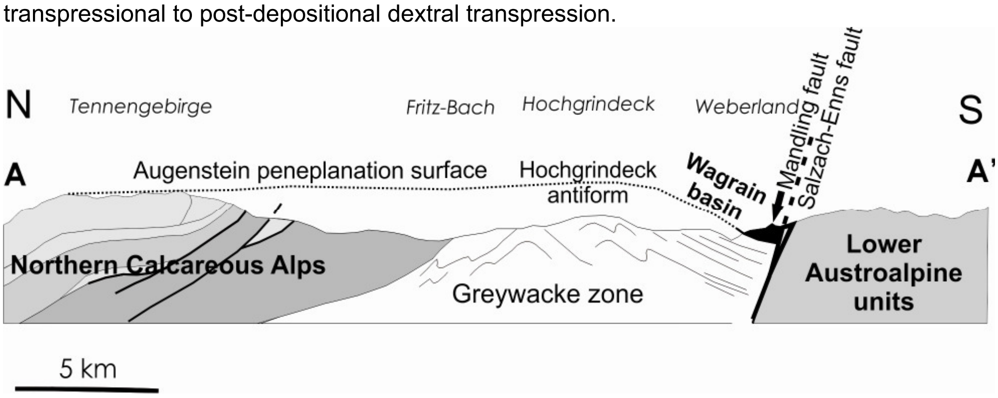

Fig. 9. N-S section displaying the halfgraben nature of the Wagrain basin and the rollover-type Hochgrindeck antiform.

Models for the development of the Enns Valley are shown in Figure 10. The model was developed for the area east of the study area, however fully applies to the Radstadt area, too (Keil and Neubauer, 2009) and the following description is taken from this publication. From Oligocene to early Miocene times (Fig. 10A), the overall drainage system was northwards directed. Both paleosurfaces and provenance analysis indicated transport from south to north (Frisch et al., 2001); no major W-E–trending orogen-parallel valley existed between the later formed Niedere Tauern and the Northern Calcareous Alps. Lateral extrusion, together with the formation of a large strike-slip faults in the middle Miocene, led to the formation of an orogen-parallel depression initially forming a sedimentary basin from Wagrain to Stoderzinken along the future Enns Valley (~16 Ma) (Fig. 10B).
The uplifting Niedere Tauern created incised rivers with V-shaped valleys (Pliocene) (Fig. 10C). Glacial overdeepening during an interglacial period, such as the Mindel/Riss Interglacial, resulted in U-shaped valley formation, with a valley bottom between 690 and 740 m.a.s.l. at that time (Fig. 10D). Overdeepening of the Enns Valley likely occurred before the Würm glaciation due to the large ice-mass of the Riss Glacier.

After the retreat of the Riss Glacier, the Ramsau Conglomerate (including the lignite seam) was deposited in the Enns Valley during the Riss/Würm Interglacial. It filled the valley up to an elevation of about 1,100 m (Fig. 10E), and predated the next advancing (Würm) ice-stream. A continuity of a valley bottom existed between the northern Enns Valley and the southern tributaries (120 ka).
The last glacial maximum (~22 ka) caused new valley over-deepening. The bedrock lay at an assumed elevation of ca. 595 m (Fig. 10F). Strong sedimentation documented the retreat of the glacier; the Holocene valley infill reached a minimum thickness between 120 and 130 m. Strong sedimentation documented the retreat of the glacier; the Holocene valley infill reached a minimum thickness between 120 and 130 m (Fig. 7G).

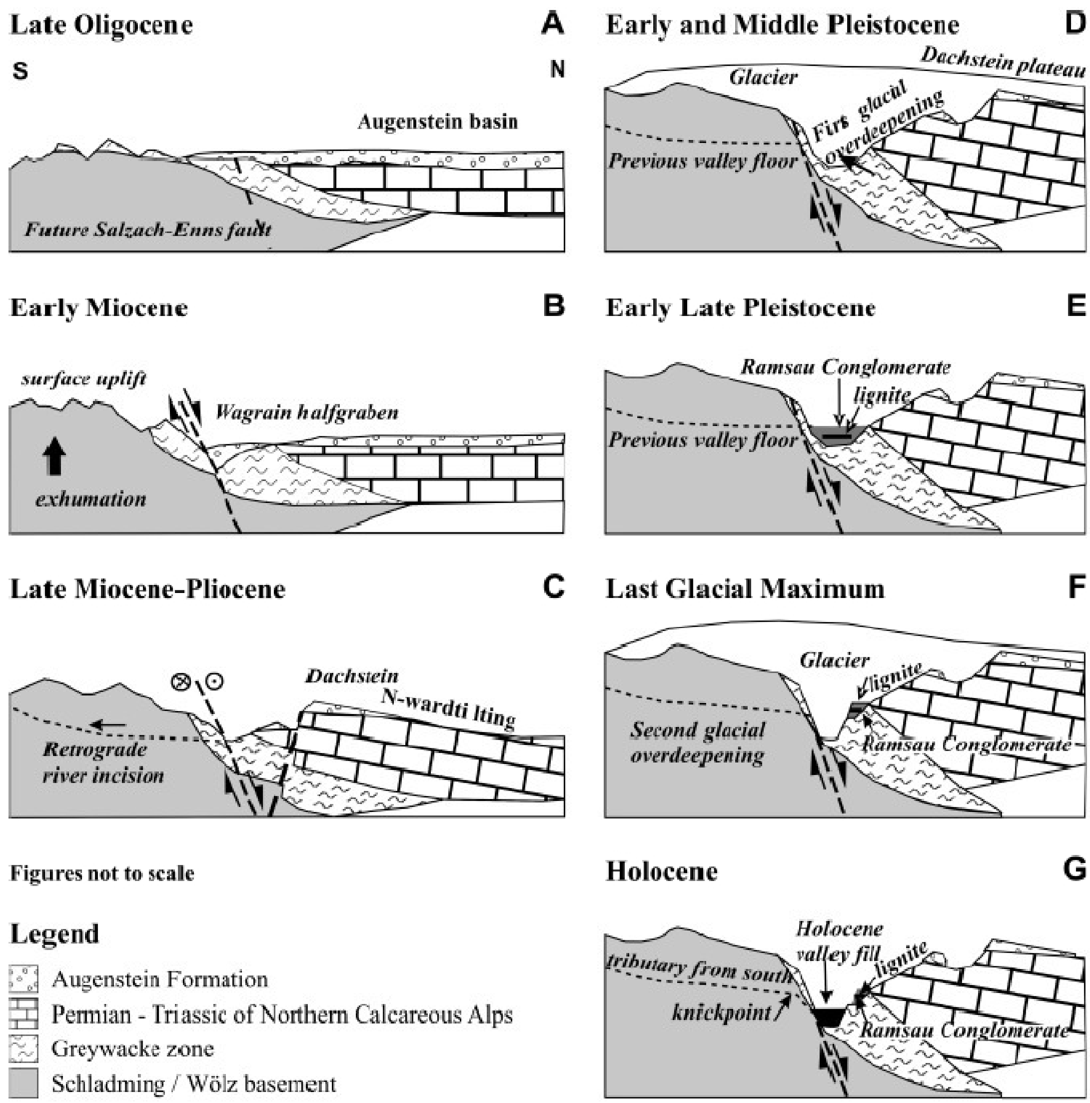

Fig. 10. Model of the tectonic uplift of the Niedere Tauern block (from Keil and Neubauer, 2009). NCA – Northern Calcareous Alps.

Acknowledgements
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Structural Development of Austroalpine Units: the Radstadt- to Tennen Mts. Section : Excursion stops

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10TH ANNIVERSARY 15-20|SEPT SALZBURG

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Introduction

The excursion route is from south to north and describes most lithologies, which are easily accessible along a major road. A map with locations of stops in a geological overview map (after Braunstingl et al., 2005) is in the back of the booklet. Not all of stops can be visited within a one-day field trip. So, we have to select according to the interests of participants.

Stop 1: Mylonitic marble

Location: Roadcut south of Obertauern, ca. 200 m S of Jugendheim Schaidberg, S bridge with a parking lot opposite the exposure
Description: The outcrop exposes a fine-grained mylonitic marble of Liassic age (Häusler, 1995a, b) with a pronounced gently E-dipping foliation and a stretching lineation. According to some thin section investigations, the sense of shear is top to the ESE. We interpret the shear fabric as a result of shearing during the exhumation of the Tauern window.

Stop 2: Jurassic phyllitic schist, metasandstone, fully reset during Eocene metamorphism

Location: Southern boundary of the Obertauern village
Description: The outcrop exposes a succession of phyllitic schists, well-preserved mica-bearing metasandstone and calcareous phyllite of Liassic-Doggerian age (Häusler, 1995a, b). New single-grain Ar-Ar ages of apparent detrital white mica in the size of 0.250 -0.350 µm show ages ranging between 50 and 60 Ma. We interpret these ages as a result of Eocene thermal metamorphism. These ages indicate that the corresponding unit was fully reset during Eocene metamorphism, and no record of Early Alpine metamorphism has been found.

Stop 3: Panoramic view towards Seekar basement

Location: Surroundings of Seekarhaus N of Obertauern.
Description: The outcrop near the Seekarhaus exposes retrogressed amphibolites, greenschists, and mica-rich paragneisses. The age of amphibolite-grade metamorphism is Variscan (Ar-Ar ages of coarse white mica: ca. 300 and ca. 250 Ma), and two stages of Alpine overprint are visible in nearby outcrops. Finer-grained white mica gave ages at ca. 80–85 Ma, and a low-temperature overprint at ca. 50–60 Ma. The Seekar basement is considered to represent the basement of the inverted lying succession of the Permian Alpine Verrucano Fm., Lower Triassic Lantschfeld Quarzite and Reichenhall Rauhwacke (Anisian), which are exposed along the western margin underneath the Seekar basement. There, a minor lens of phyllite, greenschist and Fe-rich dolomite was also found. The boundaries of this lens remain unclear.

Stop 4: Dark Wetterstein Dolomite with fully preserved sedimentary features

Location: Roadcut N of Gnadenbrücke (bridge) near Gnadenfall (Gnaden Cascades)
Description: The outcrop exposes well bedded dark dolomites of the Wetterstein Fm. level (Rossner, 1979). The dolomite exhibits only minor effects of recrystallization.

Stop 5: Wagrain Phyllite

Location: South entrance of the little brook NE Unterberg south of Radstadt, near to the Kemahd cable car
Description: The exposure exhibits a typical phyllite and calcareous phyllite of the Wagrain Phyllite unit, and further up black phyllite and Fe-bearing dolomite.

Stop 6: Acidic metatuff (Blasseneck porphyroid?)

Location: Radstadt, SW corner of ancient city wall.
Description: The outcrops along the northern part and at the southwestern edge of the city wall expose greenish well recrystallized acidic tuffs, with well preserved quartz and feldspar phenocrysts. We consider these acidic metatuffs to belong to the Blasseneck Porphyroid level.

Stop 7: Holocene deformation at the Salzach-Enns-Mariazell-Puchberg fault

Location: Forest path SE Hackl farm south of Altenmarkt, at an elevation of ca. 965 m

Description: The WSW-ENE trending, sinistral Salzach-Enns-Mariazell-Puchberg (SEMP) fault plays a key role in the Neogene tectonic evolution of Eastern Alps, and here we see evidence for post-glacial activity and surface rupture along the SEMP fault near Altenmarkt, Salzburg Province. There, gravels of the last deglaciation cycle, exposed ca. 100 m above the present valley floor, are affected by rupturing along the SEMP fault, and an oblique normal fault component of > 0.5 m (southern block down) was detected (Fig. 1). Unfortunately, dating of the fault activity with the ^{14}C-method failed. Nevertheless, geological and morphological aspects argue for postglacial activity of the SEMP and could have resulted from a superposition of accumulated tectonic stresses during the last maximum glaciation and differential post-glacial unloading of the thick ice-sheet.

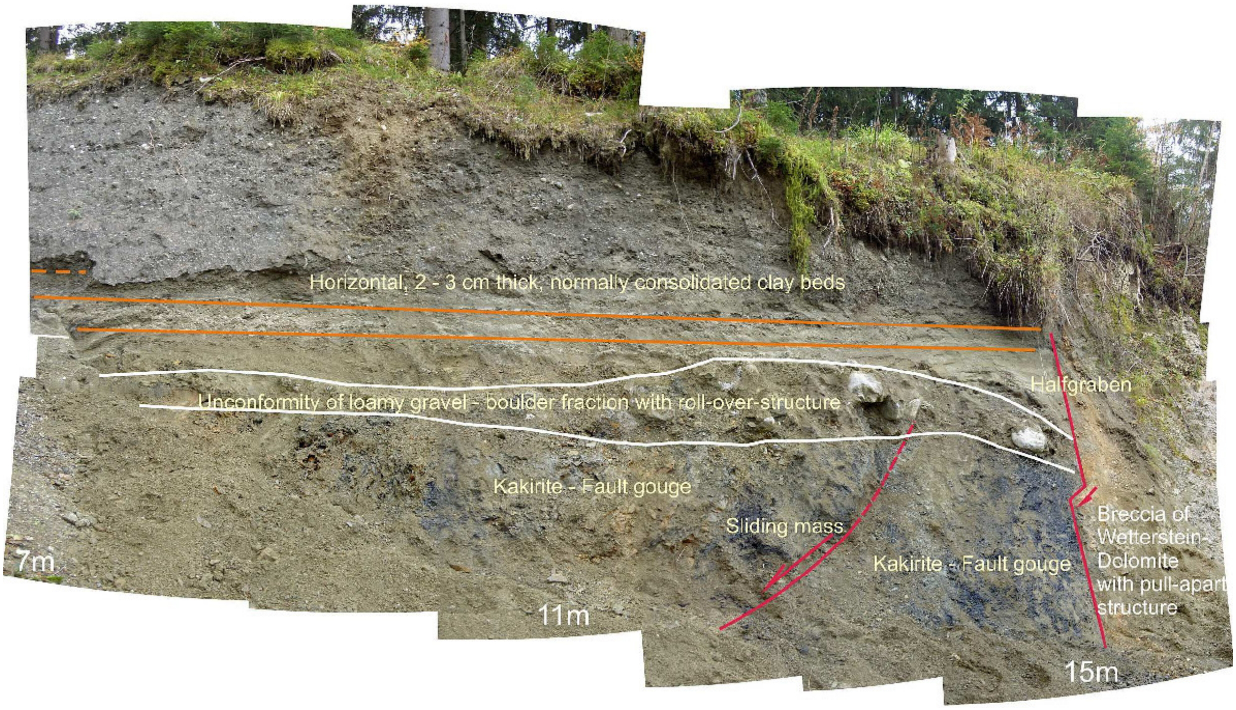

Fig. 1. Exposure of Holocene post-glacial gravels lake sediments affected by activity along the Salzach-Enns fault (from Windberger 2010).

Stop 8: Panoramic view along Salzach-Enns-Mariazell-Puchberg and Mandling fault systems

Location: Gasthaus Winterbauer at Am Feuersang

Description: From the hill Am Feuersang, a view to the east Fig. 2a) shows the N-S section with the Lower Austroalpine Permian to Middle Triassic section, the SEMP fault, the Mandling wedge, the Mandling fault, the Greywacke zone with Lower Paleozoic successions and the overlying Northern Calcareous Alps. A view to the north (Fig. 2b) exposes the Greywacke zone with Lower Paleozoic successions and the overlying Northern Calcareous Alps. The formations at the base of the NCA belong to the Werfen imbricate zone with its successions from Permian to Middle Triassic.

A view to the west (Fig. 2c) shows the same units and, in addition to the view to east, the Miocene Wagrain basin along the combined SEMP and Mandling faults.

Fig. 2a. Panoramic view from Feuersang. a – View to the east.

Fig. 2b.. Panoramic view from Feuersang. b – view towards north.

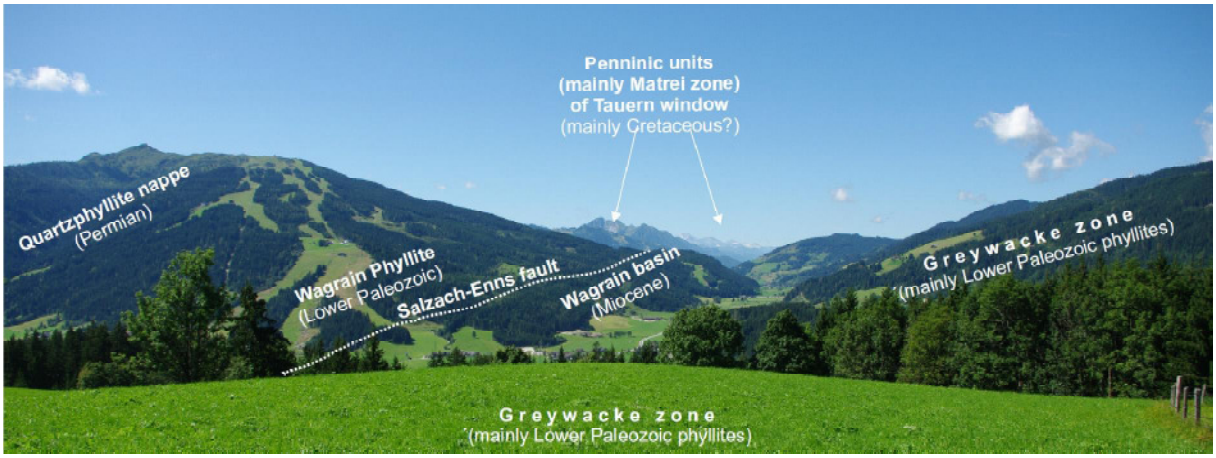

Fig. 2c Panoramic view from Feuersang. c – view to the west.

Stop 9: Peterlehen/Steinbach E of Wagrain: Neogene Wagrain basin

Location: Brook S Steinbach S of the road between Reitdorf and Wagrain

Description: In Peterlehen, southeast of Mayerdörfl, Lower Miocene sedimentary rocks are exposed along a nearly S-N trending valley (Fig. 3). This sedimentary sequence includes a conglomerate at the bottom, upwards follow alternations of conglomerate and micaceous sandstone, and fine-grained sandstone, mudstone and shale at the top. The middle section of the succession occurs in Peterlehen. The rock association comprises mainly gray, middle- to fine-grained micaceous sandstone and conglomerate with intercalations of a thin coal layer. The conglomerate shows well rounded pebbles and boulders. The diameter of the components of the conglomerate is between 5 and 8 cm. The beds dip to the SE (158°) at an angle of 52°. Occasionally, steep normal faults cut through the sequence. A lot of slickensides and striations occur in the sandstone and only a few in the conglomerate. Most of the slickensides dip to the SE with striations indicating down-sliding of the hangingwall, but a minority of them with low angle striations indicate dextral strike-slip shear. Tensor analysis yielded two stages of palaeostress. One maintains the principal stress axes: $\sigma1$: 84/358, $\sigma2$: 06/194, $\sigma3$: 21/104, the other shows the principal axes $\sigma1$: 03/157, $\sigma2$: 86/287, $\sigma3$: 04/066, which represents dextral strike-slip shear.

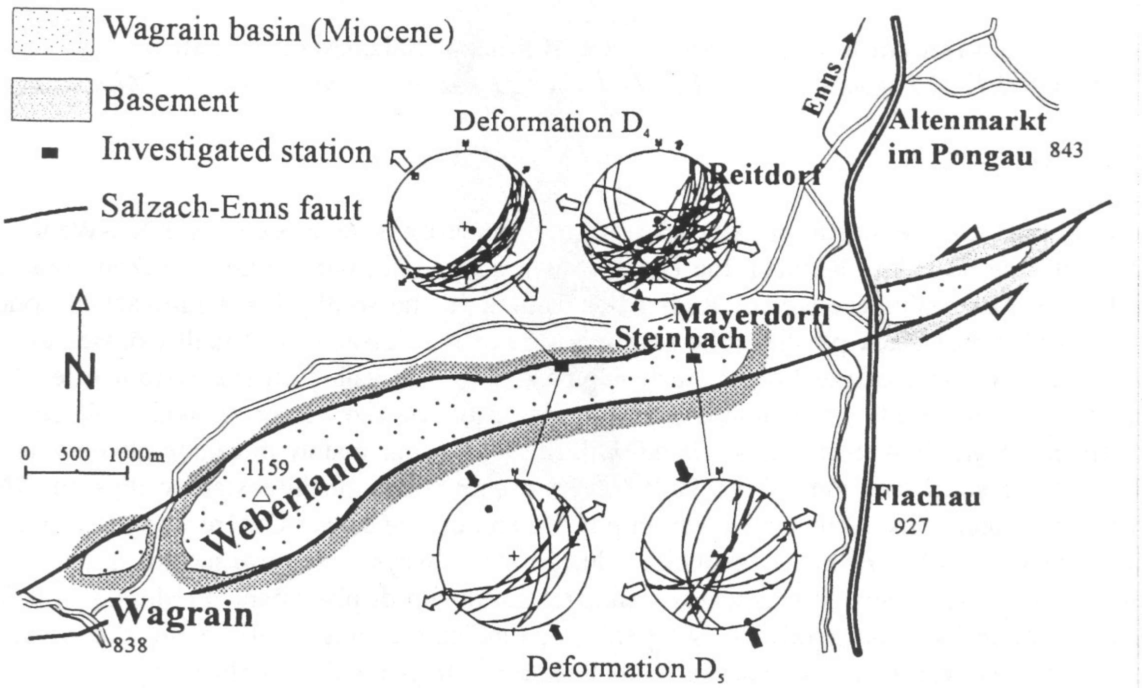

Fig. 3. Palaeostress patterns of the Wagrain basin (from Wang and Neubauer, 1998).

Stop 10: Base of the Wagrain basin fill

Location: Gorge to the east of the base station of the cable car

Description: The valley exposes the basal red lithostratigraphic unit, which comprises reddish hematite-rich conglomerates and red mica-rich sandstones. The massive conglomerates comprise well-rounded reddish boulders and pebbles with a maximum diameter of ca. 30 centimeters. The clasts are coated with red hematite. The red conglomerate lithofacies is ca. 3 – 8 meters thick. The overlying grey-brownish conglomerate lithofacies comprises a coarse-grained clast-supported conglomerate with variable clast sizes, ranging from a few centimeters to several decimeters. Clast size seems to increase upwards, and reaches a maximum of 50 centimeters in topmost layers, which form steep slopes. The clasts are well-rounded or rounded. The conglomerate is polymict and comprises mostly metamorphic basement rocks. Locally, up to 30 centimeter thick mica-rich sandstone lenses are intercalated within conglomerate beds. The thickness of gray-brown conglomerates reaches ca. 80 meters. Between Steinbach and Steinbachgraben, a ca. 20 meter thick alternation of conglomerates and sandstones has been found between red and gray-brownish conglomerates. The individual beds are several centimeters to decimeters thick and also display some sedimentary structures including scour and fill structures. The gray-brown conglomerate lithofacies is dominated by vein quartz, pegmatite and aplite gneiss and mica-poor, light-colored orthogneiss and augengneiss. Among these, the orthogneiss and foliated pegmatite gneiss are particularly abundant components. Quartzitic micaschist, grayish and light-colored laminated/foliated mylonitic quartzites, garnet-rich paragneiss, and plagioclase amphibolite are further medium-grade metamorphic components.

Stop 11: Panoramic view Flachauwinkel: Structure of the Penninic/Lower Austroalpine boundary

Location: Flachauwinkel

Description: On a view to the west, the fold and nappe structure of the Lower Austroalpine and Penninic boundary is visible there. On the eastern valley floor inverted, metamorphosed Permian to Middle Triassic formations are exposed (on top Permian Alpine Verrucano, then Lower Triassic Lantschfeld Quartzite, then Middle-Upper Triassic carbonates at the base). These formations are folded on the scale of kilometers and amplitudes of ca. 1.5 to 2 kilometers. Folds represent an anticlinal synform respectively the northern limb of a synformal antiform. On the western valley slope, Penninic units are exposed in an antiform. So, the thrust boundary of Lower Austroalpine units over Penninic units is folded.

Stop 12: Filmoos Metaconglomerate/Breccia

Location: Gasthofberg north of Eben, roadcut at turn west of Berg farm

Description: The roadcut exposes one of the best exposures of the polymict Filzmoos Metaconglomerate. The components vary in size and include vein quartz, phyllite and dolomite. The conglomerate includes a pronounced gently N-dipping foliation and a ca. WNE-ESE trending stretching lineation displaying mainly stretched vein quartz pebbles. The fabric is considered to have formed during Cretaceous-aged metamorphism and associated ductile deformation. We interpret the breccia/conglomerate as a terrestrial escarpment breccia, and the precursor of the N-trending Halm fault is considered as the limiting primary normal fault.

Stop 13: Alpine Verrucano

Location: Gasthofberg north of Eben, roadcut farms Reit and Stauch

Description: The roadcut exposes the highly variable succession of the Alpine Verrucano of Permian age. The succession includes greenish-grayish phyllite, metabreccia, metaconglomerate, metasandstone. We interpret the succession as a deposition of alluvial fans, and the phyllites as the infill of a lake. Similar as in the exposure of the Filzmoos Metaconglomerate, the rocks include a pronounced foliation and a ca. WNE-ESE trending stretching lineation mainly displaying stretched vein quartz pebbles and quartz grains. The fabric is considered to have formed during Cretaceous-aged metamorphism and associated ductile deformation.

Stop 14: Panoramic view of the Rettenstein with a ductile low-angle normal fault

Location: Filzmoos village

Description: The Rettenstein Mountain comprise a base with a ductilely Greywacke zone and the overlying Permian to Lower Triassic clastic succession and Middle Triassic rauhwacke and thin dolomite, which are also metamorphosed within greenschist facies metamorphic conditions. The carbonates are overlain by a ca. 10 – 15 m layer of cataclastically deformed gypsum and claysthe Permian-Lower Triassic Haselgebirge Formation. These rocks are overlain by unmetamorphosed marls of the Jurassic Allgäu Formation, radiolarite, and have a likely tectonic contact with mainly massive white limestone of the Jurassic Plassen Limestone Formation. We consider, therefore, the gypsum/clay layer of the Jurassic Haselgebirge Formation as a ductile low-angle normal fault, which brought the unmetamorphosed rocks of the Rettenstein top in contact with the Permian to Middle Triassic rocks of the base of the Northern Calcareous Alps.

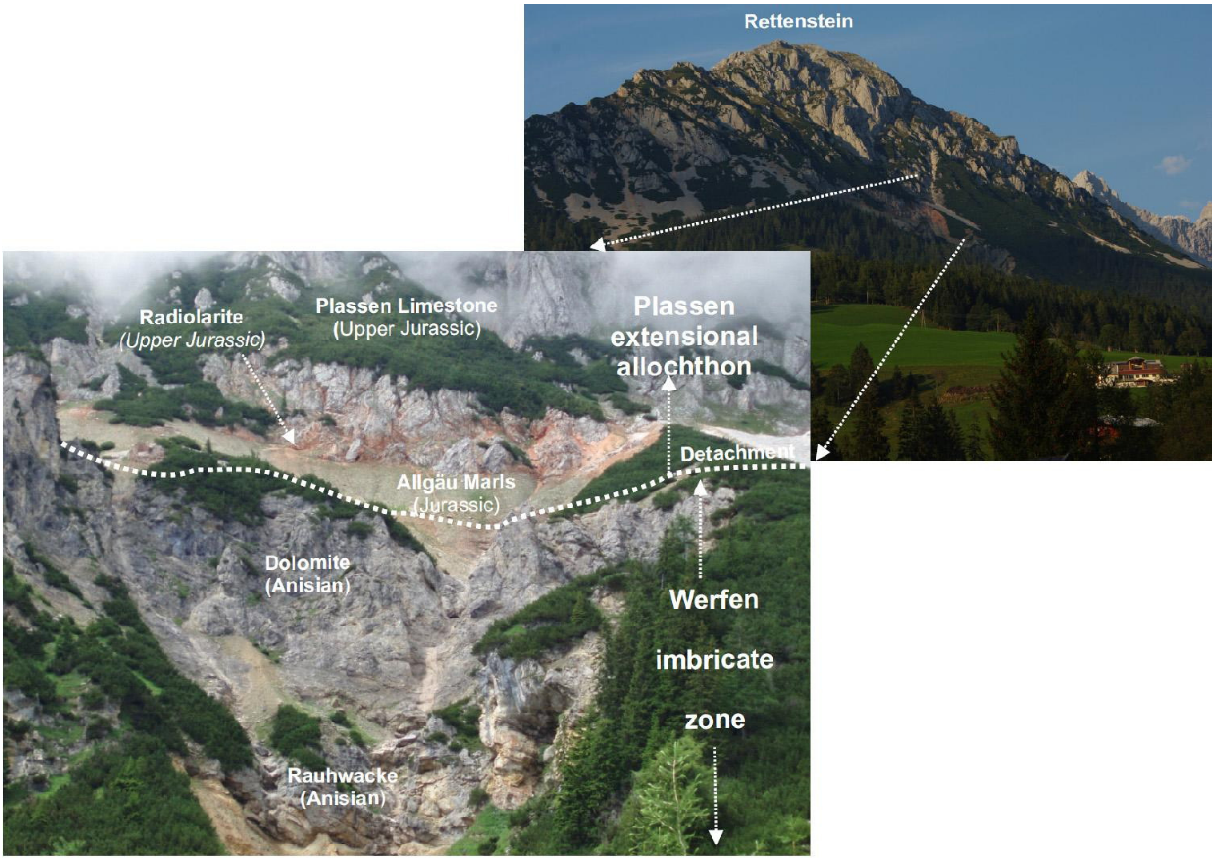

Fig. 4. Panoramic view from Filzmoss displaying the Plassen extensional allochthon above the Haselgebirge shear zone.

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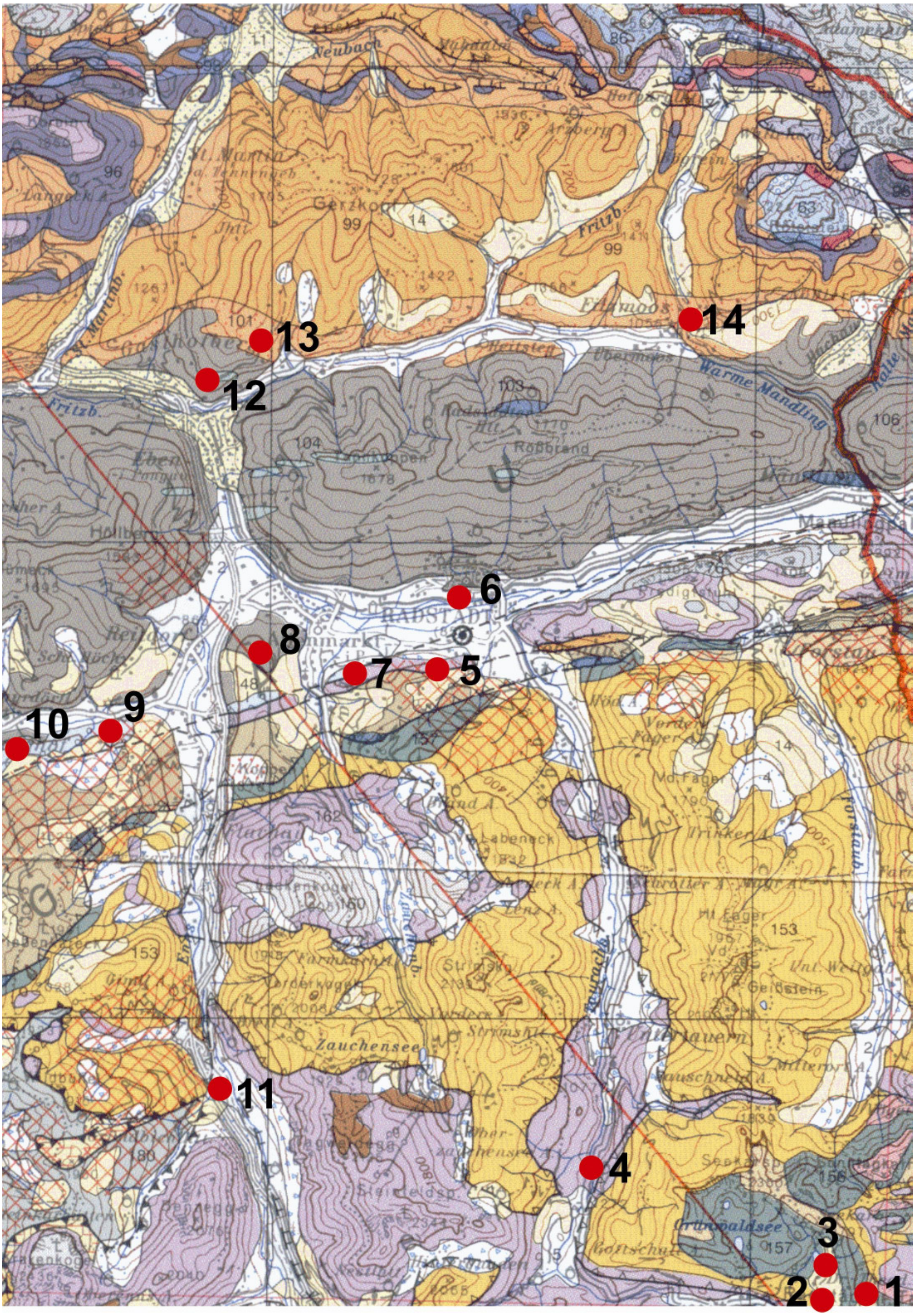
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Grünwaldsee
Labeneck