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Mesozoic slope-aprons and submarine fans in the NE Tauern Window (Austria)

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KEYWORDS

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Abstract

Several coarse grained metasediment units with preserved primary sedimentary structures were investigated within and in the surroundings of the Penninic Tauern Window. In its NE part - the central area of the study, breccias and conglomerates form elongated lenses a few kilometres in length, composed of multiple layers separated by erosional boundaries. Most of the breccias and conglomerates are matrix-supported, but a few are clast-supported. They were mainly deposited by debris flows and to a lesser extent by high-concentration turbidity currents. Various coarse-grained to fine-grained, thick- to thin-bedded turbiditic sandstones occur west of the breccias. They are interpreted as turbidity current deposits. Some layers are contorted, probably due to syn-sedimentary slumping. The entire organization of the bedforms implies that the coarse-grained sediments represent mainly fault controlled slopea-prons and the more fine-grained sandstones submarine fans, respectively. Black shales and mudstones that separate the breccias, conglomerates and sandstones are regarded as slope and/or base-of-slope to hemipelagic sediments.

Additionally, observations from other areas e.g. Penken, Tarntal and Radstadt Mountains, show breccias and conglomerates formed as slope-aprons. Breccias from Richbergkogel display features of both slope-apron and submarine fan. Large elongate blocks of dolomite and limestone cropping out along the northern and southern margins of the Tauern Window were derived mainly from units to the south containing Triassic carbonate platform sediments and represent olistoliths.

Our findings suggest that the slope-aprons and the submarine fans were related to the development of the southern margin of the Penninic Ocean and reflect its diachronous opening lasting from Middle Jurassic to Early Cretaceous. Moreover, the mass transport deposits from the Matrei Zone indicate the beginning of the ocean closure which is supposed to have taken place in the late Early Cretaceous.

Im penninischen Tauern Fenster und seinem Rahmen wurden grobkörnige Sedimente mit erhaltenen Primärstrukturen neu untersucht. Im nordöstlichen Tauern Fenster, dem zentralen Untersuchungsgebiet, bestehen diese häufig aus Breccien, sowie aus Konglomeraten. Sie bilden einige Kilometer lange Linsen, die aus mehreren Lagen bestehen und durch erosive Grenzen voneinander getrennt sind. Die Mehrheit der Breccien ist matrixgestützt, komponentengestützte Breccien treten nur untergeordnet auf. Synsedimentäres Slumping ist in einigen Lagen noch erkennbar. Die Breccien wurden im Allgemeinen als Schuttströme, seltener als hochkonzentrierte Turbiditströme abgelagert. In metamorphen Sandsteinen, die zumeist westlich der Breccien abgelagert wurden, finden sich alle Formen von grobkörnigen zu feinkörnigen und massiven zu dünn-gebankten Turbiditen. Die Architektur der Schichtgeometrien spricht dafür, dass die feinkörnigen und grobkörnigen Sedimente vorwiegend störungskontrollierte „slope-aprons“ und in geringerem Ausmaß submarine Fächer darstellen. Schwarzschiefer und Tone, die die einzelnen Sandstein- und Breccienlagen trennen, sind hemipelagische Hang- bzw. Hangbasissedimente.

Breccien und Konglomerate in anderen Gebieten, z. B. am Penken, in den Tarntaler Bergen oder in den Radstädter Tauern, werden ebenfalls als „slope-aprons“ interpretiert, diejenigen vom Richbergkogel zeigen auch Anzeichen submariner Fächer. Zusätzlich finden sich an beiden Rändern des Tauern Fensters, im Süden und im Norden, große ausgelängte Dolomit- und Kalkschollen. Zumindest ein Teil davon sind Olistholithe, die von einer südlich gelegenen Zone mit triadischen Karbonatplattform Sedimenten hergeleitet werden können.

Die „slope-aprons“ und submarinen Fächer hängen genetisch mit der Entwicklung des Südrandes des Penninischen Ozeans zusammen und spiegeln die Öffnungsphase vom Mittleren Jura bis in die Frühe Kreide wider. Die grobklastischen Sedimente der Matreier Zone könnten dagegen bereits den Beginn der Schließung des Penninischen Ozeans in der zu Ende gehenden Frühen Kreide anzeigen.

1. Introduction

Apart from the Foreland, the Eastern Alps are divided in three large tectonic units, i.e. the Helvetic, the Penninic and the Austroalpine units. The most complete sequence of the Penninic is found in the Tauern Window (TW), which is framed by the tectonically higher Austroalpine units, in particular the Lower Austroalpine ones, in its NW and NE parts (Fig. 1).

Traditionally, the Penninic realm of the TW is subdivided into the structurally lower Venediger nappe system, and the higher Glockner nappe system (Staub, 1924; Frisch, 1976). The former consists of the pre-Variscan Habach Group, a Variscan crystalline basement and a Permo-Mesozoic cover, including the Kaserer Formation. The pre-Variscan Habach Group and the Variscan crystalline basement are intruded by Variscan granitoids, now termed Central Gneiss (Fig. 1). The Glockner nappe system contains the majority of the Mesozoic Bündnerschiefer and ophiolites and a large part of Permo-Mesozoic coarse clastic sequences. The Seidlwinkl nappe, build up by metamorphosed Permo-Mesozoic sediments and volcanics including the Brennkogel Formation, with an intermediate tectonic position between the Venediger and the Glockner nappe systems (Frisch, 1976), is now assigned to the former one (Pestal et al., 2009).

Schmid et al. (2004) include the Venediger nappe system into the Subpenninic nappes which are derived from the European continental margin of the Penninic Ocean. The Glockner nappe is subdivided into two units. The large area of the Bündnerschiefer and ophiolites represents in their opinion the Lower Penninic nappes in the TW.

The breccias and sandstones in the NE part of the TW (Figs. 1 and 2), those from Richbergkogel, the breccias from Penken and the Matrei Zone were previously regarded as Lower Austroalpine, but are seen now as part of the Penninic realm (Frasl and Frank, 1966; Thiele, 1980; Popp, 1984; Pestal et al., 2009). They represent the Upper Penninic nappes in the concept of Schmid et al. (2004). The remaining breccias and conglomerates, i.e. the Radstadt nappes and the Tarntal nappes, are assigned to the Lower Austroalpine units. These are divided again into two subunits: the former into Pleisling and the Hochfeind nappes, the latter into Reckner and Hippold nappes.

The Tauern Window as a whole was metamorphosed during the Cenozoic under greenschist and amphibolite facies conditions, overprinting earlier blueschist and eclogite facies events (Frank et al., 1987; Hoinkes et al., 1999; Schuster et al., 2004). All these led to recrystallization, transforming e.g. the black and green mudstones intercalated with thin-bedded sandstones into black and green (quartz)phyllites, the marly mudstones and sandy marls into calcschists, and the quartzitic sandstones into quartzites, respectively. In the following we will use the sedimentary terminology to emphasize the original lithology of these metasediments except where we refer to the actual lithology. The metamorphism and deformation changed the primary shape of grains and clasts. Some original structures, including the thickness, were overprinted and modified by foliation, large-scale folding, and recrystallization. However, mainly on a macroscopic to mesoscopic scale, the general lithology, some sedimentary structures and textures are still preserved. Nonetheless, the reconstruction of the original sedimentary sequence affinity and its interpretation remains difficult.

The metamorphosed Permo-Mesozoic formations in the Penninic Tauern Window (TW) and its surroundings (Fig. 1) are in many places dominated by coarse clastic metasediments such as breccias, conglomerates and sandstones. Their lithologic and stratigraphic importance was already recognized by Kober

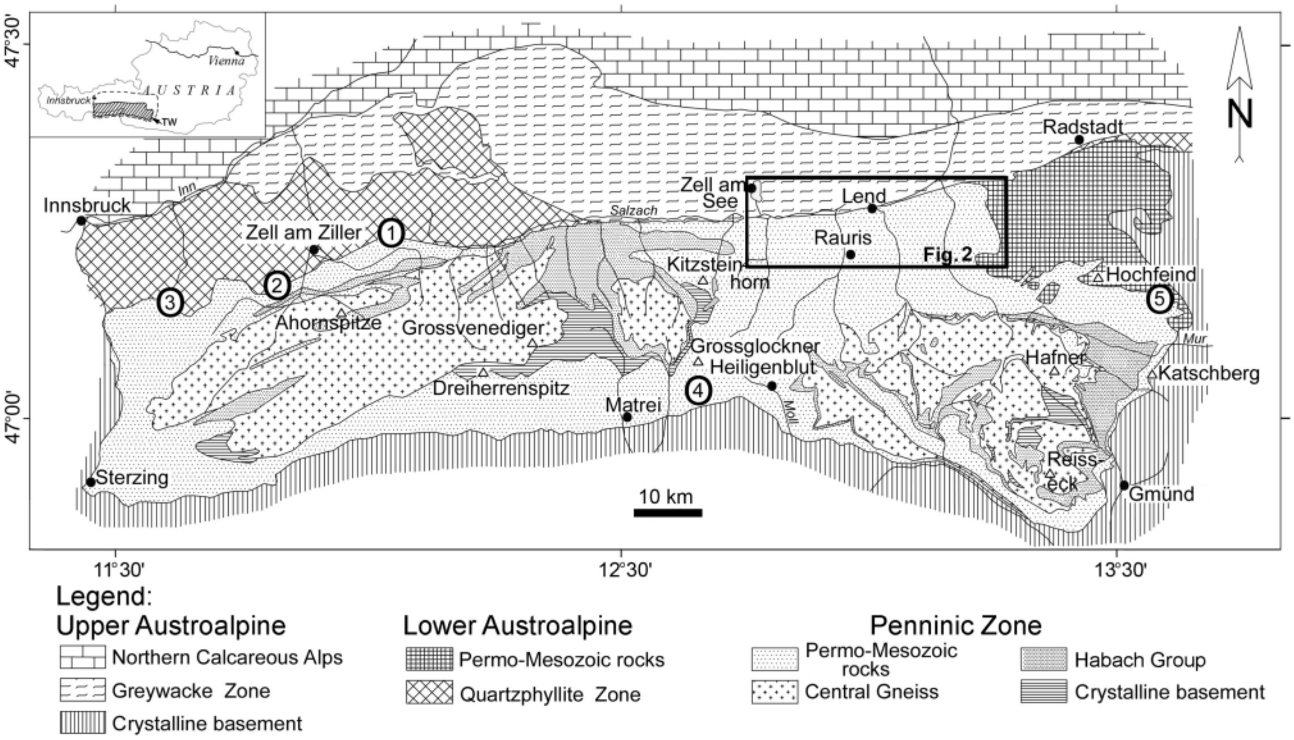

Figure 1: Geological sketch map of the Tauern Window and the surrounding areas (modified from Höck et al., 2009). The insert in center-right marks the study area displayed in more detail in Fig. 2. Further localities discussed in the text are: 1 – Richbergkogel, 2 – Penken, 3 – Tarntal Mountains, 4 – Matrei Zone, 5 – Radstadt Mountains. The upper left insert shows the location of the map within Austrian territory. TW – Tauern Window.

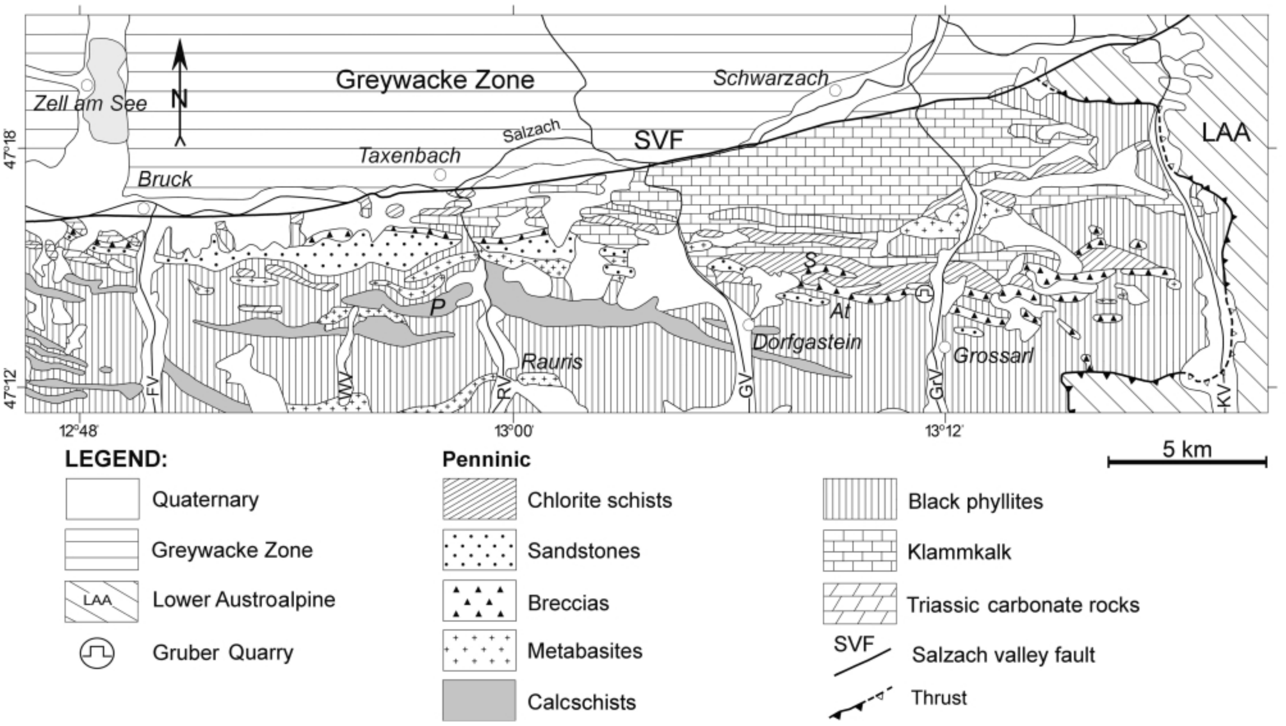

Figure 2: Geological sketch map of NE Tauern Window based on Exner (1979), Peer and Zimmer (1980) and our own field data. Abbreviations: FV – Fusch valley, WV – Wolfbach valley, RV – Rauris valley, GV – Gastein valley, GrV – Großarl valley, KV – Kleinarl valley, S – Schuhflicker, P – Plattkopf, At – Arltörl, LAA – Lower Austroalpine.

(1928). Furthermore, the research focused on various breccias and conglomerates in the Radstadt Mountains (Fig. 1, locality 5; Clar, 1937a,b,c), the Tarntal Mountains (Fig. 1, locality 3; Clar, 1940) and in the area between Großarl and Fusch valleys (Fig. 2; Braumüller, 1939).

Other breccia-bearing areas include the Richbergkogel (Fig. 1; locality 1; Frisch and Popp, 1981; Popp, 1984), the Penken (Fig. 1, locality 2; Kristan-Tollmann, 1961), and the Matrei Zone (Fig. 1, locality 4; Cornelius and Clar, 1939; Schmidt, 1950, 1951, 1952; Frisch et al., 1987). The breccias of the Brennkogel Formation (Cornelius and Clar, 1939; Frasl and Frank, 1966) and the Kaserer Formation (Höck, 1969; Thiele, 1970, 1974, 1976; Ledoux, 1984) are not considered here.

Since Kober (1928) the age of the breccias and conglomerates is believed to be Early Jurassic, based mainly on the assumption that most of the dolomite clasts and pebbles are derived from an originally southerly situated Triassic carbonate platform. The second line of evidence comes from the similarity to the dated Lower Austroalpine breccias in the Tarntal and Radstadt Mountains, underlain by Upper Triassic limestones and dolomites and covered by Middle to Upper Jurassic limestones, siliceous shales and radiolarites (Tollmann, 1977; Häusler, 1988).

This study aims to reconstruct the original depositional environment and processes in a regionally metamorphosed part of the Penninic realm. We focus here on the clastic metasediments exposed in the north-eastern part of the TW, between the Großarl valley and the Fusch valley (Figs. 1 and 2). Additional observations in the Richbergkogel, Penken, Tarntal and Radstadt areas (localities 1, 2, 3 and 5 in Fig. 1) as well as in the Matrei Zone (Fig. 1, locality 4) are included.

2. Study Areas

2.1 NE Tauern Window

2.1.1 Geological setting

The NE part of the Tauern Window (Fig. 2) between the Fusch valley in the west and the Großarl valley in the east is part of the Upper Penninic nappes (Schmid et al., 2004). It includes the “Sandstein-Breccien-Decke” sensu Braumüller (1939), or the “Nordrahmen Zone” of Cornelius and Clar (1939) and Pestal et al. (2009), and part of the “Fusch Facies” of Frasl and Frank (1966). Prey (1975, 1977) referred to the lithology of this area as “Tauernflysch”, emphasizing the typical flysch-like sedimentary structures. Here we use the name Sandstone-Breccia nappe (SBN), for the “Sandstein-Breccien-Decke” of Braumüller (1939). The sedimentary succession according to Exner (1979) and Peer and Zimmer (1980) comprises mainly limestones, mudstones intercalated with thin-bedded sandstones, quartzitic sandstones, dolomite- and limestone conglomerates, breccias and black mudstones intercalated with thin-bedded sandstones. Between sedimentary rocks, small lenses of serpentinite and more extended sills of metagabbros are found in places.

The dominant rock types in the northern part of the investigated area are the bluish-greyish limestones (Klammkalk) that wedge out just west of the Rauris valley (Fig. 2). South of the main body of Klammkalk and west of the Rauris valley, the metamorphic rocks are represented by lens-shaped dolomitebearing breccias and conglomerates, black phyllites, chlorite-quartz-schists and graded sandstones with phyllites (Ślączka and Höck, 2000; Hoeck and Ślączka, 2001). The southern part of the area is built up by black phyllites ("Rauris phyllites" according to Frasl, 1958).

Reitz et al. (1990) described spores in the black phyllites associated with the Klammkalk, and with quartzites, conglomerates and breccias. The spores are regarded as post-lower Early Cretaceous but pre-Late Cretaceous in age (Reitz et al., 1990). The identification of Saccocoma sp. in a clast of our breccia samples (Gruber quarry, Großarl valley; Fig. 2), indicates that Late Jurassic (Kimmeridgian) limestones were the source of some of the clasts.

2.1.2 Facies analysis

Klammkalk lithofacies

The Klammkalk forms an elongated lithosome with a maximum thickness between the Großarl and the Kleinarl valleys where it reaches 3,000 m (Fig. 2). However, the primary thickness is difficult to estimate because of the possible tectonic repetition of the original sequence. The lithosome consists of individual limestone lenses, each up to several hundreds metres in width. West of the Gastein valley, the lithosome is drastically reduced by a factor of 5-6 (compare geological map of Exner, 1979). Only a few limestone layers, up to 20 - 50 m thick occur between several types of mudstones. The total visible length of the Klammkalk lithosome is approximately 30 km.

The Klammkalk is mainly represented by bluish-grey recrystallized limestones occasionally grading into calcareous mudstones. The limestones are mostly massive and homogenous and consist of fine-grained calcite, although some layers have grains of quartz, K-feldspar and rarely plagioclase. Sporadic laminations, rare small, millimetre-sized intraclasts and local grading are noticed as well.

Breccia and conglomerate lithofacies

Breccias and conglomerates occur in two main lithofacies. They were firstly recognized by Peer and Zimmer (1980) in the area of Schuhflicker, a prominent mountain located between the Großarl valley and the Gastein valley (Figs. 2 and 3). The first lithofacies consists of grey-greenish conglomerates and breccias intercalated with mudstones. East of the Rauris valley, this litho-facies closely associated with the Klammkalk facies (Fig. 2; Fig. 4 - Schuhflicker profile, lower part) forms a continuous, elongated body, up to few hundreds of metres thick. Towards the west only small lenses of breccia occur.

Figure 3: Southern slope of Schuhflicker. The lowermost part of the mountain slope is built up of black phyllites (a). The middle part of the slope consists of calcschists (cropping out on the lower left side of the picture), breccias, black phyllites and quartzites (b). The summit of the mountain consists of Triassic dolomite olistoliths (c).

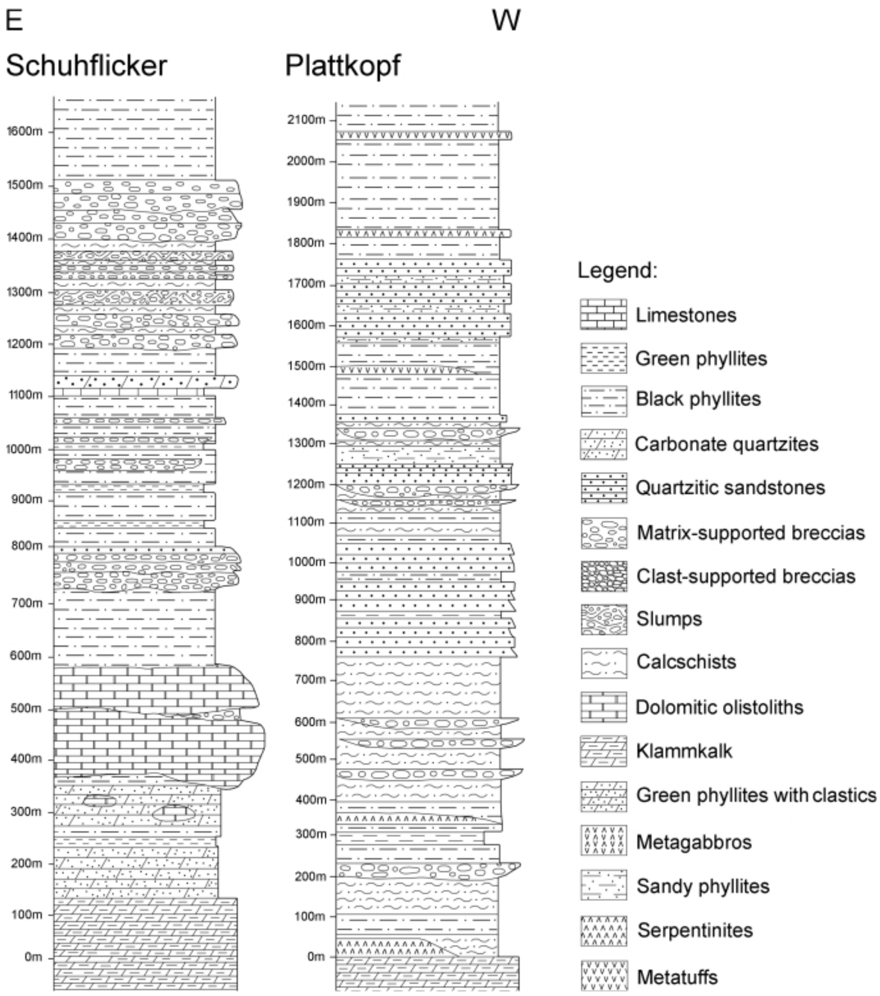

Figure 4: Schematic logs of the sedimentary sequences in the NE Tauern Window (the locations are shown in Fig. 2). The Schuhflicker log covers a large part of the eastern side in Fig. 3 and is representative for the breccia succession. The Plattkopf log is situated several kilometres further to the west and is representative for the sandstone succession.

The second, more common lithofacies is represented mainly by dolomitic conglomerate and breccia occurring farther to the south, outside the Klammkalk area (Fig. 2; Fig. 4 - Schuhflicker profile, upper part). Breccias and conglomerates of the second lithofacies grade into each other. This lithofacies prevails between the Kleinarl valley and the Gastein valley (Fig. 2). It is subdivided into several elongate, lens-shaped bodies up to few hundreds metres thick separated by thin mudstone intercalations, but locally they merge into a single unit. Farther to the west, the individual lenses display the same lithofacies but decrease in size.

For the characterization of the breccias and conglomerates of the second lithofacies we adopt in the following the classification scheme of Pickering et al. (1986, 1989). It describes sedimentary lithofacies in a more accurate and less ambiguous manner, allowing the comparison of features between different deep-water sediments. Breccias and conglomerates belong to the disorganized (A1) type and to the organized (A2) type. Commonly matrix-supported conglomerates (A1.3 – disorganized gravelly mud, A1.4 – disorganized pebbly sand, A2.7 – normally graded pebbly sand; A2.8 – graded-stratified pebbly sand; Fig. 5a) occur. Less common are clast-supported conglomerates (A1.1 – disorganized gravel; A2.1 – stratified gravel; A2.3 – normally graded gravel; Figs. 5b,c). Generally, they can be classified as debrites (Stow, 1985), together with rare debrite/turbidite couplets. Clast-supported conglomerates and breccias form either separate layers or, occasionally, the lower part of matrix-supported layers. Some beds up to few decimetres in thickness are internally contorted (F2 type – contorted/disturbed strata) and are bounded by normally stratified layers below and above (Fig. 5d). The lower boundaries of beds, where visible, are sharp. They are planar or channelized (Fig. 6a) and may display load and flame structures (Figs. 6b,c). The visible depth of the channels does not exceed 1 m and the width of a few metres. The conglomerates and breccias are lens-like in form and vary in thickness from a few decimetres to tens of metres, whereas the thicker beds are amalgamated.

The size of the clasts ranges from a few millimetres to several decimetres or even metres. They are usually ellipsoidal (Fig. 5d) and vary from commonly well rounded to angular (Figs. 5b,c). It is often difficult to tell whether the ellipsoidal shape is a primary feature or resulted from flattening during ductile deformation. However, the simultaneous occurrence of clasts with flat and angular shapes indicates that at least some of them were deposited in their present shape. They

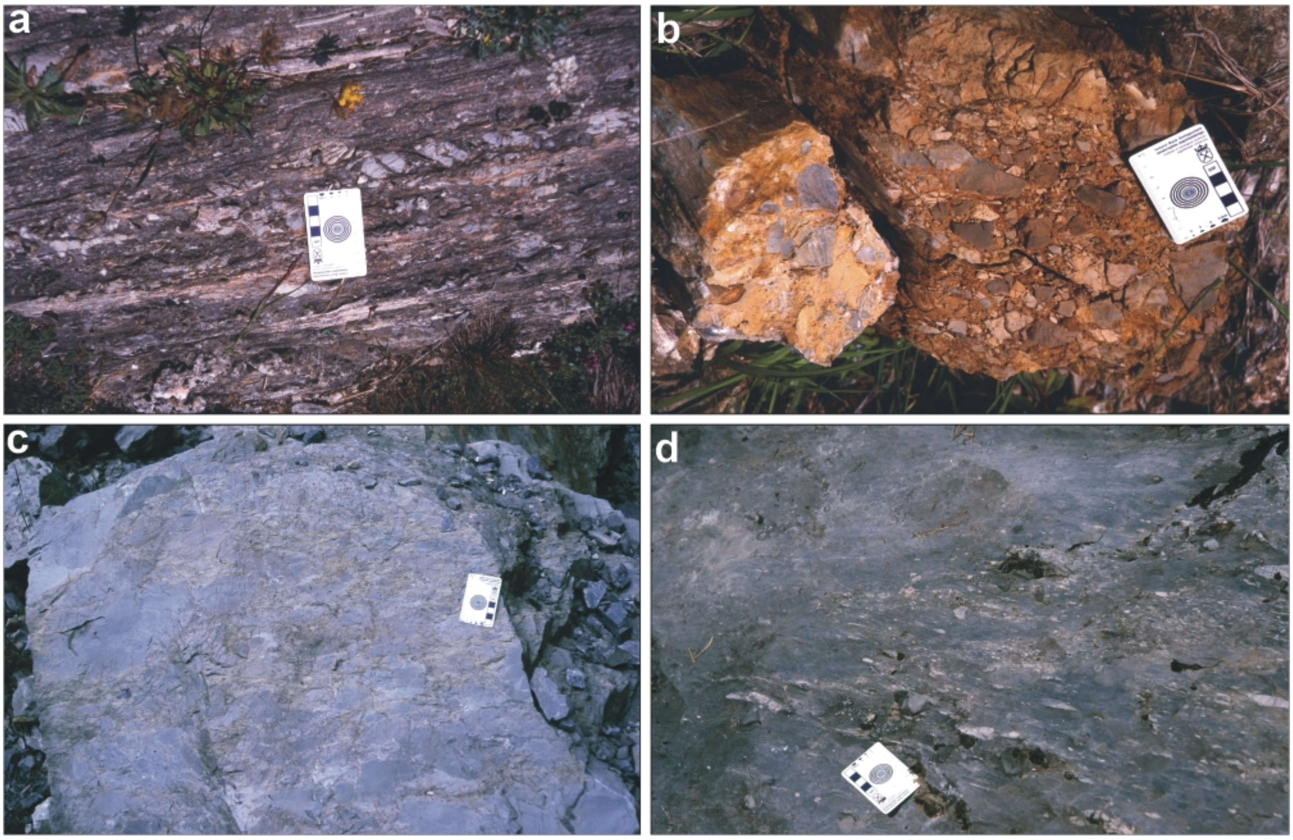

Figure 5: Photographs of various breccias. a) Laminated calcschist with subangular and angular clasts of dolomite, interpreted as debris flow deposits (southern slope of the Schuhflicker); b) Clast-supported, poorly sorted breccia deposit with angular clasts of yellowish dolomite and grey limestone. This disorganized breccia is representative for debris flow. The outcrop is located on the western slope of the Großarl valley; c) Clast-supported, poorly sorted breccia, mainly composed of angular limestone clasts. Some clasts are flattened, probably due to tectonic-metamorphic overprint. Location of the outcrop: Gruber quarry north of Großarl; d) Black phyllite with scarce fragments of dolomite and contorted layers of clast-supported conglomerate. Blocks are generally flattened. The small folds visible within the black phyllites resulted from submarine sliding. Outcrop on the southern slope of Schuhflicker.

are sporadically imbricated, dipping towards the east. The yellow dolomitic clasts are believed to be derived from Triassic dolomites, the light grey limestone from Jurassic carbonates. Occasionally, huge dolomite blocks, tens or hundreds of metres in diameter occur, particularly in the vicinity of the Großarl valley (e.g. Fig. 3; Fig. 4 - Schuhflicker profile). Breccias and conglomerates are interbedded with greyish calcareous mudstones, more rarely with black mudstones. The intercalations vary in thickness from a few to tens of metres. In some cases, the primary sedimentary laminae in mudstones are contorted.

A characteristic change was observed in the coarse clastic lithosome in the area of Schuhflicker, west of the Großarl valley. Individual layers are several metres thick, clasts-supported and disorganized breccias prevail (Fig. 2; Gruber quarry). The clasts display various shapes and are almost exclusively represented by greyish-white, occasionally grey or green limestone (Fig. 5c). Angular clasts are relatively common (Fig. 5d). The average size of the clasts is a few centimetres to decimetres, although larger blocks occur. Towards east and west of the Großarl valley, the breccias and conglomerates become matrix-supported and the clasts decrease in size and become less angular. The limestone clasts almost disappear and are replaced by dolomitic clasts. However, locally (e.g. west of Fusch) clast-supported, thick-bedded conglomerates with limestone are still present.

South of Schuhflicker the coarse clastic lithosome reaches its maximum thickness of 500-700 m. The primary thickness of this lithosome is difficult to determine as the primary bottom surface of the beds cannot be established. However, a part of the sequence is locally refolded.

Sandstone lithofacies

Sandstone beds occur through-out the area, generally south and west of the breccia and conglomerate facies (Fig. 2). Usually they are irregularly interbedded with pelitic deposits such as mudstones and sandy mudstones (Exner, 1979; Peer and Zimmer, 1980). The best outcrops are found in the Wolfbach valley (Figs. 7a-d). Between the Großarl and the Fusch valleys these sandstones form one or two distinct lithosomes. The upper sandstone lithosome (Fig. 2; Fig. 4 - Plattkopf profile) is relatively thick, up to 200 m and is mostly associated with black mudstones, locally with conglomerates. The lower sandstone lithosome is interbedded with conglomerates (Braumüller, 1939) and reaches a thickness of 300 m. Part of the sequence is folded, thus the thickness of the original sedimentary pile most likely did not exceed 100-150 m.

Most of sandstones are graded (Fig. 7b) and represent different groups of lithofacies, from coarse to fine grained, and from massive disorganized (B1.1 – thick/medium-bedded, disorganized sands, and B1.2 – thin-bedded coarse grained sands types of Pickering et al., 1986, 1989), to well organized (C.2 – organized sand-mud couplets). They vary from generally medium-bedded to thick-bedded (C2.2 and C2.1 types; Fig. 7c), although thin-bedded sandstones locally predominate (C2.3 type). Packages of thin-, medium-, and thick-bedded sandstones appear to be interbedded. The sandstone layers are separated by dark grey to black mudstones of variable thickness, from a few millimetres to a few decimetres. The ratio of sandstones to mudstones varies considerably. Some intervals consist of almost pure sandstone, in others sandstone and mudstone are of equal proportions, and finally there are

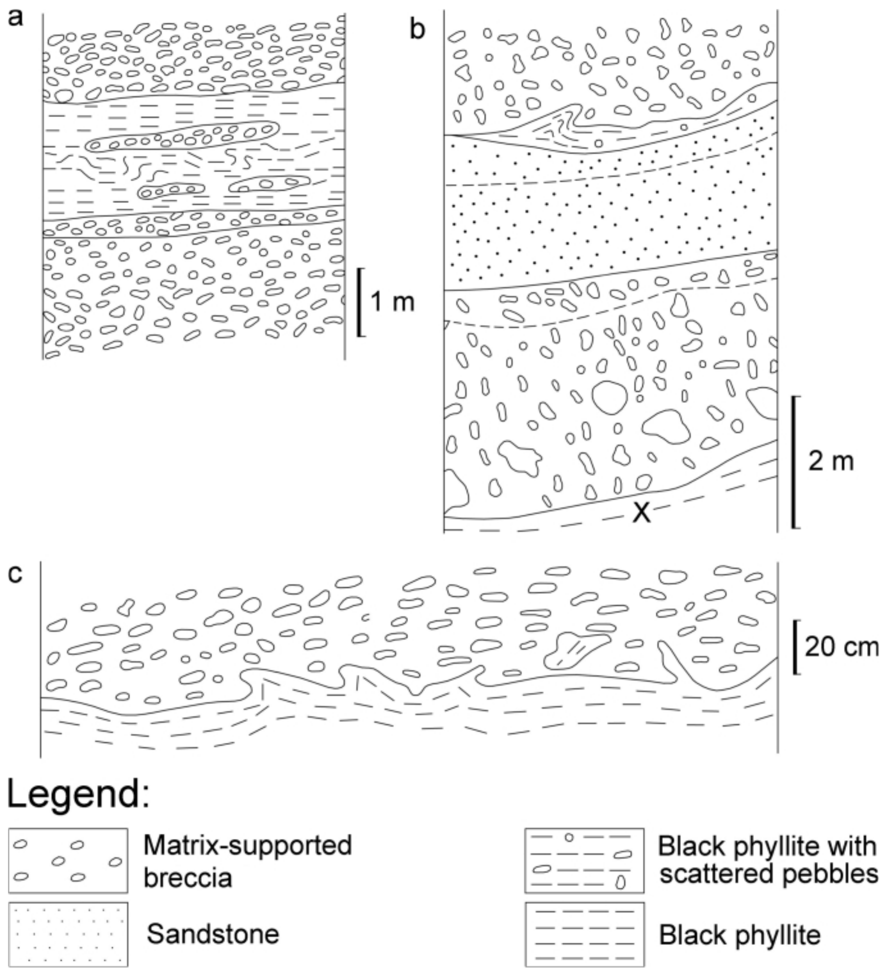

Figure 6: Sketch drawings of sedimentary structures within breccias in outcrops west of Großarl. a) Breccia interbedded with partially contorted calcschists with small breccia lenses. An erosional base of the upper breccia layer is visible. The contact between calcschists and the lower breccia is sharp. The lower breccia itself is normally graded; b) Breccia and sandstone with an erosional scour (x) and load structure. Thin internal lamination is visible in sandstone. The breccia above shows clast imbrication; c) Load structure in a breccia (normal stratigraphic position).

sections in which mudstone predominates over thin-bedded sandstone. Some of the sandstone layers display a sharp, uneven lower boundary with shallow, broad scours (Fig. 7c) and may grade upwards into mudstone. In a few cases we observed flute and drag marks (Fig. 7d), also noticed by Prey (1975, 1977). They indicate a direction of current from SW to NE. However, the original contacts between sandstone lithosomes and mudstone are obliterated by tectonic shearing.

The sandstone consists of quartz and feldspar grains set in a marly matrix. Commonly some dolomite pebbles are interspersed. The heavy minerals (in the grain size fraction between 0.12 and 0.60 mm) are dominated by zircon, tourmaline, rutile, apatite and hematite (see also Peer and Zimmer, 1980).

2.2 Breccia and conglomerate deposits in other areas

As outlined already in the Introduction, breccias and conglomerates are also known in other parts of the Tauern Window and in adjacent areas (Fig. 1; localities 1-5). The Richbergkogel (Fig. 1; locality 1), Penken (Fig. 1; locality 2) and Matrei (Fig. 1; locality 4) breccias and conglomerates are assigned to the Upper Penninic nappes (Schmid et al., 2004). The breccias and conglomerates of the Tarntal and Reckner areas (Fig. 1; locality 3) belong to the Tarntal nappes (Hippolt and Reckner nappe, respectively) of the Lower Austroalpine nappe system (Dingeldey et al., 1997; Schmid et al., 2004; Pestal et al., 2009). The breccias and conglomerates of Türkenkogel and Schwarzeck (Hochfeind nappe) as well as those of the Pleissling (Pleissling nappe) belong to the Radstadt nappe system of the Lower Austroalpine (Fig. 1; locality 5; Tollmann, 1977; Häusler, 1988).

The Richbergkogel Breccia is restricted to a relatively small area east of Zell am Ziller (Thiele, 1974; Popp, 1984). It has a total thickness of more than 300 m and consists of stacked lenses of coarse clastic rocks within black phyllites. The columnar profile (Fig. 8) shows details of the sequence, with prevalence of matrix-supported breccias and conglomerates. The clasts are mostly dolomite, but subordinately limestone and some crystalline components may occur. Their size varies from a few to tens of centimetres. Occasionally, the conglomerates contain large blocks (Fig. 9a), up to a few of decimetres. In the upper part of the sequence slump deposits occur. The thickness of individual clastic layers increases upwards in the

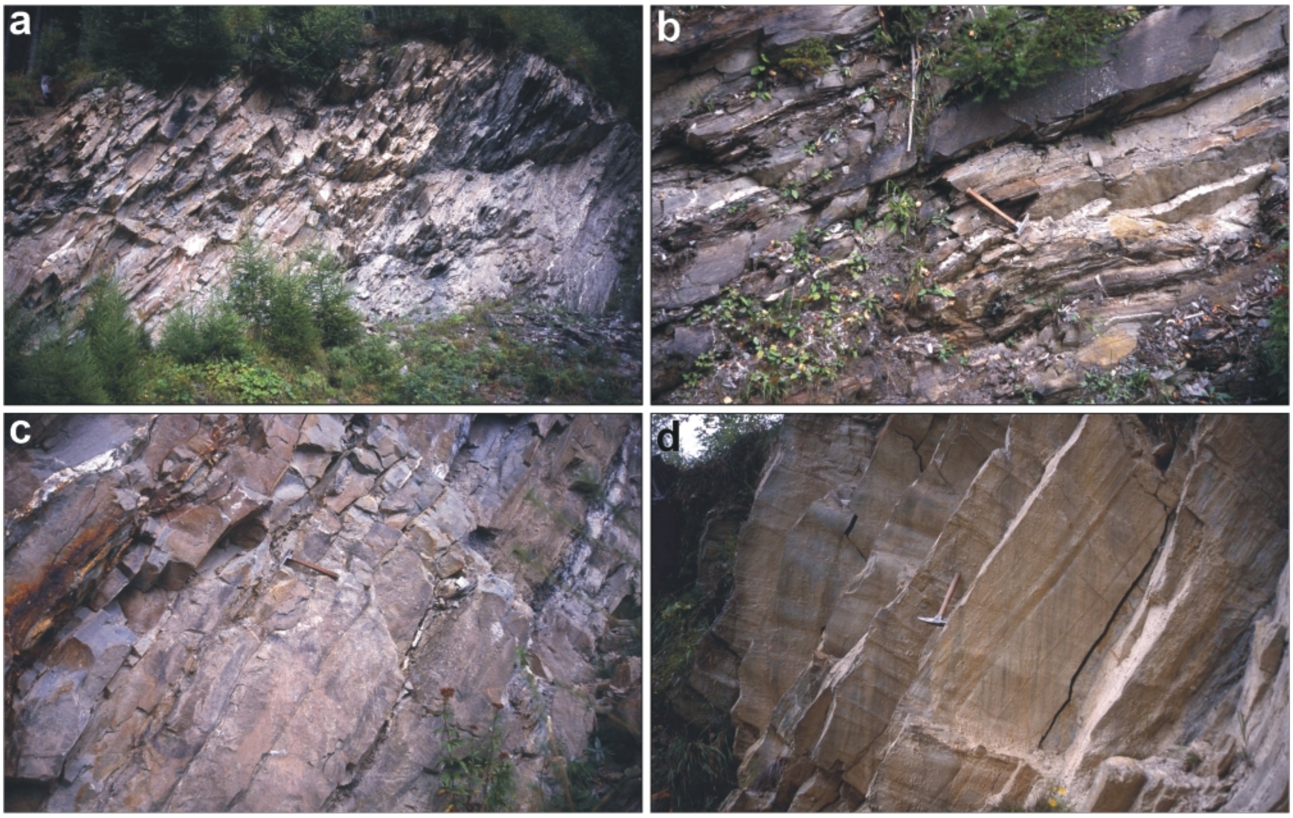

Figure 7: Photographs of sandstones cropping out on the eastern slope of the Wolfbach valley. a) General view of an association of medium- and thick-bedded sandstones. The base of sandstones is to the right, where they are underlain by black phyllites representing basinal deposits. Part of the sandstones displays graded bedding and uneven thickness. The latter is due to local erosional scours. These sediments are interpreted as turbidity current deposits. Spruces on the bottom of the outcrop are ca. 2 m high; b) Thin- to thick-bedded sandstone interbedded with black and green phyllite, interpreted as deposits of low- to medium-density turbidity currents. The sediments show lamination and are often lens- shaped in cross section. c) Medium- to thick-bedded sandstones, partly graded, practically devoid of fine-grained intercalations. In several places, small scours, up to few tens of centimetres wide, are visible. The stratigraphic base is to the right. This is an example of a sandy sequence from the internal part of a sandstone lobe or suprafan. d) Lower bottom surfaces of sandstones. The current structures running from the left to the right are represented by elongated scours, drag marks and V-shaped flute casts. The flute casts indicate a current direction from SW to NE. Scale: length of hammer is 40 cm.

profile. In general, a coarsening upward trend is observed, showing features of channel and lobe deposits (see also Popp, 1984).

There are no stratigraphic age constraints available for the Richbergkogel Breccia. However, the coarse clastic sediments are part of a sequence covering the Permo-Triassic carbonate and quartzitic rocks. Based on lithological comparison with the "Nordrahmenzone" in the NE Tauern Window as well as on paleogeographic and tectonic considerations, Popp (1984) concluded that the formation of the coarse clastic sediments (Richbergkogelzone) could have lasted until the end of the Early Cretaceous.

Another conglomerate-bearing sequence exposed still farther to the west, on the summit of Penken (location 2 in Fig. 1), consists of lens-shaped conglomerates and breccias. Matrix-supported sedimentary breccias up to several tens of metres thick prevail. They contain mainly blocks of Triassic dolomites and limestones, sometimes more than 100 m in diameter. Generally, the breccias display chaotic internal structures without grading and are interbedded with mudstones containing quartzose to arkosic layers. Less abundant are lenses of chaotic clast-supported breccias (Fig. 9b). The clasts (dolomite, limestone and rare gneiss) are angular to subrounded blocks ranging from tens of centimetres to several decimetres in size. They show imbrications that suggest that the clastic material was supplied from southern areas. The whole sequence of Penken coarsens upwards and ranges from arkosic sandstones to matrix-supported conglomerates. The map and the cross-sections of Kristan-Tollmann (1961) indicate that the conglomerate and breccia-bearing complex overlies Anisian-Ladinian dolomites and Lower Jurassic limestones.

The Matrei Zone is more than 80 km long and varies in width from several hundreds of metres to two kilometres. It forms a generally E-W trending unit along the southern border of the TW and contains sequences of mainly black mudstones, grey calcareous mudstones, quartzitic sandstones, conglomerates, breccias and ophiolites (serpentinites and metabasalts). There are also a few occurrences of augengneiss (Cornelius and Clar, 1939) as well as highly porous dolomite with cellular structure (rauhwacke) and occasionally gypsum. We investigated the coarse grained sequences occurring between the Matrei Tauern valley in the west and the Leiter valley in the east (Fig. 1; locality 4). They are build up of breccias and conglomerates with dolomite and limestone clasts. Thinner lenses of conglomerates and breccias are composed of a single layer, whereas thicker lenses consist of multiple layers, interbedded with black mudstones. Some of the conglomerate and breccia beds display a distinct grading with a channelized and/or scoured lower surface. The size of clasts ranges from a few centimetres to a few metres, but larger blocks occur as well. Most of the clasts lack primary internal structures. However, stromatolite-like laminations similar to those found in the Upper Triassic Hauptdolomite can be occasionally seen in some dolomite clasts. Quartzitic breccias are also common but their thickness does not exceed a few tens of metres.

In the Matrei Zone there is no clear evidence of an older coherent substratum, as the pre-Jurassic rocks only occur as elongate lenses of uncertain tectonic or sedimentary origin.

The Early to Middle Jurassic Tarntal Breccia (Enzenberg, 1967; Enzenberg-Praehauser, 1976) was deposited in places above a partly eroded Triassic basement of the Hippold nappe (location 3 in Fig. 1). It consists of several breccia and conglomerate layers enclosed in black shales (Fig. 9c). A massive central part with clast-supported conglomerates and breccias grades laterally into interbedded black mudstones, marls and conglomerates. In the south of the Hippold nappe slump deposits are present. Farther north, large channels are filled by coarse material (Fig. 9d). The clasts in the breccias and conglomerates are mainly dolomites, less common limestones, rare arkoses, and locally quartzites. Häusler (1988) concluded that the extension of a channel-slope association in the south and a breccia-fan association in the north are indicative of transport of clastic material from the south to the north in the present-day position.

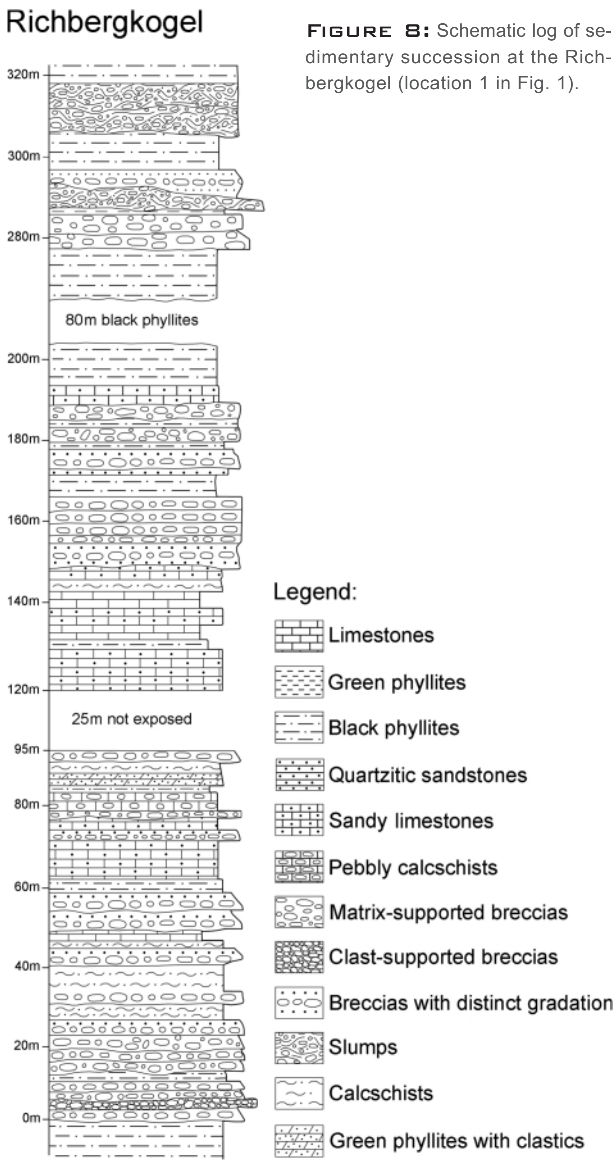

Figure 8: Schematic log of sedimentary succession at the Richbergkogel (location 1 in Fig. 1).

In the Hochfeind nappe of the Radstadt Mountains (Fig. 1; locality 5) predominantly clast-supported conglomerates and breccias occur at two different stratigraphic levels: the Lower to Middle Jurassic Türkenkogel Breccia and the Upper Jurassic-Lower Cretaceous Schwarzeck Breccia, respectively (Häusler, 1988). The first one consists predominantly of Upper Triassic limestone and dolomite clasts. Their size ranges from a few centimetres to a few decimetres. By contrast, the components of the Schwarzeck Breccia (Clar, 1937a) are Permo-Triassic quartzites, Triassic dolomites, limestones and micaschists. It is characterized by the occurrence of large blocks (olistoliths) ranging from tens to hundreds metres in size.

The prevailing matrix-supported breccias and conglomerates in the Pleissling nappe display mainly carbonate rocks as clasts up to one metre in size. The conglomerates are interbedded with crinoidal limestone (Häusler, 1988).

All coarse clastic sediments discussed so far, i.e. breccias, conglomerates and sandstones exhibit a surprisingly uniform range of heavy minerals despite the apparently different age and tectonic position within and around the Tauern Window. The mineral spectrum includes zircon, tourmaline, rutile, apatite, ilmenite and hematite. Cr-spinel is generally missing but is found in the coarse clastic deposits of the Tarntal nappes. In the Matrei Zone Ti-magnetite is probably derived from spinel, which is not stable under the local PT conditions. This suggests a crystalline basement as a source area for the heavy minerals, except for the Tarntal Breccia and Matrei Zone where obviously oceanic material contributed additionally, as documented by numerous ophiolite fragments.

3. Interpretation of depositional processes

3.1 Klammkalk lithofacies

The primary sediment of the Klammkalk was mainly a calcareous mud with variable amounts of coarser grains composed of quartz, feldspar and crinoid fragments. The lens shape of the Klammkalk lithosome, its composition and sedimentary structure suggest that it may have originated as calcareous mud lithofacies, resedimented by hyper-concentrated muddy turbidity currents (Jones and McCave, 1990; Ślączka, 1990).

3.2 Breccia and conglomerate lithofacies

Using the scheme of Walker (1978), we infer that the brec-

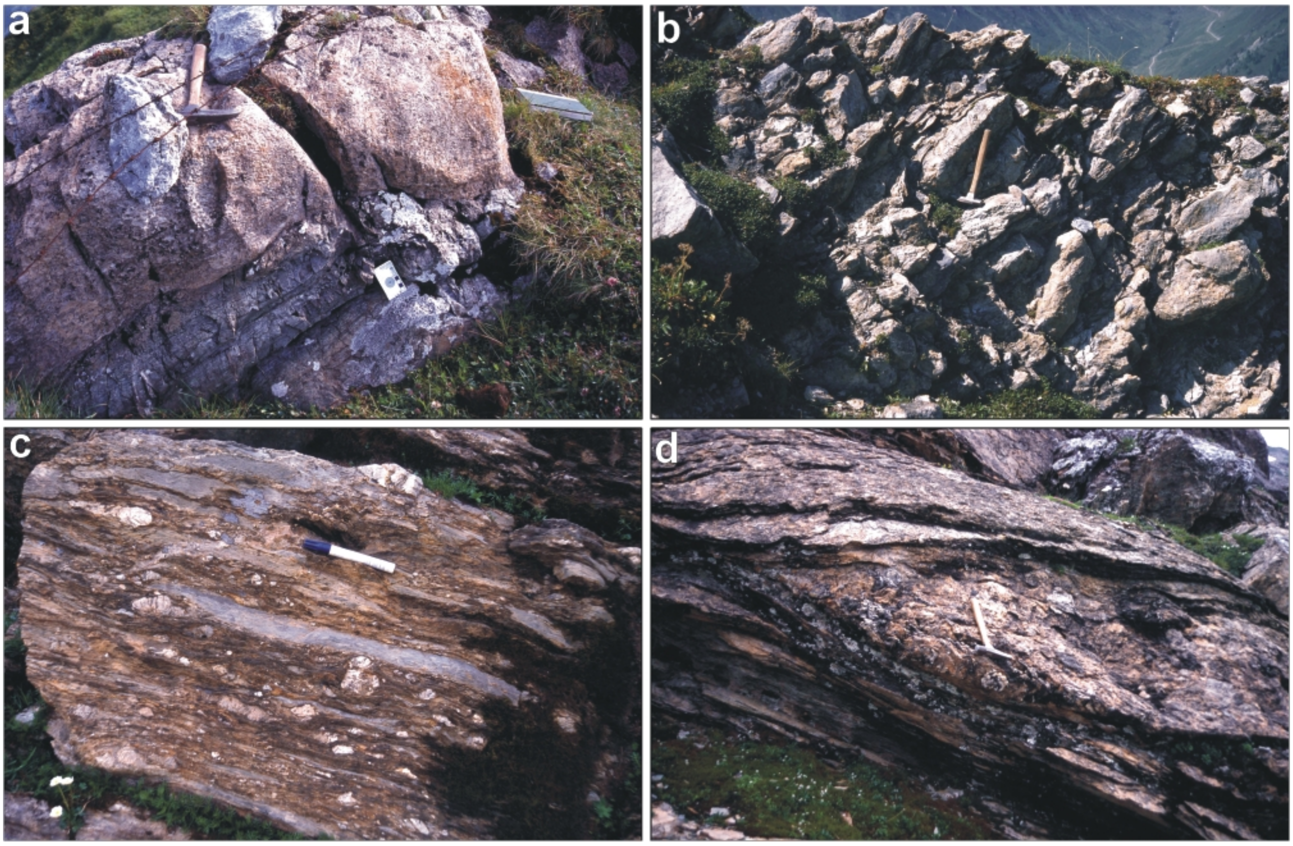

Figure 9: Photographs of breccias from different localities for comparison. a) Northern ridge of the Richbergkogel (locality 1 in Fig. 1): conglomerate with subangular blocks of calcschists, similar to those underlying the conglomerate. An erosional scour 30 cm deep is visible in the right part of photograph. It is an example of sediment deposited by high-density turbidity current. b) Northern slope of Penken (locality 2 in Fig. 1): poorly sorted, clast-supported conglomerate. The flattened blocks are imbricated, dipping to the southeast. The rock probably represents a coarse gravity deposit transported from a southerly source. c) Tarntal Mountains (locality 3 in Fig. 1): calcschists with irregularly shaped blocks of yellowish dolomite up to 5 cm across and elongated lenses of blue-grey limestones. The rock was originally a pebbly mudstone deposited by debris flows. d) Eastern slope of the Tarntal valley (locality 3 in Fig. 1): Lens-like matrix-supported breccia surrounded by laminated calcschists. The breccia probably represents a channel–fill deposit. Scale: length of pencil is 15 cm, length of hammer is 40 cm.

cias and conglomerates generally represent debris flow and high-concentration turbidity current deposits (Mutti and Ricci-Lucchi, 1972). As a whole, they can be classified as debrites (see Stow, 1985). These sediments are similar to the olistostromes type A and B (Pini, 1999; Lucente and Pini, 2003; Festa et al., 2010) and represent layers with blocks ranging in size from a few centimetres to a few metres dispersed in a muddy matrix, and layers where blocks can reach the size of tens of metres, respectively. Debrites with thin graded layers on top are interpreted as deposits of debris flows followed by turbidites. The thick, clast-supported breccias without grading, which include large blocks (olistoliths), might have been formed by rockfall processes (e.g. Reading, 1986). They show similarities to type C olistostromes (Pini, 1999; Lucente and Pini, 2003; Festa et al., 2010). Locally observed contorted layers that are bounded downwards and upwards by undisturbed layers can be explained by syn-sedimentary slumping or sliding, although in some cases tectonic shearing or reorientation of primary slump structures cannot be excluded. The occurrence of imbricated clasts allows to infer the direction of currents generally from east towards west.

Several lines of evidence suggest that the breccias and conglomerates represent primary submarine slope apron systems (Stow, 1986; Nelson et al., 1991; Stow et al., 1996; Wagreich, 2003) as well as base-of-slope aprons (Mullins and Cook, 1986). These include the following features: a) the narrow, rectilinear distribution of the detrital material along the presumed margin of the basin, b) the interbedding of debrites and fine grained deposits, c) the lateral variation of lithofacies over short distances, d) the occurrence of slump deposits, e) the lenticular shape of clastic bodies sometimes stacked, and f) the sharp contacts between layers. Additionally, the general lack of a) a lateral transition from debrite to sandstone lithofacies, b) clear thinning- or thickening-upwards sequences, c) a fan shape, d) deposits that can represent an outer fan, e) a point source of material typical for clastic submarine fans (sensu Mutti and Ricci-Lucchi, 1975; Stow, 1985) also suggest a slope apron depositional system.

According to Shanmugam (2006) similar lithofacies associations are connected with depositional systems dominated by non-channelized and channelized non-fan debris-flows. The exceptional thick lenticular conglomeratic and breccia beds with predominant limestone clasts in the Großarl valley (Fig. 10) show features of a main axis thalweg (Clarke and Pickering, 1996). This is characteristic for a fan system, but might also occur within a slope-apron (see also Stow, 1985 and Shanmugan, 2006).

We also interpret the clastic sediments from other investigated areas as mainly debris flow and high-concentration turbidity current deposits. The breccia- and conglomerate-layers are separated by mudstones, shales and turbiditic sandstones that occasionally exhibit graded- and cross-bedding. The predominant debrite sediments at Penken and Tarntal show similar features that fit to slope-apron models. The channels and lobe facies identified in other areas, e.g. Richbergkogel, are characteristic for submarine fans (Stow, 1986).

3.3 Sandstone lithofacies

The deposition of the investigated sandstones by high- to low-concentration turbidity currents can be inferred from the preserved sedimentary structures. The clastic sediments built up a fan system in a lower-slope to base-of-slope setting (Mutti and Normark, 1987). The metamorphic black phyllites and greenschists intercalated with sandstones represent primary siliceous muds with fine-clastic material. Black muds of similar age are generally regarded in the Alpine domain as deep water sediments below the Calcite Compensation Depth -CCD (Lemoine, 2003). The occurrence of calcareous material in the black mudstones implies that they were deposited above or near the CCD. However, the rapid deposition of carbonate material by gravity flows below the CCD prevented its dissolution. The thick-bedded and massive sandstone sequences can be interpreted as the central part of lobes, deposited by subaqueous flows (Felix et al., 2009) while the thin- to medium-bedded sandstones and the mudstones record the marginal part of fans and basin-plain deposits. Very coarse grained

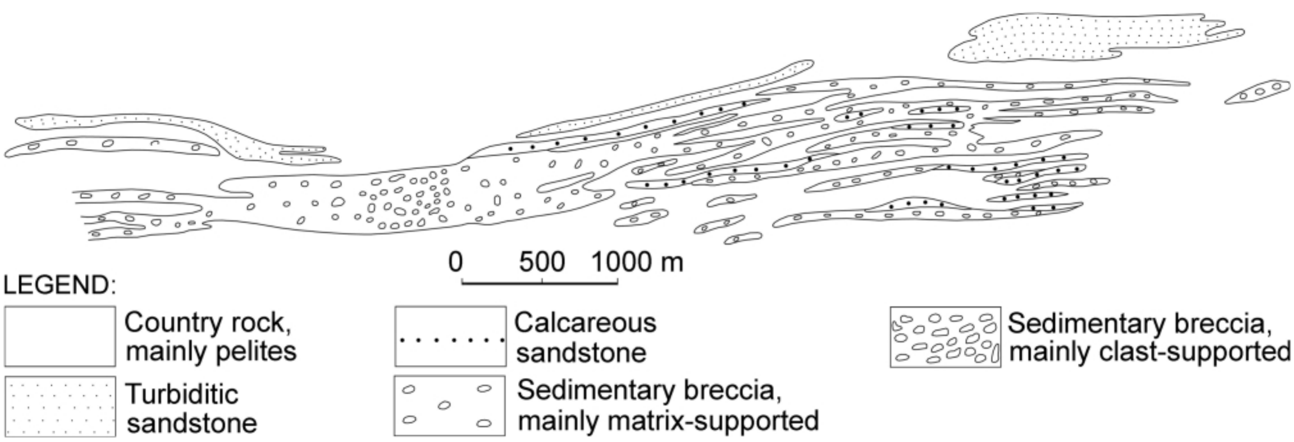

Figure 10: 2D-facies model of a slope apron-system which mainly comprises breccias, seen perpendicular to the flow direction; the model refers to the outcrop situation along the NE Tauern Window area. It exhibits general lateral changes of lithofacies, from a massive center which represents a channelized section, to thinner bedded parts and lens-like breccias on both flanks.

sandstones, especially where intercalated with conglomerates e.g. in the western part of the Schuhflicker area, may represent distributary channels and suprafan deposits (Stow, 1985; Pickering et al., 1989). Sequences of thin-bedded sandstones and pelitic rocks between thick-bedded complexes are envisaged as interchannel and levee deposits. Flute casts on sandstone bottom bedding planes suggest a source area of the fan system situated to the SW. Shales and mudstones separate the different fantype sediments and apparently represent slope and basin, partly hemipelagic, deposits.

4. Implications and tectonic setting

In the studied areas, there are general similarities in the architecture and the sedimentary structures between the different breccia and conglomerate occurrences. The similarities include the lenticular shape, the predominance of matrix-supported breccias and conglomerates, substantial variations in thickness of individual beds, the lateral and vertical variations of clast size and the presence of channelized bodies (Fig. 10). These features suggest that the sediments represent probably mainly fault-controlled slope-aprons and to a lesser amount submarine fans. We interpret the breccias from the Schuhflicker, Penken, Tarntal and Radstadt areas as slope-aprons. The coarse clastic sediments of Richbergkogel have additionally features of a submarine fan, whereas the sandstones of the SBN were most likely deposited as submarine fans.

The steep slopes, along which the linear slope-aprons developed, have formed probably during the opening of the Penninic Ocean. Block tilting, rotation and subsequent reactivation of faults created a topographic relief that triggered the supply of clastic material from the crystalline basement and its sedimentary cover. The sedimentary structures and the distribution of debrites described here fit well to type 1 and 2 sedimentary mélange related to extensional tectonics and passive margins respectively (Festa et al., 2010). The presence of Cr-spinel grains in the Lower to Middle Jurassic Tarntal Breccia indicates the exhumation of ultramafic rocks in this source area. In addition, the occurrence of serpentinite together with other ophiolitic lithologies in the Reckner nappe (Dingeldey et al., 1997) supports the existence of a small oceanic basin along the northern margin of the Lower Austroalpine realm (Apulian Plate), originally related to the transtensional opening of the Penninic Ocean.

The available evidence indicates that the coarse grained deposits developed in basins located along the southern margin of the main Penninic Ocean. During the opening of the ocean, this margin was probably dissected by listric faults separating various local swells and basins, a process which took place diachronously from the south to the north. The Lower Austroalpine basins (now represented in the Tarntal and Radstadt nappes) opened in Jurassic, as indicated by the age of the breccias in these areas. The sediments in the area around Schuhflicker, i.e. debrites and black shales with spores (Reitz et al., 1990), formed most likely during Early Cretaceous. We suppose that the same probably holds true for the Richbergkogel and Penken areas. The general appearance of these debrites and their similarity with type 1 and 2 mélanges, as well as their restricted occurrence, argue for deposition related to local processes such as faulting during the opening of the Penninic Ocean. This model contrasts with earlier models (Faupl, 1978; Popp, 1984; Frisch et al., 1987) which envisaged an active continental margin. Nevertheless, a genetic relation of the Matrei Zone deposits, characterized by intrabasinal and extrabasinal clasts extending for 80 km, with the beginning of the closure of the Penninic Ocean in the late Early Cretaceous (Faupl and Wagreich, 2000) is possible. This is also supported by the similarity of the Matrei Zone deposits with type 4a mélanges (Festa et al., 2010), which are related to accretionary wedges.

The sedimentary succession in the NE Tauern Window fits into the existing stratigraphic scheme of the Bündnerschiefer or Schistes Lustré put forward by Lemoine (2003). He suggested several sequences of argillaceous and siliceous compositions (denominated as A) alternating with calcareous lithologies (denominated as C). He distinguishes several first-order sedimentation episodes starting from C1 (Lower Liassic) to C4 (Upper Cretaceous) calcareous sediments alternating with argillaceous ones (A1-A3) widely developed in the Alpine-Carpathian domain. C3 in Lemoine’s notation represents Upper Jurassic limestones, and A3 marly and argillaceous shales of the Lower Cretaceous respectively. The Upper Jurassic to Lower Cretaceous Klammkalk and the Lower Cretaceous black mudstones including breccias and other clastic sediments that occur in the NE Tauern Window are similar to the Late Jurassic-Early Cretaceous sequences C3/A3. Furthermore, they are also similar to some Upper Jurassic and Lower Cretaceous successions in the Gresten Klippen Zone (Hoeck et al., 2005; Wessely, 2006) as well as in the Outer Carpathians (Ślączka et al., 2006). There, the Upper Jurassic calcareous pelitic sediments pass upwards into calcareous graded breccia of Late Jurassic-lowermost Cretaceous age and eventually to Lower Cretaceous dark grey and black mudstones and pelites with lenses of sandstones and conglomerates.

5. Conclusions

The preserved sedimentary structures imply that many of the coarse clastic metasediments of the TW deposited by various gravity flows represent fault-controlled slope-aprons and minor submarine fans. The predominance of lens-like debris flows within the pelitic deposits and the linear distribution in several sections suggest that apron models similar to faulted slope-apron of Stow (1985) and to the base-of-slope type apron of Mullins and Cook (1986) prevailed. We interpret the associated black shales and sandy marls as basinal pelagic or hemipelagic sediments. Some of the large, often elongate blocks of dolomite and limestone (olistoliths) occurring along the northern and southern sides of the TW are derived from a Triassic carbonate platform located to the south.

The opening of the Penninic Ocean started in the Early Jurassic and continued at least into the Lower Cretaceous. Evidence comes from breccias and conglomerates from the Lower Austroalpine Tarntal and Radstadt Mountains, which developed in the Early to Middle Jurassic. Based on few stratigraphic data, we may assume that the breccias and conglomerates of the NE Tauern Window, Richbergkogel and Penken were formed in the time interval from Late Jurassic to Early Cretaceous. The sedimentological evidence combined with the stratigraphic range argues for a formation in small basins along the southern passive margin of the Penninic Ocean.

The mass transport deposits from the Matrei Zone indicate the beginning of the Penninic Ocean closure which is supposed to have taken place in the late Early Cretaceous.

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