Field trip 8

Innsbruck´s geology in a nutshell: from the Hafelekar to the Hötting Breccia

Karl Krainer[1] and Michael Meyer[1]

[1] Institute of Geology, University of Innsbruck, Innrain 52, 6020 Innsbruck

1 Introduction

Hafelekar Spitze provides an excellent panoramic overview of the main geologic units around Innsbruck. The city of Innsbruck is located on an alluvial fan which was formed by the Sill river at its confluence with the Inn river. The mountain group southeast of Innsbruck is termed Tuxer Alpen, southwest of Innsbruck Stubaier Alpen and north of Innsbruck Karwendel as part of the Northern Calcareous Alps.

The excursion starts at the cable railway station Hungerburgbahn next to the Innsbruck Congress Centre (Fig. 1). The Hungerburgbahn will bring us onto the Hungerburg terrace (868 m), from there we continue with a cablecar (Seegrubenbahn) to

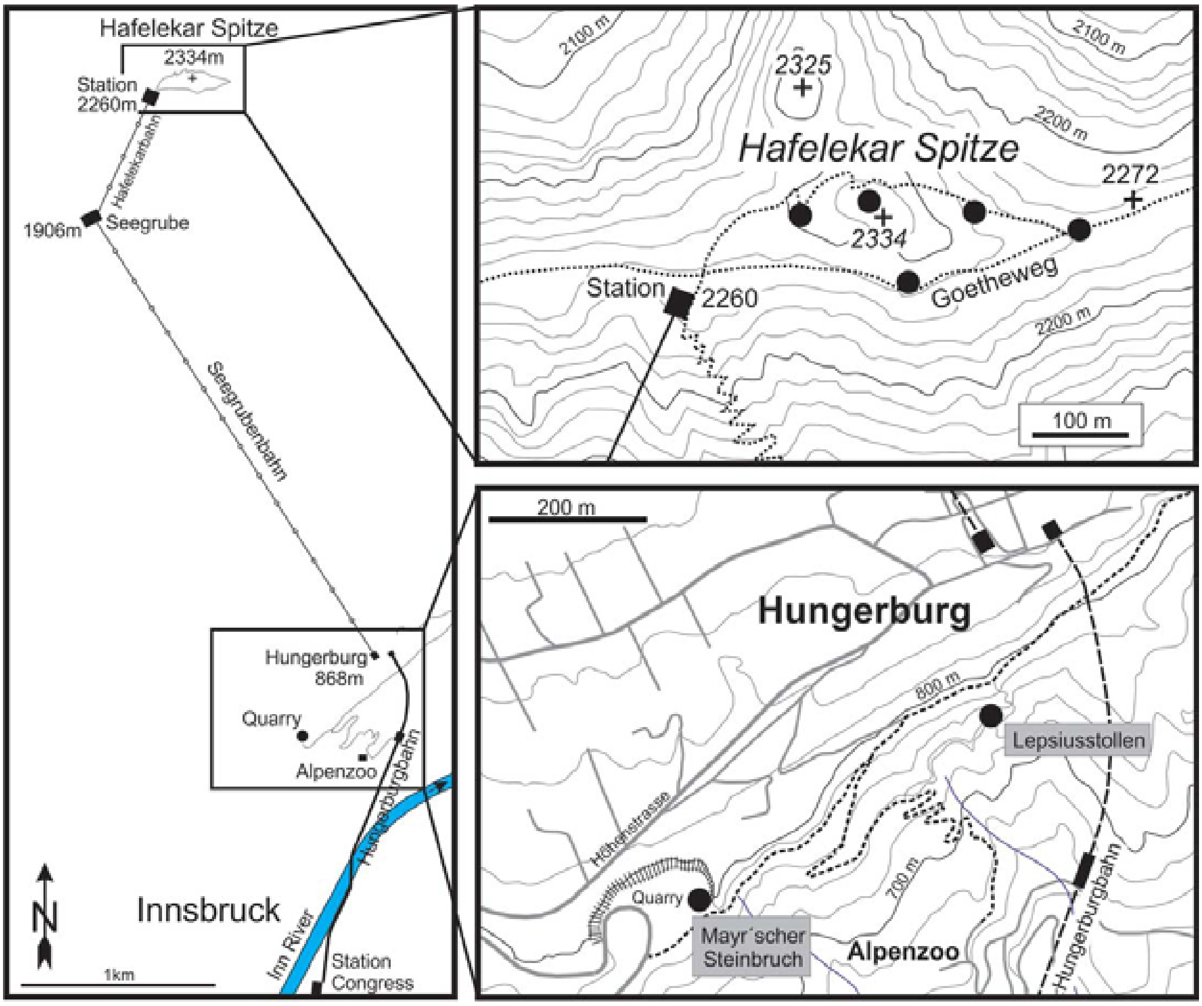

Fig. 1: Map showing excursion route to Hafelekar Spitze (Wetterstein Reef Complex) and Hungerburg – Alpenzoo (Hötting Breccia).

Seegrube (1905 m) and ascend Hafelekar (2260 m) via a second cablecar. From the top station of the Hafelekarbahn the excursion route follows the trail to Hafelekar Spitze and continues East where the trail meets the Goetheweg, one of the most spectacular panoramic trails around Innsbruck. Following the Goetheweg we come back to the cablecar station at Hafelekar. Hafelekar Spitze provides a good opportunity to introduce the regional geological setting and to summarize the Quaternary dynamics of the Inn valley. Several outcrops along the hiking trail allow the Hafelekar Reef Complex to be studied (Fig. 1).

The second part of the excursion focuses on a famous Pleistocene clastic sediments succession north of Innsbruck known as the Hötting Breccia. The excursion route starts at Hungeburg and follows the trail to Lepsiusstollen, a classic location of Quaternary Geology in the Alps, and from there to an abandoned quarry (Mayr´scher Steinbruch), where the Höttinger Breccie is well exposed. From the quarry we will walk to the Alpenzoo (Innsbruck´s zoological garden) from where the Hungerburgbahn carries us back to Innsbruck (Fig. 1).

2 Geologic Overview

2.1 Inn Valley and Sill Valley

The Inn Valley marks one of the large, approximately ENE-WSW-trending sinistral faults separating the Northern Calcareous Alps north of the fault from the geologic units (Innsbruck Quartz Phyllite Complex, Ötztal-Stubai Metamorphic Complex) to the south (Fig. 2).

A core drilling near the Innsbruck airport showed that the Valley in the area of Innsbruck is filled with more than 360 m thick Quaternary sediments. The Inn Valley SW, SE and NE of Innsbruck is also characterized by distinct terraces („Mittelgebirgsterrassen") formed by Quaternary sediments (lacustrine sediments – Bändertone – grading into sandy and gravelly glacial outwash sediments – Vorstoßschotter – overlain by lodgment till of the last glacial maximum). The terrace north of the city of Innsbruck (Hungerburgterrasse) is mainly composed of the famous Höttinger Breccie (see . excursion route part 2 – the Hötting Breccia)

The Valley which extends from Innsbruck to the Brennerpass in the south (Silltal-Wipptal) represents a big west-dipping normal fault (Brenner Abschiebung) which formed as a result of N-S-compression and E-W-extension of the Eastern Alps. Deformation along the fault was brittle in the northern part and ductile in the south (Brennerpass). The fault was active during the Neogene. At the Oligocene-Miocene boundary the rocks of the western part of the Tauern Window were still located at a depth of approximately 23 km. Since 13 Ma rocks of the Tauern Window and Innsbruck Quartz Phyllite formed the footwall which were exhumed along the Brenner normal fault. In the north the Brenner normal fault joins the sinistral fault running along the Inn Valley.

2.2 Northern Calcareous Alps

Hafelekarspitze is one of the peaks of the Nordkette which is part of the Karwendel Mountains. The Karwendel Mountains belong to the Northern Calcareous Alps, a main geologic unit of the Eastern Alps extending from Liechtenstein over approximately 500 km to the East (Baden bei Wien). The Northern Calcareous Alps are a complex geologic unit formed of a number of stacked nappes. NCA are overthrusted on the underlying nappes of the Helvetic zone and Rhenodanubian Flysch. From Schwaz to the East rocks of the Graywacke Zone are exposed south of the NCA. The Graywacke Zone formed the basement of the thick sedimentary pile of the NCA. West of Schwaz the Inntal Fault separates rocks of the Innsbruck Quartz Phyllite and Ötztal-Stubai Metamorphic Complex from the NCA.

The NCA are mainly composed of carbonate sedimentary rocks, subordinately of siliziclasitc rocks and cherty sediments (radiolarite); volcanic rocks are very rare (see Fig. 2). Sedimentation started during the Lower Permian. During the Permian nonmarine red beds and evaporitic rocks („Haselgebirge") were deposited. In the westernmost part of the NCA acid volcanic rocks are intercalated. During the Lower Triassic a transgression from East to West occurred, causing deposition of shallow marine siliciclastic and carbonate sediments of the Werfen Formation in the Eastern

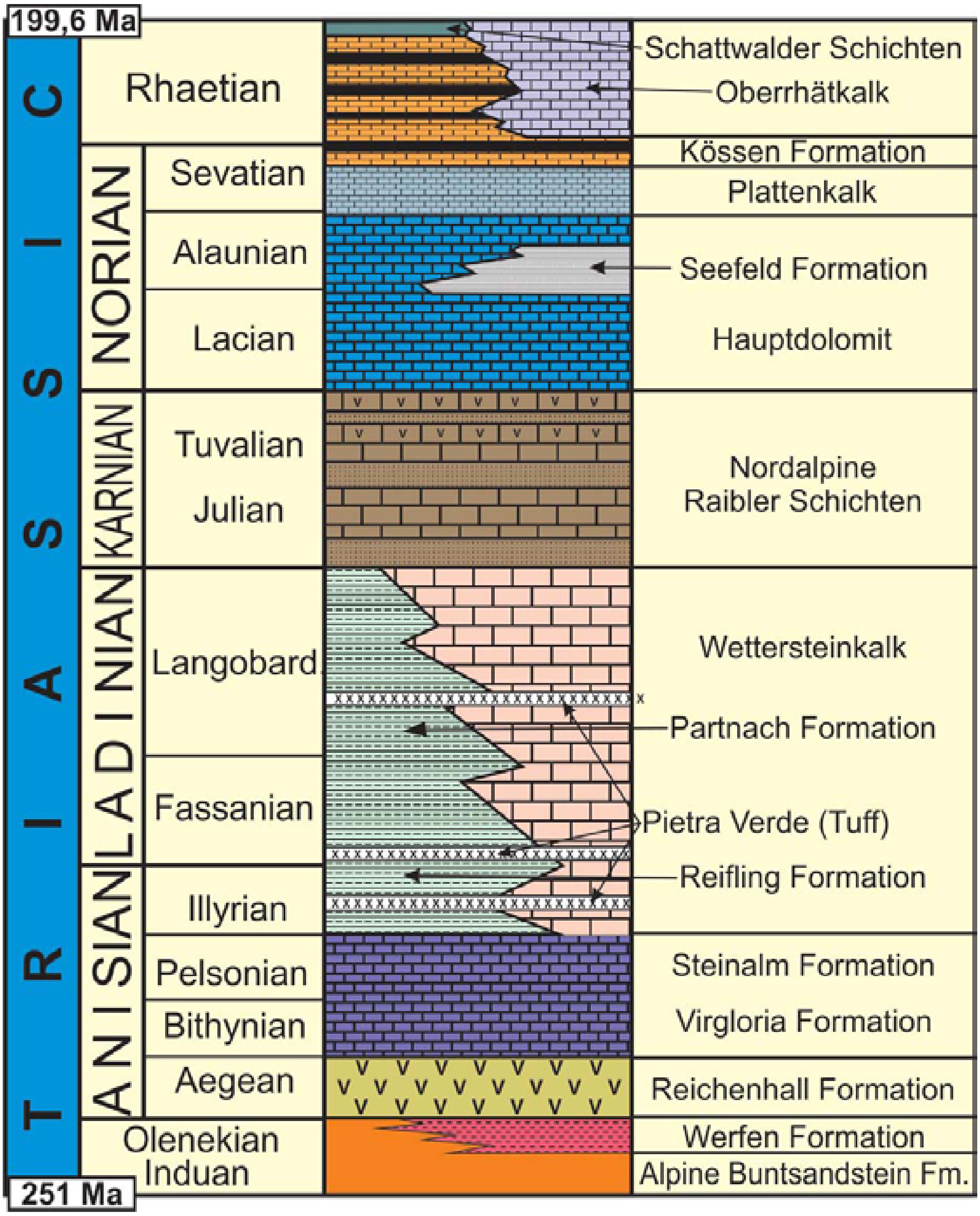

Fig. 2: Stratigraphy of the Triassic succession in the western part of the Northern Calcareous Alps.

part of the NCA which towards the West interfinger with the nonmarine deposits of the Alpine Buntsandstein (Fig. 2). During the Middle and Upper Triassic mainly shallow marine carbonate sediments were deposited. Locally intraplatform basins developed which were filled with basinal sediments (limestone and mudstone). The sedimentary succession of the Triassic is more than 3000 m thick, particularly during the Middle and Upper Triassic extremely thick platform carbonates accumulated (Wetterstein Formation: 800 m, Hauptdolomite up to 1800 m. Fig. 2). During the Jurassic dominantly pelagic sediments (limestones, marls, cherty sediments) were deposited in a number of pull apart basins which developed as a result of the opening of the Central Atlantic and Penninic Oceans. During the Cretaceous pelagic sedimentation was increasingly replaced

by siliciclastic deep sea sediments as a result of plate tectonic processes (beginning of the subduction of the Penninic Ocean).
Compressional tectonics („Pre-Gosauic movements") resulted in overthrusting of nappes and uplift above sea-level. During a short extensional phase sedimentary basins (Gosau Becken) developed which were filled with fluvial, lacustrine and shallow- to deep marine sediments. Compressional tectonics caused deformation of the Gosau sediments and overthrusting (Tollmann 1976, Brandner 1984, Mandl 2000).

2.3 Innsbruck Quartz Phyllite Complex

This geologic unit which is exposed southeast of Innsbruck (Fig. 3) is a thick succession of mainly phyllitic rocks. The succession is divided into a lower unit composed of quartz phyllite with intercalations of greenschist and porphyroids, a middle unit composed of phyllitic rocks and intercalated marbles, and an upper unit consisting of black phyllitic rocks and intercalated marbles. An Ordovician to Devonian age is assigned to the succession, based on conodonts and lithologic correlations with similar geologic units in the Eastern Alps. The rocks are characterized by a polyphase (pre-alpidic and alpidic) deformation and metamorphic history (Haditsch and Mostler, 1982; Rockenschaub et al., 2003b).
The Innsbruck Quartz Phyllite was long considered part of the Lower Austroalpine Nappe system, but recently was assigned to the Upper Austroalpine Nappe System (Silvretta-Seckau Nappe System) by Schmid et al. (2004).

2.4 Patscherkofel Metamorphic Complex

Locally rocks of the Innsbruck Quartz Phyllite are overlain by metamorphic rocks (mica schists, paragneiss, quartzite, amphibolite) which are similar to the Ötztal-Stubai Metamorhic Complex (Fig. 3). The rocks were overprinted by Variscan and Eoalpine metamorphism (Rockenschaub et al., 2003b).

2.5 Tarntal Mesozoic

In the southern part the Innsbruck Quartz Phyllite is overlain by a succession of rocks termed Tarntal Mesozoic (Fig. 3). The succession can be divided into a Permotriassic part composed of quartzite, evaporitic rocks (Rauhwacke), limestone, dolomite, mudstone and sandstone, and a Jurassic part including sandstone, mudstone, breccia (Tarntaler Breccie), cherty limestone, calcareous schist, cherty sediments (Radiolarit), serpentinite and ophicalcite. The rocks underwent polyphase alpidic deformation. The Tarntal Mesozoic is part of the Lower Austroalpine Nappe System (Tarntal and Hippold nappes). Reckner Nappe (calcareous schists, phyllitic rocks, marble, siliceous schists, serpentinite, ophicalcit) are assigned to the Penninic nappe system of the Tauern Window (Enzenberg, 1966; Rockenschaub et al., 2003b).

2.6 Tauern Window (Penninic and Subpenninic nappes)

South of the Innsbruck Quartz Phyllite and Tarntal Mesozoic rocks of the Tauern Window are exposed and composed of various rocks that belong to the Penninic and Subpenninic nappes respectively (Fig. 3). Orthogneiss („Zentralgneis") and metamorphic rocks of continental crust („Altes Dach": micaschist, paragneiss, amphibolite) form a large part of the Subpenninic Nappes. Metamorphically overprinted Permotriassic to Jurassic sedimentary rocks of the Helvetic shelf such as quartzite, marble, various phyllites („Bündnerschiefer") are also part of the Subpenninic Nappes. Penninic nappes include the Matreier Zone and Nappes forming the northern margin of the Tauern Window). These nappes are mainly composed of metamorphic sedimentary rocks (various types of phyllitic rocks; originally deep marine marly and muddy sediments of the Penninic Ocean) locally containing olistoliths of Triassic and Jurassic marbles, schists and quartzites (Rockenschaub et al., 2003a).

2.7 Geologic Units West of the Wipptal

The mountains on the western part of the Wipptal are termed Stuabai Alps and represent the downthrusted hangingwall of the Brenner normal fault (Brenner Abschiebung). This downthrusted hangingwall is composed of three superimposed nappes of the Upper Austroalpine Nappe System: The Ötztal Nappe which is part of the

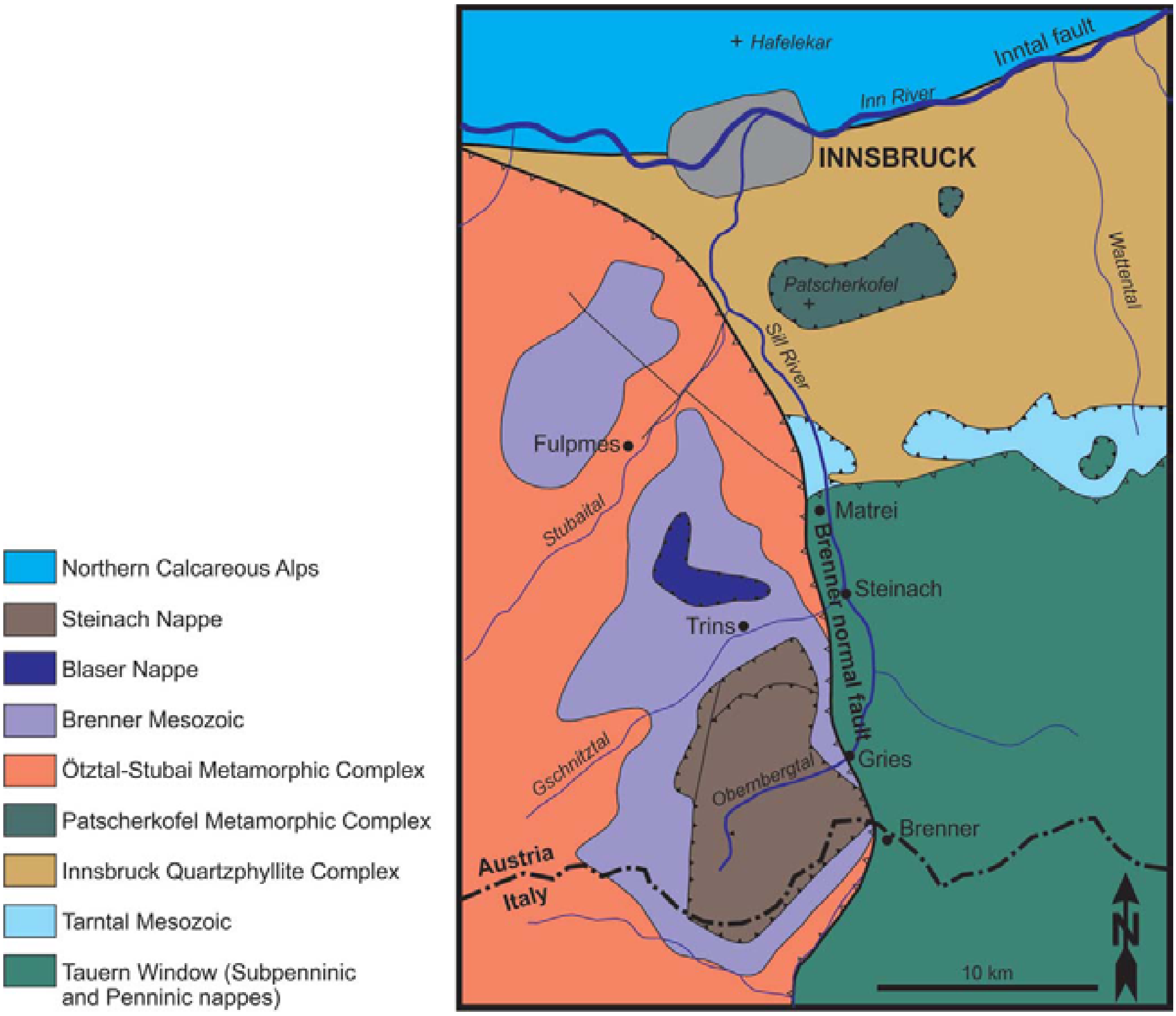

Fig. 3: Simplified geologic map showing the main geologic units south of Innsbruck (Wipptal - Brennerpass area) (redrawn after Rockenschaub et al. 2003c).

Ötztal-Bundschuh Nappe System, is composed of rocks of the Ötztal-Stubai Metamorphic Complex, overlain by Mesozoic sedimentary rocks („Brenner Mesozoic"). Locally the Ötztal Nappe is overlain by the Blaser Nappe and Steinach Nappe System. Blaser Nappe and Steinach Nappe Systems are ascribed to the Drauzug Gurktal Nappe System (Schmid et al., 2004).

2.8 Ötztal-Stubai Metamorphic Complex

The main rocks of this geologic unit in the Wipptal area are various types of mica schists and paragneisses with intercalatations of otho-gneisses and amphibolites (Fig. 3). The main metamorphic event (amphibolite facies) occurred during the Variscan deformation phase. During eoalpine metamorphism the rocks were overprinted in greenschist facies in the northern part, which increased to amphibolite facies in the southern part (Hoinkes and Thöni, 1993; Rockenschaub et al., 2003c).

Rocks of the Ötztal-Stubai Metamorphic Complex are overlain by sedimentary rocks which were overprinted in greenschist facies during eoalpine metamorphism. The succession starts with quartz-rich conglomerates and sandstones (overprinted to quartzites) with a sedimentary contact to the underlying basement rocks. These quartzi tes are interpreted as equivalents of the Alpine Buntsandstein (Krois and Stingl,1989) and overlain by dolomitic rocks („Basis-Dolomit"), interpreted as equivalents of the Anisian Steinalm- and Reifling Formation of the Northern Calcareous Alps. The overlying succession is ascribed to the Partnach Formation, Wetterstein Dolomite, Raibl Beds and Hauptdolomite (Kübler-Müller, 1962; Tollmann, 1977; Rockenschaub et al., 2003c; Brandner et al., 2003). The upper Triassic to Jurassic succession is summarized as „Metamorpher Kalkkomplex" (marbles, mica-marbles, calcareous phyllites, phyllites, quartzites) and interpreted as equivalents of the Plattenkalk, Kössen Formation and Allgäu Formation. Locally a breccia is exposed on top of the Metamorpher Kalkkomplex which is interpreted as deposits of the Gosau Group (Rockenschaub et al., 2003c).

2.9 Blaser Nappe

The metamorphic succession of the Brenner Mesozoic is locally overlain by the Blaser Nappe which is composed of nonmetamorphic sedimentary rocks such as Hauptdolomite, Plattenkalk, Kössen Beds, Oberrhätkalk, Jurassic limestone and radiolarite (Fig. 3; Rockenschaub et al., 2003c).

2.10 Steinach Nappe System

The Steinach Nappe System is composed of two superimposed nappes: Steinach Nappe I and II (Fig. 3). Steinach Nappe I at the base is composed of garnet mica schists and mica schists with intercalations of diabase, amphibolite and mylonitic gneisses. The overlying Steinach Nappe II consists of phyllitic rocks and greenschists with intercalated iron-rich dolomites, locally calcaraeous marbles and magnesite. Graphitic phyllites yielded Chitinozans which indicate an Ordvician to Devonian age.

The phyllitic basement rocks are overlain by nonmetamorphic, nonmarine sediments including quartz rich conglomerates, sandstones, siltstones and schists and thin intercalated anthracite seams. Plant fossils indicate a Late Carboniferous (Stephanian) age (Krainer, 1990; Schmidegg, 1949; Rockenschaub et al., 2003c).

3 Excursion route part 1 – the Hafelekar Reef Complex

3.1 Introduction

A massive reef (Hafelekar Reef Complex) is developed in the upper part of the Middle Triassic (Ladinian and Cordevolian) Wetterstein Limestone at Hafelekar north of Innsbruck (Fig. 2). This reef complex was studied in detail by Brandner and Resch (1981).

The Wetterstein Limestone is 500-1700 m thick and mostly developed in a well-bedded lagoonal facies (Fig. 4) of an extensive shallow marine carbonate platform with locally developed reefs at the platform margin. According to Brandner and Resch (1981) the Hafelekar Reef Complex marks the final stage of reef development which started with the formation of patch-reefs in the lower part of the Wetterstein Limestone. The reef complex shows a regressive trend.

The Hafelekar Reef Complex shows a distinct biological zonation which reflects the various ecological zones within the reef. Reef formation was influenced by sea-level fluctuations and tectonic events. The patch-reef sequence is approximately 200 m thick, individual patch reefs are lenticular in shape and up to 40 m thick. Reef debris and basinal sediments represented by reddish limestone containing ammonites and radiolarians were deposited between the patch reefs.

The Hafelekar Reef Complex represents the first massive reef development within the Wetterstein Limestone at Nordkette north of Innsbruck. The reef complex shows a clear zonation into fore-reef, central reef area, and back reef with reef-flat (calcarenite facies) and sand shoals. The fore-reef was a gently inclined slope where reef debris (reef rubble) was deposited in a matrix of well-sorted grainstone. The platform margin reef development was influenced by tectonic activity which is documented by neptunian dikes and megabreccias, dividing the reef into two parts with two separate stages of development (Goetheweg reef and younger Hafelekar reef).

Reef growth started on top of reef debris (block rubble). The primary framework of the reef was built by corals, calcisponges and *Tubiphytes*. Organisms which encrusted the primary reef

Fig. 4: View from Hafelekar Spitze towards NE (Karwendel Mountains) showing well bedded middle Triassic limestone (Wettersteinkalk).

framework were *Tubiphytes*, calcisponges, bryozoans and various calcareous algae. Caverns and niches were inhabited by foraminifers, distinct sphinctozoans and *problematica*. Among the reef dwellers were echinoderms, ostracods, molluscs, brachiopods. Within the reef Brandner and Resch (1981) distinguished different reef biocoenoses: Codiacean Algae B., *Tubiphytes* B., Calcisponge B., *Thecosmilia*-Calcisponge B. and Coral-Echinoderm-*Tubiphytes* Biocoenosis.

Main cementation of the reef was preceded by an early dolomitization phase during which hypersaline water from the lagoon seeped into the reef. Subsequently early diagenetic lagoonal influx caused cementation in the form of thick aragonite coatings which alternate with dolomite layers. These cements are also known as „Grossoolith“ (Fig. 5) .

3.2 Excursion stops

Along the trail from the station to the summit of Hafelekar (2334 m) the central reef complex and reef flat are exposed. On the eastern slope of Hafelekar different reef communities can be studied at outcrops along the trail. Immediately east of the point where the trail meets the Goetheweg a coarse reef breccia is exposed (near the saddle). Along the trail back to the station *Tubiphytes* biocoenosis and very large Grossoolith structures (cements) are exposed (for details see Brandner and Resch, 1980 and 1981).

Fig. 5: Large Grossoolith structures exposed in a megabreccia along the trail south of Hafelekar Spitze (Goetheweg).

4 Excursion route part 2 – The Hötting Breccia

4.1 Introduction

Quaternary sediments that pre-date the last glacial maximum (i.e. are older than ca. 20 ka; Ivy-Ochs et al., 2008) are rare in an inner-alpine context, because such sediments are often eroded or only partly preserved and if present frequently buried below last glacial maximum and Holocene sediments and thus not directly accessible. A thick and complex sequence of Pleistocene slope deposits that contain a well preserved fossil flora – known as Hötting Breccia – occurs on the south-facing slopes of the Nordkette north of Innsbruck (Fig. 6). Only patches of this sediment succession are preserved and scattered over an area ~ 100 km^2 in size between ~ 650 and 1900 m asl. along the valley slope. The Hötting Breccia is subject of a long-standing scientific debate that dates back into the second half of the 19th century (see below). Yet, the absolute age and paleoclimatic significance of this deposit is still not precisely constrained, but recent geochronological research suggests that deposition of the Hötting Breccia dates back at least 167 ka (kilo years; Spötl et al., 2015). Furthermore, the red-colored debris flow facies of this Quaternary rock (the so-called Red Hötting Breccia) has been quarried extensively since the late medieval age and the Red Breccia is thus frequently encountered as building material in the historical old town of Innsbruck.
A schematic summary-section of the Hötting Breccia is shown in Fig. 7. The sediment succession consists of (i) a basal lacustrine sediment

package comprising a diverse and well-preserved fossil flora of interglacial character ("Rossfall-Lahner interval", Penck, 1921; Murr, 1926; Sanders & Ostermann, 2006), (ii) alluvial fan deposits that grade upwards into lithified talus slopes (e. g., Penck, 1921; Sanders and Ostermann, 2006; Sanders, 2010) and (iii) loess-like silt layers that are intercalated in the alluvial fan unit between ~ 780 and 850 m asl. and record an apparently cool climate (e.g. contain loess snails; Penck, 1921). Furthermore, the Hötting Breccia is both, under- and overlain by lodgement till, with the upper till level clearly related to the last glacial maximum (Fig. 7). As such the Hötting Breccia has provided the key historical evidence for the multiple Quaternary glaciations of the Alps (Böhm, 1884; Penck and Brückner, 1909; Ampferer, 1914).

Lower Triassic red beds crop out between ~ 1040 and 1120 m asl. and the Rossfall-Lahner unit directly rests on these red beds. The sediments of the Rossfall-Lahner unit attain a thickness of ~ 20 m and are composed of (i) parallel-laminated lime mudstones from lacustrine background sedimentation, (ii) lime mudstones to calcarenites with graded laminae and ripple-drift cross lamination interpreted as deposits of density currents, and (iii) carbonate-lithic breccias and calciwackes that accumulated from cohesive debris flows and mud flows. The latter sediments are particularly rich in plant leaf imprints (e.g. *Rhododenron ponticum*) and other plant fragments indicative of a climate broadly similar or even warmer than today (Murr, 1926; Gams, 1936; Denk, 2006). This facies association is unique within the Hötting breccia sequence, and suggests sedimentation in a shallow ephemeral lake subject to depositional events sourced from nearby steep mountain slopes (Sanders and Ostermann, 2006). Part of the fame of the Hötting Breccia is based on this fossil flora that has a unique character that cannot be readily reconciled with the modern local flora or any known Pleistocene floras from an alpine or circum-alpine setting (Murr, 1926; Gams, 1936; Denk, 2006).

Erosion of the red beds is responsible for the reddish coloration of the lower part of the Hötting breccia (Red Hötting Breccia). The lithified talus slope and alluvial fan deposit that accumulated above these red beds are composed of carbonate

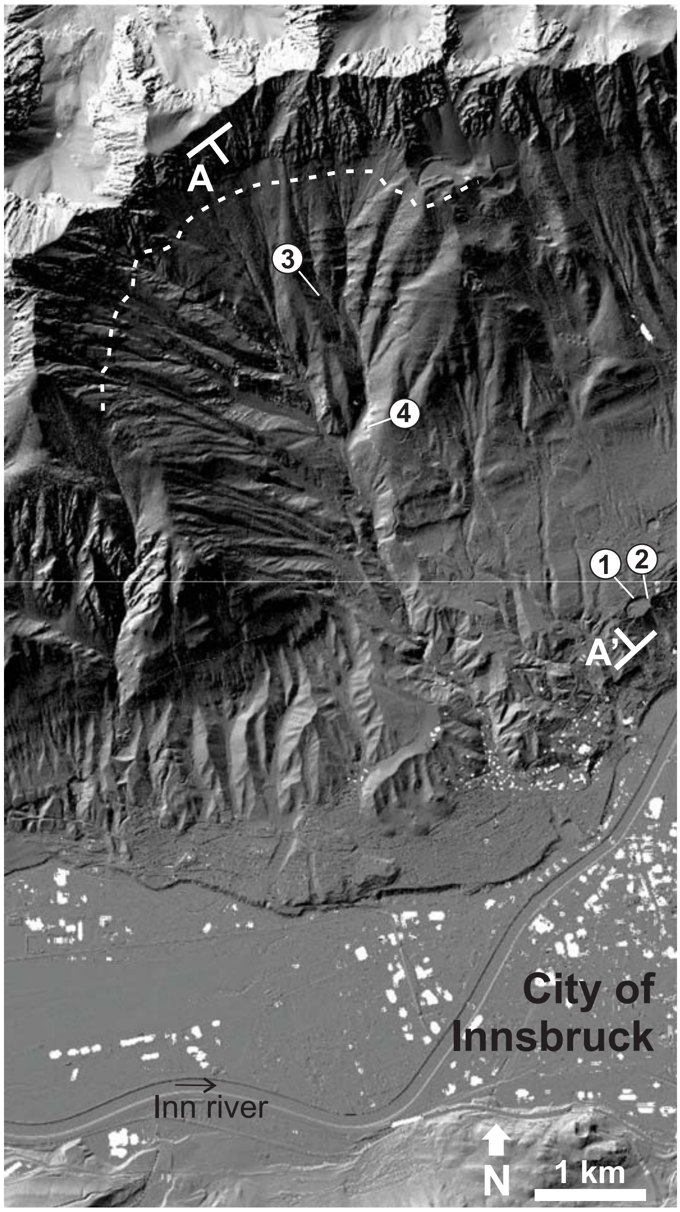

Fig. 6: Geomorphological overview of the Pleistocene talus-slope succession (Hötting Breccia) on the mountain slope north of Innsbruck (digital terrain model, Land Tirol, tiris, www.tirol.gv.at/tiris). The numbers refer to sites with numerical age control as described in the text and correspond to the numbers in Fig. 7. Site 1: Calcite speleothems precipitated in vertical cracks in the lower alluvial fan unit (i.e. the Red Breccia); Site 2: Loess-like silt layers intercalated into the Red Breccia; Site 3: Calcite cement precipitated in pores of lithified talus slopes (White Breccia); Site 4: Fossiliferous lacustrine to peri-lacustrine sediments ("Rossfall-Lahner interval"). The schematic summary section in Fig. 7 is approximately drawn along the profile line A – A´. The dashed line demarcates the highest preserved onlap of talus deposits on the carbonate cliffs.

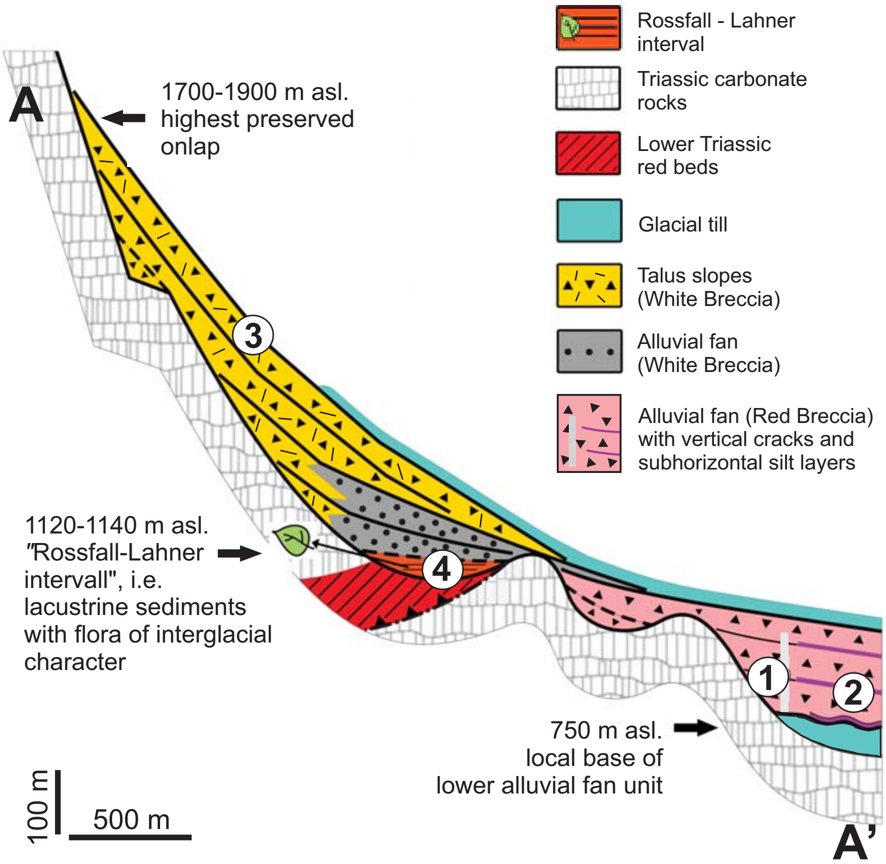

Fig. 7: Schematic and vertically exaggerated summary section of the Hötting Breccia (compare Fig. 6 for profile line A – A´ and sites numbers). From Sanders (2010), modified.

rocks only and thus white in color, hence frequently referred to as the White Hötting Breccia. The last two stops of this excursion are in the Red Hötting Breccia and will focus on (i) the contact between the Red Breccia and the underlying lodgement till (stop Lepsiusstollen; Fig. 1), and (ii) the occurrence of loess-like layers in the alluvial fan facies of the Red Breccia and the latest efforts to date the depositional age of this sediment sequence (stop Mayr´scher Steinbruch; Fig. 1).

4.2 Excursion stop Lepsiusstollen

This outcrop is situated in the eastern Weiherburggraben north of the Alpenzoo. The oldest layers of the Red Hötting Breccia are exposed and consist of individual cohesive to cohesionless debris flow layers. These debris flows were deposited onto a pre-existing moraine topography composed of lodgement till (Grundmoräne). A thin layer of fine-grained sediment is intercalated at the boundary between the Breccia and the lodgement till (also referred to as Streifenlehm), suggesting that a thin loess layer was draping the moraine topography before debris flow accumulation commenced. The lodgement till contains striated clasts that are mainly composed of limestone and dolomite.

The Lepsiusstollen (Lepsius adit, also known as Geologenstollen) has been excavated into this basal contact of the Red Hötting Breccia in order to settle a scientific dispute regarding the nature of ice ages. At the turn from the 18th to the 19th century the recurring nature of ice ages was not a commonly accepted theory (Penck, 1882) and the sediment succession of the Hötting Breccia provided a unique opportunity to test whether one or multiple glaciations have occurred in the geological past. It was well established that the Hötting Breccia is overlain by lodgement till (indicating large-scale glaciation), but providing unambiguous evidence that the Breccia is also stratigraphically *underlain* by a second lodgement till would lend strong support to the multiple glaciation theory. In 1913, this dispute was finally resolved via the construction of a 20 m long adit (funding obtained by L. Lepsius), showing that this lower till layer is indeed underlying the Hötting Breccia and must therefore be older (Lepsius, 1913; Ampferer, 1914).

4.3 Excursion stop Mayr´scher Steinbruch (Mayr quarry)

In this quarry (abandoned in the early 20th century) the Red Breccia is intercalated with up to 20 cm thick layers of loess-like sediment. The west facing quarry cliff is used as a crag for ambiguous local climbers (most routes rated from 6a to 7c+ according to French grading system) and also provides the main outcrop with an approximate height of 40 m. In the quarry slightly bedded breccia beds up to 10 m in thickness and composed of cohesive debris flows and conglomeratic breccias can be observed. The loess-like layers are composed of polymicitic silt to fine sand composed of subangular to subrounded grains that are draped over their substrate and locally show lamination and ripple-drift cross-laminasets. These fine-grained sediments are interpreted as aeolian in origin but were obviously re-deposited, probably via sheet flow events (Ladurner, 1956; Obojes, 2003). Penck (1921) reported loess snails from these layers, albeit from outcrops in the nearby Höttinger Graben that are presently not accessible.

4.4 Chronology and paleoenvironmental interpretation

The age of the Hötting Breccia has been classically ascribed to the Riß-Würm Interglacial based on (i) the interglacial character of the fossil flora encountered in the Rossfall-Lahner interval, and (ii) the occurrence of lodgement till stratigraphically below and above this clastic sediment succession (with the lower till layer assumed to be the Riß glacial moraine while the upper till layer belongs to the Würm glacial; Ampferer, 1914; Penck, 1921). However, only with the advent of modern dating techniques was it possible to test any such tentative age relations. The first reliable minimum ages for the alluvial fan unit (Red Breccia) were provided by Spötl and Mangini (2006), and Spötl et al. (2015), who applied $^{234}U/^{230}Th$ dating to flowstones (calcite speleothems) that precipitated in vertical cracks in the breccia (location 1 in Fig. 6). Flowstone formation occurred at 167±2 ka, from 100.5±1.5 ka to 70.3±1.8 ka and during the Holocene (Spötl and Mangini, 2006; Spötl et al., 2015), implying that deposition and lithification of the alluvial fan unit must have been completed before 167 ka (Spötl et al., 2015). For a sample of calcite cement precipitated in pores of lithified talus at ~ 1460 m asl., Ostermann (2006) determined a $^{234}U/^{230}Th$ errorchron age of 109±7 ka (location 3 in Fig. 6), and thus provided a minimum age for scree-slope accumulation from the upper part of the Hötting Breccia.

Gemmell and Spötl (2009) conducted an OSL study on the loess-like silt layers that are intercalated into the alluvial fan unit at the Mayr quarry (location 2 in Fig. 6). They extracted coarse-grained quartz and polymineral fine grains from these silt layers but both, coarse and fine grain data scattered widely and age underestimations and age inversions were common, giving reason to treat the resulting optical ages (ca. 30 < 105 ka) with caution. More recently, modified dating protocols were applied to the Rossfall-Lahner interval, including a single-grain OSL approach on coarse-grained quartz, and a minimum age of 203±22 ka was obtained for these lacustrine sediments (Meyer and Sanders, 2016; submitted).

The thick succession of alluvial fans and talus slope deposits cannot be reconciled with modern sedimentary dynamics at Nordkette or elsewhere in the Alps. Enhanced weathering under periglacial conditions is the most likely mechanism to stimulate scree production significantly and allow a sediment succession like the Hötting Breccia to accumulate. This interpretation is in-line with the occurrence of loess-like layers containing loess snails that are interbedded with the debris flow layers. The fossil flora of the Rossfall-Lahner interval clearly calls for warm (interglacial) conditions and is thus in stark contrast to these loessic and coarse clastic sediments. The sedimentary record in combination with the currently available age control thus suggest (i) localized lacustrine sedimentation ca. 203±22 ka ago (i.e. during the interglacial marine isotope stage 7 or even an earlier interglacial; Meyer and Sanders, 2016), followed by (ii) deposition of talus and alluvial fan sediments under subsequent deteriorating climatic conditions (possibly during the marine isotope stage 7/6 transition). Further dating efforts are required to substantiate this preliminary chronological scenario.

References

Ampferer, O., (1914): Über die Aufschließung der Liegendmoräne unter der Höttinger Brekkzie im östlichen Weiherburggraben bei Innsbruck. Zeitschrift für Gletscherkunde 8, 145-159.

Böhm, A., (1884): Die Höttinger Breccie und ihre Beziehungen zu den Glacial-Ablagerungen. Jahrbuch der Geologischen Reichsanstalt 34, 147-162.

Brandner, R. (1984): Meeresspiegelschwankungen und Tektonik in der Trias der NW-Tethys. Jahrbuch der Geologischen Bundesanstalt 126, 435-475.

Brandner, R. and Resch, W. (1980): Mid-Triassic Carbonate Platform Margin. Wetterstein Reef Limestone north of Innsbruck, Tyrol. Abhandlungen der Geologischen Bundesanstalt 34 (Outline of the Geology of Austria and selected excursions), 300-305.

Brandner, R. and Resch, W. (1981): Reef development in the Middle Triassic (Ladinian and Cordevolian) of the Northern Limestone Alps near Innsbruck, Austria. In: Toomey, D.F. (ed), European Fossil Reef Models, SEPM Special Publication 30: 203-231.

Brandner, R., Resch,W. & Reiter, F. (2003): Das Brennermesozoikum. Sedimentäre Faziesentwicklung in metamorphen Gesteinen und tektonische Konsequenzen. Geologische Bundesanstalt, Arbeitstagung 2003, Blatt 148 Brenner: 95-110.

Denk, T. (2006): Rhododendron ponticum L. var. sebinense (SORDELLI) SORDELLI in the Late Pleistocene flora of Hötting, Northern Calcareous Alps: witness of a climate warmer than today? Veröffentlichungen des Tiroler Landesmuseums Ferdinandeum 86, 43-66.

Enzenberg, M. (1966): Die Geologie der Tarntaler Berge (Wattener Lizum), Tirol. Mitt. Ges. Geol. Bergbaustud. 17: 5-50.

Fügenschuh, B. & Mancktelow, N.S. (2003): Brennerabschiebung und Kinematik im Bereich der Periadriatischen Naht. Geologische Bundesanstalt, Arbeitstagung 2003, Blatt 148 Brenner: 125-126.

Gams, H. (1936): Die Flora der Höttinger Breccie. In: G. Götzinger (ed.), Führer für die Quartär-Exkursionen in Österreich (III. Internationale Quartär-Konferenz, Vienna 1936), vol. 2, pp. 67-72.

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

Hoinkes, G & Thöni, M. (1993): Evolution of the Ötztal-Stubai. Scarl-Campo and Ulten Basement Units. In: Raumer, von J.F. & Neubauer, F. (eds), Pre-Mesozoic Geology in the Alps, Springer, Berlin: 485-494.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, W.P. and Schlüchter, C. (2008): Chronology of the last glacial cycle in the European Alps. Journal of Quaternary Science 23, 559-573.

Krainer, K. (1990): Ein Beitrag zum Oberkarbon der Steinacher Decke („Karbon des Nößlacher Joches“, Tirol). Mitt. Ges. Geol. Bergbaustud. Österr. 36: 87-99.

Krois, P. & Stingl, V. (1989): Die stratigraphische Neueinstufung der basalen klastischen Gesteine im Brennermesozoikum (Stubaier Alpen/Tirol).– Zentralbl. Geol. Paläontol., Teil I, 1989 (9/19):1455-1466.

Kübler, H. & Müller, W. (1962): Die Geologie des Brenner-Mesozoikums zwischen Stubai- und Pflerschtal (Tirol). Jahrb. Geol. B.-A. 105: 173-242.

Lepsius, R. (1913): Die Höttinger Breccie. Naturwissenschaften 1, 1122–1127.

Ladurner, J. (1956): Mineralführung und Korngrößen von Sanden (Höttinger Breccie und Umgebung). Tschermaks Mineralogisch-Petrographische Mitteilungen 5, 102-109.

Mandl, G.W. (2000): The Alpine sector of the Tethyan shelf – Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. Mitt. Österr. Geol. Ges. 92, 61-77.

Meyer, M.C. and Sanders, D. (2016). Luminescence dating of the Hötting Breccia (Eastern Alps) using single grains of quartz and comparison with post-IR-IRSL and IRSL ages on polymineral fine grains. Quaternary Geochronology, submitted.

Murr, J. (1926): Neue Übersicht über die fossile Flora der Höttinger Breccie. Jahrbuch der Geologischen Bundesanstalt 76, 153-170.

Obojes, U. (2003): Quartärgeologische Untersuchungen an den Hängen der Innsbrucker Nordkette (Höttinger Breccie). Unpublished Diploma thesis, Univ. Innsbruck.

Penck, A. (1882): Die Vergletscherung der deutschen Alpen, ihre Ursachen, periodische Widerkehr und ihr Einfluss auf die Bodengestaltung. 483 pp., Leipzig (J.A. Barth).

Penck, A. and Brückner, E. (1909): Die Alpen im Eiszeitalter vol. 1., 393 pp, Leipzig.

Penck, A. (1921): Die Höttinger Breccie und die Inntalterrasse nördlich Innsbruck. Sitzungsberichte der preussischen Akademie der Wissenschaften, physikalisch-mathematische Klasse 1921, 1–136.

Rockenschaub, M., Kolenprat, B. & Nowotny, A. (2003a): Das westliche Tauernfenster. Geologische Bundesanstalt, Arbeitstagung 2003, Blatt 148 Brenner, 7-38.

Rockenschaub, M., Kolenprat, B. & Nowotny, A. (2003b): Innsbrucker Quarzphyllitkomplex, Tarntaler Mesozoikum, Patscherkofelkristallin. Geologische Bundesanstalt, Arbeitstagung 2003, Blatt 148 Brenner, 41-58.

Rockenschaub, M., Brandner, R., Decker, K., Priewalder, H. & Reiter, F. (2003c): Geologie und Tektonik westlich des Wipptales. .– Geologische Bundesanstalt, Arbeitstagung 2003, Blatt 148 Brenner: 79-94.

Sanders, D., Ostermann, M. (2006): Depositional setting of the sedimentary rocks containing the "warm-interglacial" fossil flora of the Höttinger Brekzie (Pleistocene, Northern Calcareous Alps, Austria): a reconstruction. Veröffentlichungen des Tiroler Landesmuseums Ferdinandeum 86, 91-118.

Sanders, D. (2010): Sedimentary facies and progradational style of a Pleistocene talus-slope succession, Northern Calcareous Alps, Austria. Sedimentary Geology 228, 271-283.

Schmid, S.M., Fügenschuh, B., Kissling, E. & Schuster, R. (2004): Tectonic map and overall architecture of the Alpine orogen. Eclogae geol. Helv. 97, 93-117.

Schmidegg, O. (1949): Der geologische Bau der Steinacher Decke mit dem Anthrazitkohleflöz am Nößlachjoch (Brenner-Gebiet). Veröff. Mus. Ferdinandeum 26/29 (jg. 1946/49), 1-19.

Spötl, C. & Mangini, A. (2006): U/Th age constraints on the absence of ice in the central Inn Valley (Eastern Alps, Austria) during Marine Isotope Stages 5c to 5a. Quaternary Research 66, 167-175.

Spötl, C., Mangini, A., Cheng, H. (2015): Radiometric constraints on the age of the Hötting Breccia (Innsbruck, Austria). Zeitschrift für Gletscherkunde und Glazialgeologie 47/48, 135-146.

Tollmann, A. (1976): Analyse des klassischen nordalpinen Mesozoikums, Teil II, Stratigraphie,Fauna und Fazies der Nördlichen Kalkalpen. Franz Deuticke, Wien, 576p.

Tollmann, A. (1977): Geologie von Österreich. Band I Die Zentralalpen. Franz Deuticke, Wien 766p.