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The Pfitsch-Mörchner Basin, an example of the post-Variscan sedimentary evolution in the Tauern Window (Eastern Alps)

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Key words: post-Variscan sediments, Eastern Alps, Tauern Window, Pfitsch Formation, Windtal Formation, Aigerbach Formation

ABSTRACT

A review of post-Variscan metasedimentary and metavolcanic successions in the western Tauern Window is presented. U/Pb – datations of zircons in metavolcanic rocks reveal ages between 309 and 280 Ma. Deposition of grey conglomerates and black pelites started before 309 Ma in the northernmost basin of the Tauern, the Riffler-Schönach basin. In the more central Pfitsch-Mörchner basin, the onset of conglomerate sedimentation can be dated into the time span between 293 and 280 Ma. The Pfitsch and Windtal Formations are newly defined. The basins were filled with up to 1 km of mainly continental clastics until Early Triassic. Short marine ingressions in Middle- and Late Triassic times flooded only basinal parts of the area where we suppose a more or less continuous sedimentation until the Late Jurassic. Only the Hochstegen Marble documents a nearly complete submergence in the area of the Tauern Window. In spite of the metamorphic overprint, the tentative interpretations of the sedimentary facies give a reasonable picture and allow correlations to nonmetamorphic areas in South Germany or the External Massifs of Eastern Switzerland.

Introduction

The Inner Tauern Window is considered as a duplex of kilometre-thick slices of external parts of the European crust, which were stacked in the footwall of the Penninic and Austroalpine nappe systems and, finally, uplifted along a deep-reaching reverse fault, the Sub Tauern Ramp (Lammerer et al. 2008). Pre-Variscan basement rocks and Variscan granitoids form the main rock masses in the Tauern Window. They are covered by Late Jurassic marbles (Hochstegen Marble, Silbereck Marble) but, locally, Late Palaeozoic to Early Jurassic rocks are preserved. Primary petrological and sedimentological features are mostly obliterated by Alpine tectonics or metamorphism and the outcrops are scattered over a wide area. Thus, deciphering the pre-orogenic history is far from straightforward.

Numerous earlier studies have already revealed important constraints concerning the stratigraphy (Frasl 1958; Frisch; 1974, 1980 a; Thiele 1976, 1980) structure (Thiele 1974; Frisch 1975, 1980 b; Lammerer & Weger 1998), metamorphism (Selverstone et al. 1984, 1985), timing of uplift (Fügenschuh et al. 1997; von Blanckenburg 1989; Steenken et al. 2002) and geodynamic evolution of the Tauern window (Ratschbacher et al. 1989, 1991; Frisch et al. 2000; Lammerer et al. 2008). Earlier descriptions of post-Variscan sediments of the western Tauern Window were given by Frisch (1968), Thiele (1970), Lammerer (1986), Schön & Lammerer (1988), Sengl (1991) and Veselá et al. (2008).

This study provides an overview of the post-Variscan metasedimentary and meta-volcanic rocks within the western Tauern Window. For this purpose some less deformed locations of the relatively well-exposed Pfitsch area in the SW of the Tauern Window were studied in detail. There, major sedimentary structures are still preserved and datations of the meta-volcanic layers were carried out, so that lithostratigraphical correlation of the rock successions is feasible.

Geological setting

The Variscan orogeny left a large mountain chain which crossed the megacontinent Pangea at the end of Westphalian times (von Raumer 1998; Ziegler 1990). The orogenic activity was followed by a collapse of the thickened crust and intraplate reorganisation throughout Western and Central Europe. Normal faulting and strike-slip faulting were prevalent in Late Palaeozoic times (Arthaud & Matte 1977). The extension of parts of the high Andes and Tibet or the Basin-and-Range province may serve

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as an analogue to the post-collisional stage of the Variscan belt (Ménard & Molnar 1988). In contrast, Ziegler & Dezés (2006) suggest an oblique dextral collision and a wrench-induced collapse of the Variscan orogen. According to McCann et al. (2006) alternating transtensional and transpressional tectonic regimes led to the formation of many basins across the region.

The area of the future Alps was located in Late Carboniferous times close to the warm and humid equatorial zone. Post-orogenic fluvial systems were influenced by the tectonic fracture pattern and basin subsidence. Upper Carboniferous sediments comprise deposits of braided, anastomosing and meandering rivers and swamps. A change towards a drier climate during the Permian led to formation of alluvial fans and playa lakes. The denudation of the Variscan mountain belt continued until the early Mesozoic, when a peneplain formed. As known from other areas in Central Europe (e.g. Wetzel et al. 2003; Ziegler 2005), continental sedimentation prevailed during the Triassic although interrupted by some short marine ingressions. Thereafter, probably during the Jurassic, the area was progressively flooded and the sediments became increasingly calcareous.

The Tauern Window was part of the Moldanubian domain, and its sedimentary history is very similar (e.g. Pfiffner 1998). In the Alpine foreland several intermontane, fault-bounded basins were detected by seismic imaging and drilling beneath the Molasse cover (Fig. 1), e.g. the Permo-Carboniferous Northern Switzerland Basin (Matter 1987), the Lake Constance Trough or the Ries-Salzach Basin close to the Landshut-Neuötting fault scarp (Lemcke 1988) which continues to a basin within the Zentrale Schwellenzone in Austria (Kröll et al. 2006). Within the Alps, well exposed examples are the Zône Houillère in the French Western Alps (Desmons & Mercier 1993), the Salvan-Dorénaz Trough in the Aiguille Rouge Massif, where coal seams were mined at several locations (Capuzzo et al. 2003; Capuzzo & Wetzel 2004) and the basins within the Aar-Gotthard Massif (Franks 1966; Oberhänsli et al. 1988; Schaltegger & Corfu 1995). Parts of the southernmost post-Variscan basins are the Orobic and Collio Basin in the Southern Alps (Sciunnach 2003) which continue into the Val Gardena Sandstone Plain east of the Giudicarie Line. To the north of the Periadriatic Line, the post-Variscan sediments are incorporated as slices within the Austroalpine nappes (Kreiner 1993). The Sub-Penninic European continental crust sensu Schmid et al. (2004) is in the Eastern Alps exposed only in the Tauern Window. It represents insofar an important link between the basement outcrops of Central Europe and the Variscan crystalline complexes within the Tisza Block in the Pannonian Basin (Haas & Péró 2004). All basins are filled with continental clastics and some volcaniclastic material and are emplaced within the Variscan basement rocks.

The basement

The basement of the Tauern Window is composed of old gneisses or schists (“altes Dach”, Frasl, 1958) and late Variscan

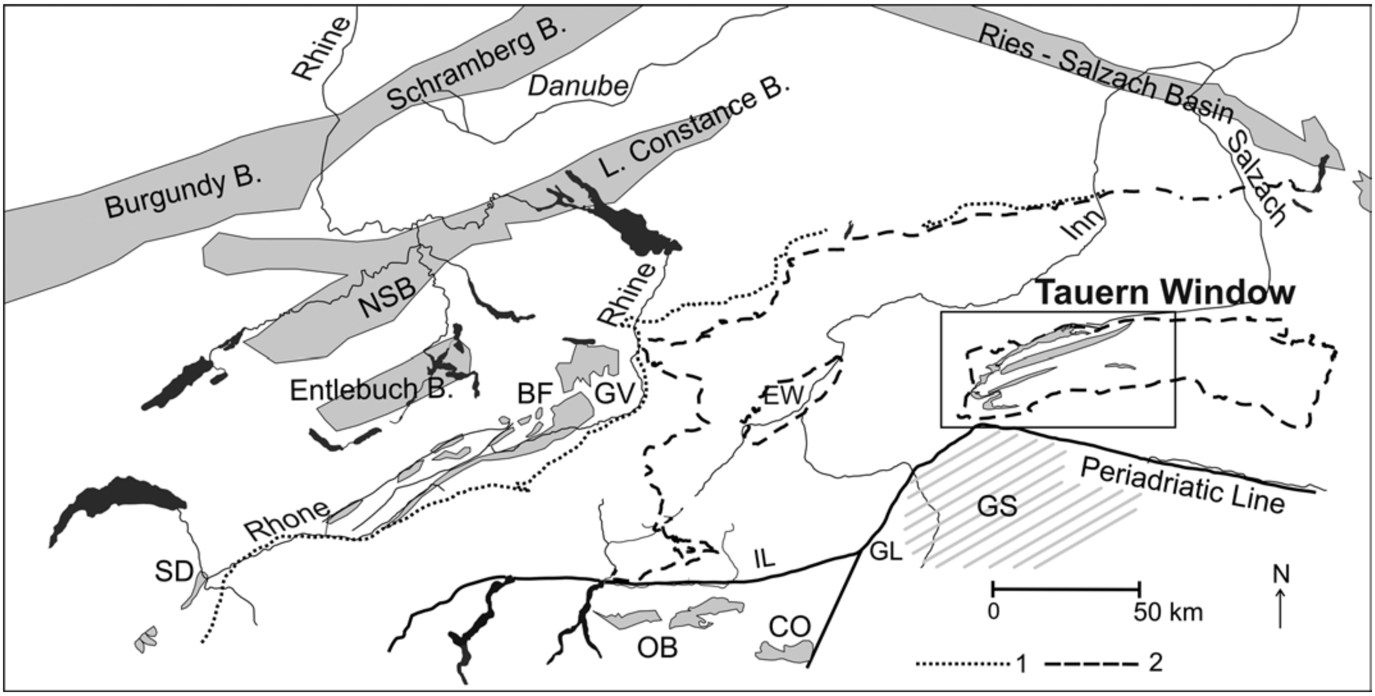


Fig. 1. Post-Variscan basins in Central Europe and Alpine realm (modified after: Lemcke 1988; Ménard & Molnar 1988; Kröll et al. 2006; McCann et al. 2006; Cassinis et al. 2007; Veselá et al. 2008). 1 – Penninic-Helvetic thrust plane, 2 – Austroalpine-Penninic thrust plane, SD – Salvan-Dorénaz Basin, NSB – Northern Swiss Permo-Carboniferous Basin, BF – Bifertengrätli Basin, GV – Glarner Verrucano Basin, OB – Orobic Basin, CO – Collio Basin, GS – Val Gardena Sandstone Plain, IL – Insubric-Tonale Line, GL – Giudicarie Line, EW – Engadine Window. The inset frame shows the position of Figure 2.

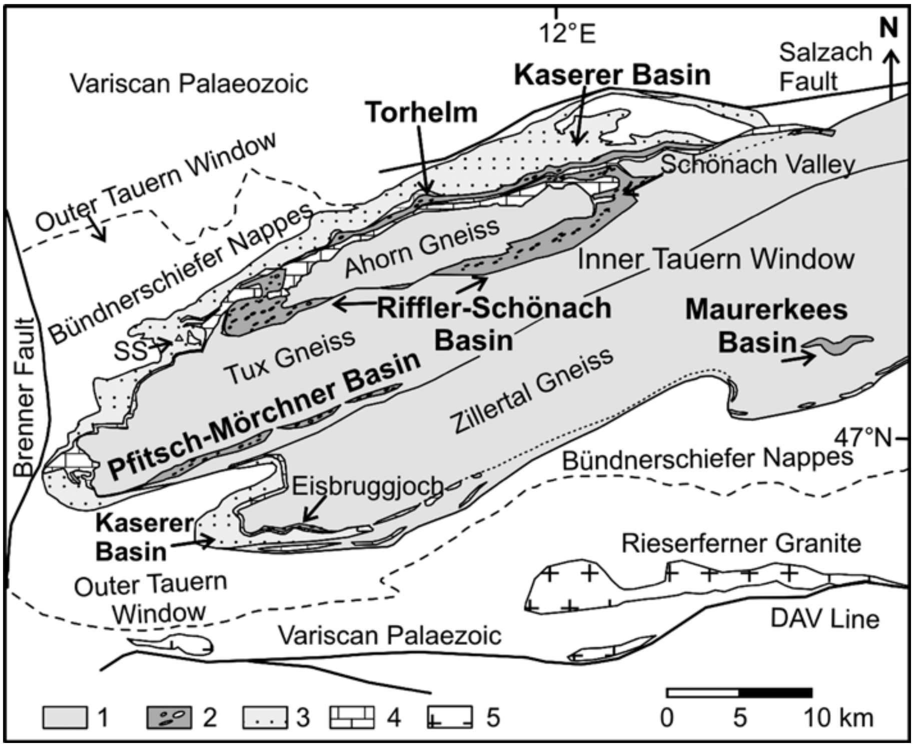


Fig. 2. Geological sketch map of the Tauern Window and the position of the post-Variscan basins (modified after Veselá et al. 2008). 1 – Palaeozoic rocks and Variscan granites, 2 – post-Variscan clastic sediments (Upper Carboniferous-Lower Jurassic), 3 – ? Triassic clastic sediments and carbonates at the base of the Bündnerschiefer, 4 – Hochstegen-Fm. (Jurassic), 5 – Alpine granites (Oligocene), DAV Line – Defereggen-Antholz-Vals Fault, SS – Schöberspitzen.

intrusives (Karl 1959; Finger et al. 1993, 1997). The old Greiner-, Stubach-, Habach-, Storz- and Zwölferzug Gneiss Series are interpreted as pre- or early Variscan terranes derived from island-arcs, back-arc-basins or marginal basins which originated along the Gondwana margin (e.g. Frank et al. 1987; Reitz & Höll 1988; Neubauer et al. 1989; Vavra & Frisch 1989; Frisch et al. 1993; Frisch & Neubauer 1989; Frisch & Raab 1987; v. Quadt 1992; Kupferschmied et al. 1994; v. Raumer 1998). Serpentinites and meta-ophicalcites in mélange-like rocks of the Greiner and Stubach Series may represent remnants of an obducted ocean floor and, hence, mark a pre- or early Variscan suture zone along which the different pieces were amalgamated.

The sedimentary domains within the basement of the Tauern Window experienced metamorphism and even anatexis during complex processes of Variscan nappe-stacking and due to the Variscan intrusive activity (Eichhorn et al. 2000). However, some of the detritial rocks seem to have been metamorphosed only during the Alpine orogeny (Habach Formation, Frasl 1958). Similar to the External Massifs in the Swiss Alps (Schaltegger & Corfu 1995; von Raumer 1998) it appears that the Pfitsch-Mörchner Basin (Fig. 2) could also be a successor basin of an older volcano-sedimentary basin, which was reactivated or continued to exist until the Permian. Kebede et al. (2005) investigated sedimentation time in the central Tauern Window (Zwölferzug, Biotitporphyroblastenschiefer, Habach Series) using detrital zircon U/Pb ages. Graphite-bearing schists and paragneisses, which probably have their continuation in the Greiner Series, contain detrital zircons with ages in the range from Upper Devonian to Lower Carboniferous indicating the maximum age of sedimentation.

Permo-Carboniferous granitoids ("Zentralgneise") intruded into the old gneisses as laccoliths or kilometre-thick sills (Fig. 3; Finger et al. 1997; Lammerer & Weger 1998; Lammerer et al. 2008), but contacts are sometimes overprinted by strike-slip faults (Behrmann & Frisch 1990) or thrusts. The granitic lamellae seem to control the taper of Alpine thrust sheets as contacts of granites to the foliated host rocks serve as plain of weakness and, hence, as detachment horizons (e.g. Tux Gneiss sheet, Eisbruggjoch lamella, Figs. 4, 7).

The plutonic protoliths of the "Zentralgneise" display, from the chemical point of view, features of volcanic arc or continental cordillera magmatism. Series of calc-alkaline magmas with dominantly granitic and tonalitic but also syenitic and monzonitic composition were produced, accompanied and followed by extrusive rhyolitic-dacitic volcanism (Finger & Steyrer 1988; Finger et al. 1993; Eichhorn et al. 2000).

In the western Tauern Window the Late Variscan magmatic activity started at 309 ± 5 Ma with calc-alkaline mafic intrusions, including minor ultramafic cumulates, in the Zillertal Gneiss complex (Cesare et al. 2001). More to the north, meta-rhyodacites of the Riffler-Schönach basin give an age of 309.8 ± 1.5 Ma (Table 1, F. Söllner pers. comm.). The magmatic activity culminated at 295 Ma with emplacement of granodioritic-tonalitic plutons (Cesare et al. 2001) and rhyolite (293 ± 1.9 Ma, Veselá et al. 2008) and ended around 280 Ma with acidic extrusivs (Table 1, F. Söllner, pers. comm.). The evolution is similar in the

Fig. 3. Banded and folded amphibolites of the Greiner Series ("old roof" rocks) are cut by Late-Variscan Tux leuco-granite. Locality Kunerbach water tunnel to the Schlegeis reservoir, Tux Gneiss. Original size is about 2,5 × 4 m.

External Massifs of the western Alps (e.g. Ménot & Paquette 1993; Schaltegger & Corfu 1992, 1995; Capuzzo & Bussy 2000) which supports the paleogeographic interpretation of the Tauern Window as an eastern continuation of the External domains (Thiele 1970; Frisch 1975; Lammerer 1988; Finger et al. 1993; von Raumer 1998).

Sedimentary basins of the western Tauern Window

Within the Inner Tauern Window several elongate, trough-like basins have been identified, representing small remnants of the Late Palaeozoic-Mesozoic sedimentary cover, which survived the post-Variscan uplift, Alpine compression and erosion (Fig. 2). Many palaeogeographic units in the Eastern Alps have their long axes in an ENE–WSW direction, parallel to the strike of the modern orogenic belt and it appears that also in the Tauern Window pre-existing Late Palaeozoic faults and associated rifts strongly affected the tectono-sedimentary development (Frasl & Frank 1966; Arthaud & Matte 1977; Frisch 1977; Kreiner 1993; Frisch et al. 2000). The orientation of Variscan granitoid intrusions follows this trend. The Riffler-Schönach Basin, the Pfitsch-Mörchner Basin, the Maurerkees Basin and the small remains of basins on the southern rim of the Tauern Window, are all confined by tectonic horsts of basement rocks (Ahorn-, Tux-, Zillertal-, and Eisbruggjoch Gneisses). The age and tectonic position of the Kaserer Basin is still not clear.

The Pfitsch-Mörchner Basin

One of the best examples of the Post-Variscan sedimentary successions in the Eastern Alps is found in a narrow syncline which extends from the Pfitsch Valley (Val di Vizze, Italy) in a north-easterly direction to the Mörchenscharte, 2872 m (Austria), (Fig. 5). The Permian-Mesozoic sediments are exposed for about 20 km in an up to 600 m wide zone, covering the Palaeozoic basement rocks of the Greiner Schists and squeezed between Tux and Zillertal Gneiss Horsts (Fig. 7). The Greiner Series comprises hornblende-garbenschists, amphibolites, serpentinites, graphite-biotite schists, quartzites, thin marble layers and migmatites. Dark meta-conglomerates and -breccias have been found in the Haupental (east of Pfitscher Joch) and in contact to the large serpentinite body of the Ochsner (north of Berliner Hütte) and numerous small serpentinite or ophicalcite lenses give the impression of an old mélange.

The Greiner Schists accommodate a large-scale Alpine sinistral shear zone, which affected the whole schist belt and parts of the neighbouring gneisses (Karl & Schmidegg 1979; Behrmann & Frisch 1990). As the syncline plunges 10–15° to the SW, the Greiner Series and the sediments of the Pfitsch-Mörchner basin wedge out close to the Mörchenscharte. All rocks suffered metamorphic recrystallisation and ductile deformation but nevertheless sedimentary structures are still recognizable at many locations in the Permo-Mesozoic rocks. Various lithofacies associations have been distinguished on the basis of lithologic changes, vertical succession, dominant grain size or grading.

An unconformity on top of the Greiner Series is marked by lenses of staurolite-chloritoid-magnetite schists. Because of a high aluminium and iron content, these lenses were interpreted by Barrientos & Selverstone (1987) as erosional remnants of a metamorphosed palaeosol. It documents a period of tectonic quiescence prior to the Permian extensional phase. A Lower Permian meta-rhyolite with an age of 293 ± 1.9 Ma cross-cuts the serpentinite and the other Greiner Schists to the west of the Mörchenscharte (Veselá et al. 2008). It gives the minimal age of the Greiner Series. The rhyolite is, on the other hand, unconformably overlain by the meta-conglomerate of the Pfitsch-Formation which marks its maximum age (Table 2).

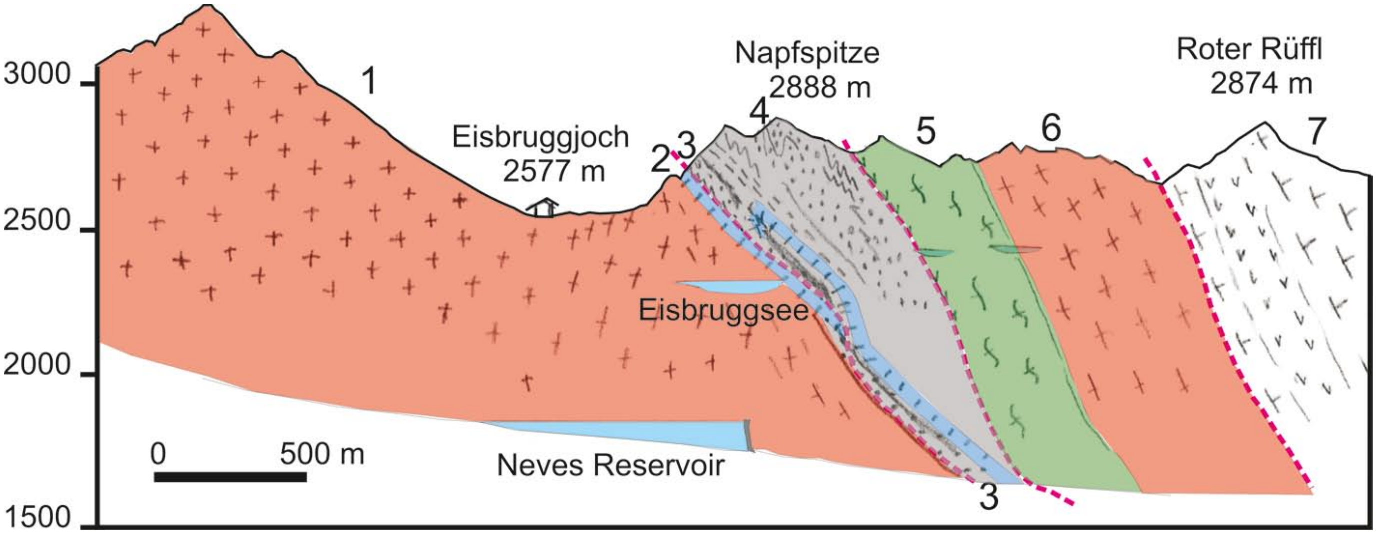


Fig. 4. Eisbruggjoch section. 1 – Zillertal Gneiss, 2 – Hochstegen Marble, 3 – ankerite-chlorite schists, quartzites, 4 – garnet- and graphite-bearing schists, quartzites, mica-schists, 5 – amphibolites, 6 – Eisbruggjoch Lamella (granite gneiss), 7 – Bündnerschiefer and amphibolites of the Glockner Nappe (Outer Tauern Window)

Pfitsch Formation

The Pfitsch Formation (hereafter Pfitsch-Fm.) comprises meta-conglomerates, meta-rhyolite and meta-pelites. The well exposed rock succession in the area of Pfitscher Joch (Passo di Vizze) on the Austrian/Italian border is used as a type section (Fig. 5, Table 2).

Meta-conglomerate (Early Permian)

Sedimentary structures are well preserved in the northern limb of the nearly isoclinal syncline close to the Pfitscher Joch Haus, where strain was relatively low. In protected zones a measurable strain can be more or less absent. Bedding planes are sub-vertical. The rock protolith was a texturally and compositionally immature and poorly sorted coarse-grained polymictic breccia and conglomerate. It was formed by crudely bedded matrix-supported clasts; the matrix consisted of a sandy or silty fraction (Fig. 6 a). Angular to subangular clasts up to 30 cm in size are predominantly aplitic and granitic in origin, but vein-quartz, amphibolites, graphite schists, marbles, greenish calc-silicate-rock pebbles and, very rare, serpentinite clasts occur as well. The base of the unit contains predominantly metamorphic basement rock clasts whereas toward the top granitoid clasts become predominant, which reflects the progressive unroofing of the Variscan "Zentralgneise" (Schön & Lammerer 1988).

Table 1. Radiometric and palaeontologic time markers in the western Tauern Window

Age (method)		**Rocks and locations**	**Reference**
309,8 ± 1.5 Ma	(U/Pb Zrn)	meta-rhyodacite, Grierkar, Riffler-Schönach Basin, Tux Alps	F. Söllner pers. comm.
309 ± 5 Ma	(U/Pb Zrn)	ultramafic cumulates, Zillertal Gneiss, Italy	Cesare et al. 2001
295 ± 3 Ma	(U/Pb Zrn)	metagranodiorite, Zillertal Gneiss, Italy	Cesare et al. 2001
293 ± 1.9 Ma	(U/Pb Zrn)	meta-rhyolite, Mörchenscharte, Pfitsch-Mörchner Basin, Zillertal Alps	Veselá et al. 2008
284 + 2/–3 Ma	(U/Pb Zrn)	rhyolitic to andesitic metavolcanic rocks, Porphyrmaterialschiefer – Torhelm Nappe, Tux Alps	Söllner et al. 1991
280.5 ± 2.6 Ma	(U/Pb Zrn)	meta-rhyolite, Pfitscher Joch, Pfitsch-Mörchner Basin Pfitsch Valley, Val di Vizze, Italy	F. Söllner pers. comm.
Fossils			
Late Carboniferous to Early Permian		plant fossils in graphite-bearing schists in the Maurer Kees Basin, southern Venediger Alps	Franz et al. 1991 Pestal et al. 1999
Middle Triassic		crinoids in dolomitic marbles, Kalkwandstange Pfitsch Valley, Val di Vizze, Italy	Frisch 1975
Late Jurassic		ammonite (*Perisphinctes sp.*), Hochsteg, Mayrhofen	Klebelsberg 1940
		belemnite, sponge spicule, radiolaria in the Hochstegen Marble, Tux Valley	Schönlaub et al. 1975 Kiessling 1992

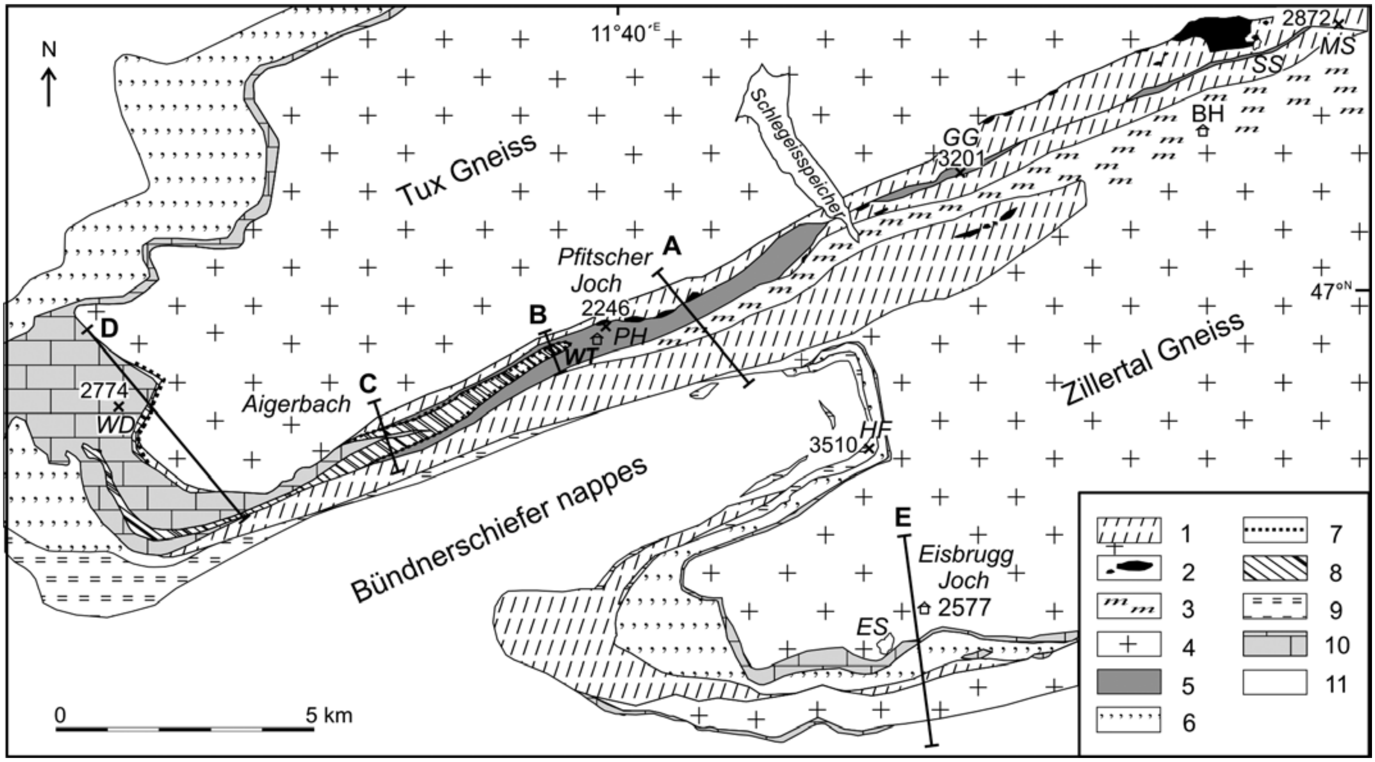


Fig. 5. Geological outline map of the SW Tauern Window. 1 – pre- and Late-Variscan basement rocks (Greiner Schists: amphibolites, hornblende-garbenschists, graphite-bearing schists, quartzites), 2 – serpentinites, 3 – migmatites and sheared gneisses, 4 – Variscan granitoids ("Zentralgneise"), 5 – Pfitsch-Fm., 6 – Kaserer Basin metasediments, 7 – Windtal-Fm., 8 – Aigerbach-Fm., 9 – Middle Triassic carbonates at the base and within the Bündnerschiefer nappes, 10 – Hochstegen-Fm., 11 – Bündnerschiefer nappes, MS – Mörchenscharte, SS – Schwarzsee, BH – Berliner Hütte, GG – Großer Greiner, PH – Pfitscher Joch Haus, WT – Windtal, HF – Hochfeiler, WD – Wolfendorn, ES – Eisbruggsee. Lines show positions of sections shown in figures (A – Fig. 7, B – Fig. 8, C – Fig. 10, D – Fig. 11, E – Fig. 4.).

Other localities show higher strain and clasts are stretched to long prolate bodies north of Berliner Hütte or are strongly flattened, e.g. to the south of the Pfitscher Joch Haus (Fig. 6 b). The average strain ellipsoid measured by the Rf/Φ method in the conglomerate of the northern limb is around x : y : z = 2. 45 : 0.93 : 0.44. In contrast, the southern limb suffered a strong flattening strain of x : y : z = 2.51 : 1.82 : 0.22. The longest axes are gently plunging (10–30°) to the WSW (250–270°), the shortest axes are horizontally NNW–SSE directed.

The actual thickness of the conglomerate member in the northern limb is 60 m, in the southern 94 m (Figs. 8, 9). Considering the strain, the primary thickness should have been around 136 metres in the northern and around 420 metres in the southern limb. Some kilometres more to the east and closer to the fold hinge, nearly plane strain ellipsoids were measured (x : y : z = 2.89 : 1.02 : 0.34) and reconstructed thickness exceeds 400 metres in the southern limb. The age of deposition is limited to the time span between 293 ± 1.9 and 280 ± 2.6 Ma by the unconformity to the meta-rhyolite of the Mörchenscharte and the overlying meta-rhyolite of the Pfitscher Joch (see below).

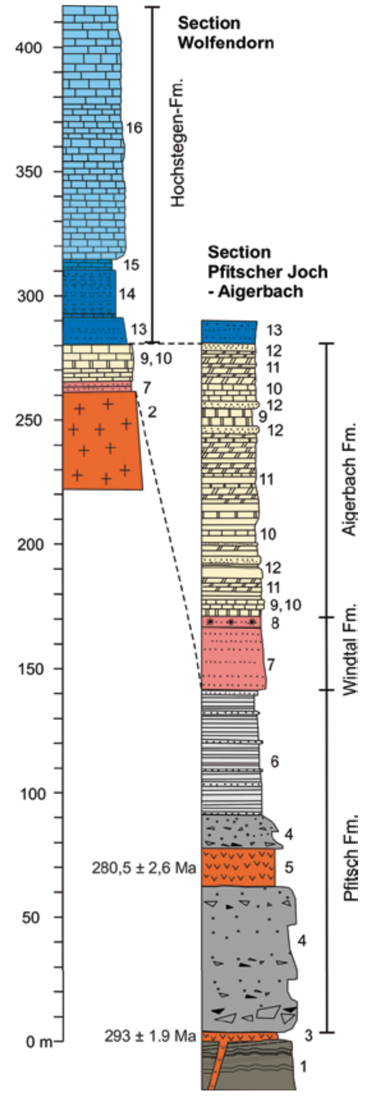
Interpretation: The meta-conglomerates are interpreted as semi-arid alluvial fans. Some coarse-grained beds give, in spite of the metamorphic overprint, the impression of clast-supported deposits which, in general, represent sieve deposits (Schäfer 2005). Small troughs were incised into the middle part of the alluvial fan, where sediments were partially reworked after heavy rains. They were filled with fining-upward successions.

The rock colour is presently light greyish-greenish from an ubiquitous presence of finely distributed hematite and magnetite and greenish iron-rich phengite. This is taken as a hint that the original rock colour was reddish. The remarkable increase in thickness from north to south and east may indicate a palaeo-relief quickly deepening towards the southeast, or by now undetected faults obliquely cutting the bedding planes in the northern limb.

Meta-rhyolite (280.5 ± 2.6 Ma)

On top of the meta-conglomerates, a 10–50 m thick light grey meta-rhyolite was deposited, Early Permian in age (280.5 ± 2.6 Ma, F. Söllner pers. comm.). It is deformed to gneiss with frequent tourmaline in the foliation plane. The matrix is strongly recrystallized, but euhedral quartz and feldspar grains up to 3 mm are still preserved. The zircon typology (Pupin 1980) presents a bimodal distribution (P2-P5, S10,13,16,17),

Table 2. Lithofacies and stratigraphy of the Pfitsch-Mörchner Basin, not included in the table: 1- Greiner Schists, palaeosol horizon, 2 – Variscan Granitoids, Tux Gneis.



age	lithostratigraphical unit/ rock type	facies/protolith	interpreted depositional environment	section line coordinates
Hochstegen Formation				
Late Jurassic	greyish, bluish calcite marbles, sandy marbles (16)	carbonates	deeper marine environment	11°32´30´´E 46°59´04´´N
? Middle Jurassic	brownish sandy calcite marbles (15), mica- graphite- bearing horizons	sandy impure carbonates	neritic environment	
? Lower Jurassic	kyanite-graphite- phyllite and quarzite-schists (14) graphite-quartzite, pure quartzite (13)	sands, Fe- and Al- rich pelites mud	floodplain deposits, swamps, fluvial sands	11°32´47´´E 46°59´12´´N
Aigerbach Formation				
	chloritoid-, mica-quartzite (12)	sands, impure sands and pelites	supratidal area, coastal flat	11°32´48´´E 46°59´16´´N
	dolomite and cargneuls (11) yellowish sandy calcite marbles (10) dolomitic marbles (9)	carbonates, anhydrite, gypsum	shallow marine to sabhka environment	
Late Triassic	chloritoid-, kyanite-quartzite, mica-, chlorite-schists (12)	fine sands high Fe content, pelites	fluvial sands, muddy floodplain, channels	
	whitish dolomitic marbles, cargneuls (11), thin calcite marble beds (10)	carbonates, anhydrite, gypsum	sabhka environment, lagoon, high evaporation	11°36´18´´E 46°58´34´´N
	calcareous/dolomitic quartzite, kyanite-, chloritoid-, mica-schists, and -quartzite (12)	impure sands and pelites	supratidal area, coastal flat, channels	
	whitish dolomitic marbles and cargneuls (11)	anhydrite, gypsum	sabhka environment, lagoon, high evaporation	
? Middle Triassic	greyish, yellowish sandy calcite marbles (10), yellowish, violet dolomitic marbles (9)	carbonates partly dolomitized	shallow marine environment	11°38´51´´E 46°59´31´´N
Windtal Formation				
? Early Triassic	locally lazulite-kyanite quartzite (8), sericite-, hematite-quartzite (7)	Fe-rich sand deposits, locally P-, Al-rich sediments	braided rivers deposits? / coastal sands ?, palaeosols in vegetated area apart from channel ?	11°39´16´´E 46°59´35´´N
Pfitsch Formation				
? Late Permian	epidote-ankerite schists and quartzite (6)	pelites, mud with sand laminae	distal part of (semi) arid alluvial fan muddy floodplain, playa lake	11°39´14´´E 46°59´29´´N
280,5 ± 2,6 Ma	meta-rhyolite (5)	volcanic deposits	subaerial lava flows	
Early Permian	meta-conglomerate (4) ?discordantly overlying meta-rhyolite (3) W of the Mörchenscharte	crude gravel, matrix/clast supported, sand	proximal, middle part of (semi) arid alluvial fan, sieve deposits	11°50´21´´E 47°02´31´´N

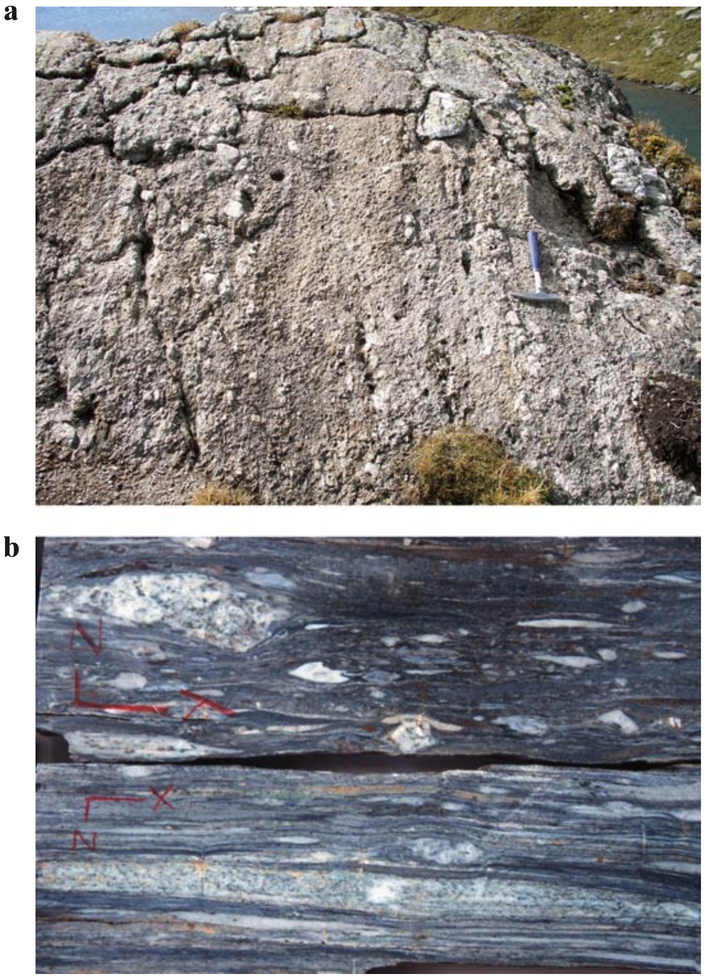


Fig. 6. a) Coarse meta-conglomerate from the Pfitscher Joch, poorly sorted and crudely bedded, consisting mainly of granitic pebbles. Subordinate clasts from graphite-bearing schists, migmatic gneisses and marbles occur. Hammer for scale (middle-right). b) Polished sections of a meta-conglomerate cut in x–z (bottom) and y–z (top) directions of the strain ellipsoid. Flattened pebbles of granites, aplites and quartzites in the highly deformed southern limb of the Pfitsch syncline. Long axis of the specimen is 28 cm.

which suggests derivation from alkaline granitic melt of mainly mantle origin contaminated by tonalitic material of prevalently crustal origin. The layer extends laterally for more than 10 km. Systematic strain analyses have not been carried out, but stretched tourmaline needles point to a similar strain as in the adjacent conglomerates.

Interpretation: As the meta-rhyolite covers terrigenous conglomerates over a large area with a relatively uniform thickness, a subaerial deposition from a pyroclastic flow seems reasonable. The age of the rhyolite is coherent with the Permian volcanic phase in the central Tauern Window (Eichhorn et al. 2000) and many other volcanic domains in the Alps, as the Bozen quartz-porphyry in the Dolomites.

Epidote-ankerite schists

On top of the volcanic bed several metres of finer-grained meta-conglomerates follow. They are arranged in fining-upward cycles and grade into meta-pelites. The sequence consists of epidote-ankerite schists, impure quartzites and mica-schists. In the more pelitic members, occasionally graded quartzite horizons with thicknesses of 2–15 cm are intercalated. Up section the quartz content and grain size increase. The boundary with the overlying Windtal-Fm. is gradual. The high amount of Fe-minerals like iron-epidote (pistacite) and iron-dolomite (ankerite) results probably from the presence of hematite in the original rocks. This points to a warm climate with dry seasons and oxidizing conditions above the groundwater table in a well drained area (e.g. Sheldon 2005). This rather monotonous unit reaches a thickness of 50 m in the northern limb. In the southern limb the thickness increases up to 250 m, which implies a sediment transport towards the south.

Interpretation: A playa lake depositional environment is inferred. Distal parts of alluvial fans delivered fine-grained sediments into the playa lake. The floodplain was transected by a network of channels and sandy beds were deposited by crevasse splays. The stratigraphic position suggests an age in the range of Late Permian to Early Triassic. Several other Variscan basins in Europe display similar lithological characteristics and environmental setting during this time period (e.g. Glarner Verrucano Basin, Trümpy 1966, 1980; German Basin, Hauschke & Wilde 1999).

Windtal Formation

The Windtal Formation is only present to the west of the Pfitscher Joch, where its fold hinge closes. Because of its resistence to erosion it forms prominent cuestas (Fig. 8).

The thickness is about 30–40 metres. Rock types comprise whitish quartzites and muscovite quartzites; a subtle grey shade comes from finely distributed hematite and magnetite. Locally, the quartzites contain albite, lazulite, kyanite, manganese-epidote (thulite), tourmaline and staurolite. Isolated flattened quartz nodules up to 7 cm in diameter occur within the quartz- and muscovite-rich groundmass. Whether they represent originally isolated pebbles or disrupted quartz veins could not be resolved. The top of the Windtal-Fm. is overstepped by the carbonates of the Aigerbach-Fm. Considering the lithological characteristics and the stratigraphical position beneath the Aigerbach Formation, affinities to the Buntsandstein and a Scythian age of the Windtal Formation were already suspected by Lammerer (1986).

Interpretation: The absence of silty horizons and relatively high textural and compositional maturity would correspond to a wide braided river system with sand and gravel bars in channels. Due to the abundant hematite, a reddish colour of the original sandstones is likely and again points to semiarid climate. En-

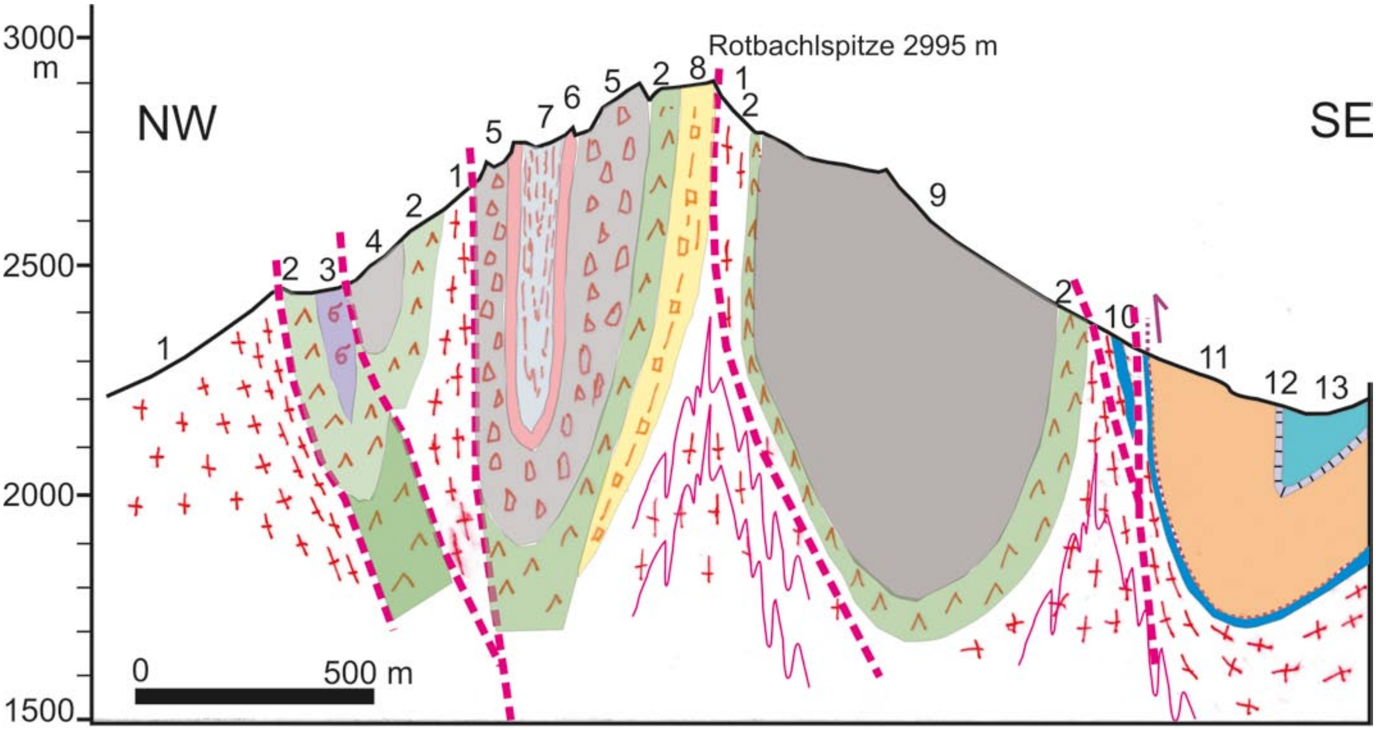


Fig. 7. Cross section through the Pfitsch Mörchner Basin to the east of the Pfitscher Joch. 1 – Tux "Zentralgneise", granite-gneiss lamellae along tectonic contacts Zillertal Gneiss in the SE, 2 – amphibolites or hornblende-garbenschists, 3 – serpentinite, ophicalcite, 4 – northern meta-conglomerates, 5 – coarse breccias and meta-conglomerates, rich in amphiboles in the matrix, 6 – meta-rhyolite, Lower Permian, 7 – Permian meta-conglomerates, quartzites and epidote-ankerite schists, 8 – quartz-pyrite schists, palaeosols, 9 – Palaeozoic graphite-bearing schists, post-Early Devonian, pre-Late Carboniferous, 10 -Hochstegen Marble, Late Jurassic, 11 – Kaserer Series (? Early Cretaceous or ? Late Permian to Early Triassic), 12 – Middle Triassic carbonates, 13 – Bündnerschiefer.

richments of Al and Fe within the sediment could have been caused by weathering effects during the deposition, as the more mobile components were leached away. An alternative explanation is provoked by the local concentration of phosphate minerals, like lazulite. Phosphate concentrations could signify metamorphosed fossil material like bones as a remnant of a bonebed horizon. Such layers are often connected with transgressions. In this case, the quartzites should represent coastal sands and the concentrations of e.g. tourmaline and magnetite could signify enrichment of heavy minerals along the beach. However, this interpretation is highly speculative.

Aigerbach Formation

The Aigerbach-Fm. covers the Windtal-Fm. conformably and continues from the Pfitscher Joch to the west. The boundary between the formations is sharp (Figs. 8, 9). Standard section is the locality Aigerbach, N of St. Jakob (Fig. 10). Its age was long presumed to be Middle and Late Triassic (Baggio et al. 1969). Isotopic studies (δ_{34}S and Sr seawater curves) confirm Late Triassic ages (Brandner et al. 2008). The formation name was given by Brandner et al. (2007).

The lowest part comprises greyish-violet marbles, yellowish calcitic and dolomitic marbles (15 m in thickness). Further up, the main rock portion is composed of thin-bedded white

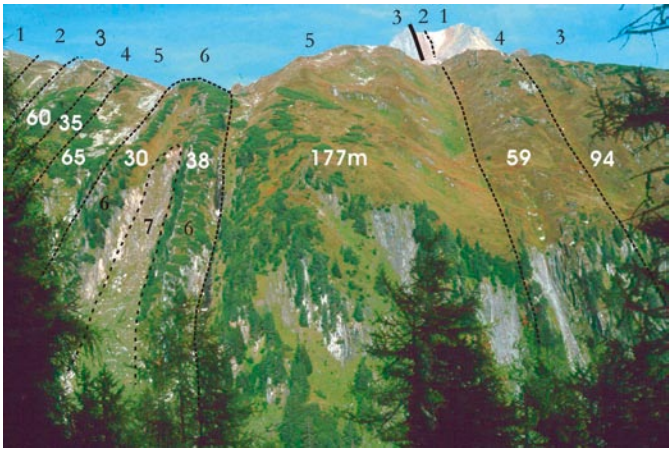


Fig. 8. The Pfitsch syncline in a view from the west towards the Pfitscher Joch and the Rotbachlspitze (2895 m) in the background. Due to an axial plunge steeper than the topography, the nearly isoclinal syncline appears like an anticline. Explanation: 1 – Tux Gneiss and granite-gneiss lamellae at Rotbachlspitze, 2 – amphibolites and serpentinites of the Greiner Series, 3–5: Pfitsch-Fm. (3 – meta-conglomerates, 4 – meta-rhyolite, 5 – epidote-ankerite schists), 6 – quartzites of the Windtal-Fm., 7 – limestones of the Aigerbach-Fm. The thickness of the southern limb (right) is despite higher flattening strain much larger than the northern limb. Bold line between 2 and 3 at the Rotbachlspitze marks the metamorphic soil horizon. White numbers show the true thickness of the beds in metres.

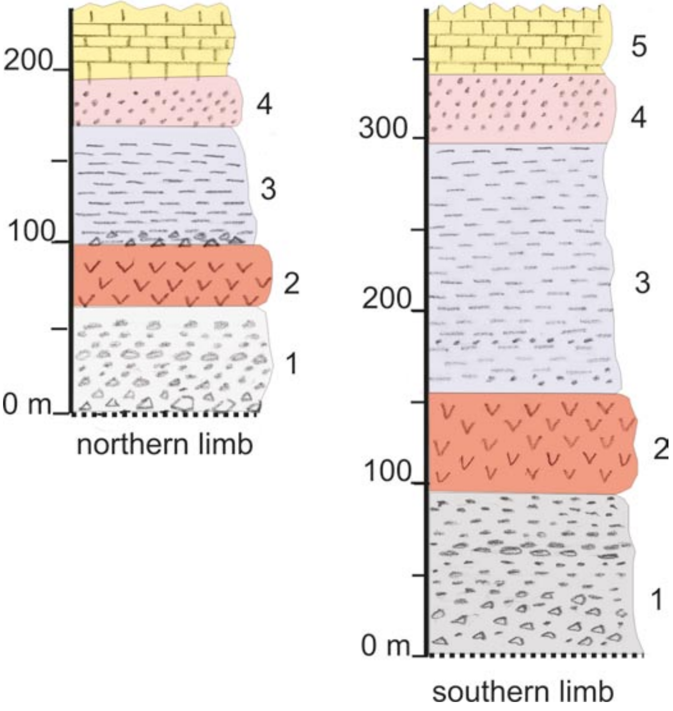


Fig. 9. Actual bed thickness in the northern and southern limb of the Pfitsch syncline, west of the Pfitscher Joch. To the west, thickness increases and has reached up to 1000 m. 1 – meta-conglomerate, 2 – meta-rhyolite (Lower Permian), 3 – epidote-ankerite schists, 4 – Windtal-Fm., 5 – Aigerbach Fm., dotted line – unconformity plane.

fine-grained dolomitic marbles, interlayered with yellowish cargneuls or dolomite which disintegrates surficially to cohesionless sands. Anhydrite and gypsum were discovered in exploration drillings to the Brenner Base Tunnel project (Brandner et al. 2007, 2008). At the surface, cargneuls (cellular dolomite) containing phyllite- and quartzite- fragments are attributed to those leached evaporitic layers. In the lower and in the upper parts of the section calcareous quartzites and various thin layers of kyanite-schists, chloritoid-schists, mica- and chlorite-schists, but also massive micaceous calcitic marble beds are interbedded. The formation reaches a thickness of about 110 m and it is covered by graphite- and kyanite-bearing quartzites, which are attributed to the Hochstegen-Fm.

Because of a thick cover of Pleistocene moraines, the outcrops to the west are not continuous, but can be extrapolated until the Wolfendorn area (Fig. 5). There, the Windtal-quartzites and the marbles of the Aigerbach-Fm. are reduced in thickness and in an onlapping contact to the once elevated area of the Tux Gneiss in the north.

Interpretation: The basal beds document a transition from continental siliciclastic to the lagoonal and shallow marine environment. The lowest part may be ascribed to the Middle Triassic but there is no proof. The higher portion of the Aigerbach-Fm. is interpreted as a sabkha and coastal sedimentary environment. It is characterized by great heterogeneity and alternation of siliciclastic and carbonate lithofacies. Evaporite formation and episodic influx of terrigenous clastics document repeated sea-level fluctuations, which resembles the Keuper facies of the Germanic Basin (Hauschke & Wilde 1999) or in the Helvetic Zone of the Swiss Alps (Frey 1968).

Hochstegen Formation

The Hochstegen-Fm. was first defined by Frisch (1980). It includes graphite-bearing quartzites and dark grey kyanite-schists at the base (10–40 m), some metres of brownish sandy lime marbles in the middle and the Hochstegen Marble on top (10–100 m true thickness, reported 200 m are due to the isoclinal folding).

The lowest unit of the Hochstegen-Fm. is composed of white or grey graphitic quartzites, graphitic kyanite-schists and, locally, a thin horizon of a black calcite marble. Aggregates of kyanite needles ("Rhätizit") are black from numerous tiny inclusions of graphite. An Early Jurassic age for this so-called "Hochstegenquarzit" has been proposed by Frisch (1968, 1980)

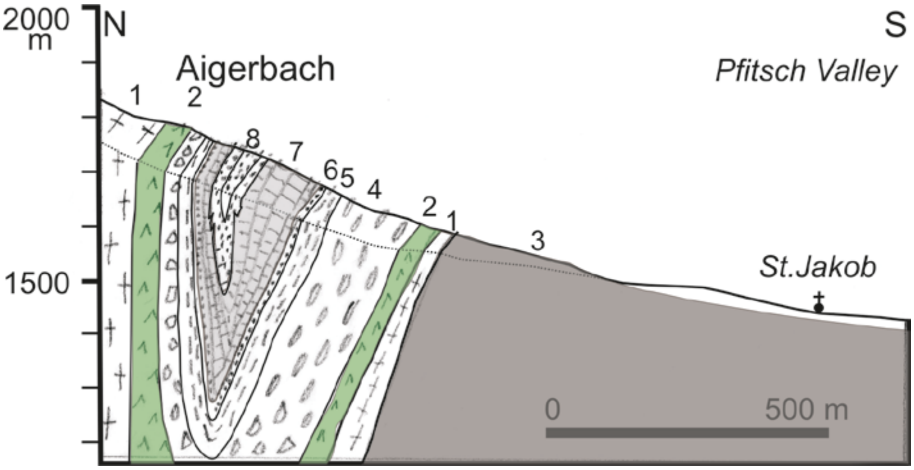


Fig. 10. Aigerbach section. 1 – Tux Gneiss, 2 – amphibolites of the Greiner Series, 3 – graphite-bearing schists of the Greiner Series, 4 – meta-conglomerates, 5 – epidote-ankerite schists, 6 – Windtal-Fm., 7 – Aigerbach Fm., 8 – quartzites of the Hochstegen-Fm.

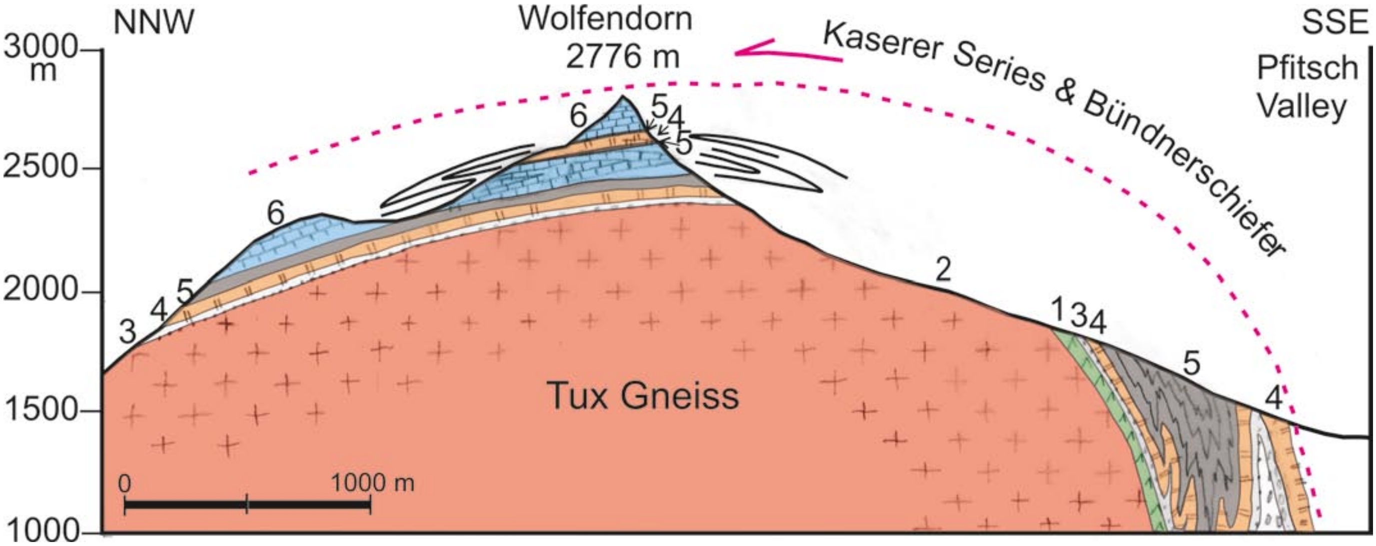


Fig. 11. Wolfendorn section. 1 – amphibolites of the Greiner Series, 2 – Variscan Granites (Tux Gneiss), 3 – Windtal-Fm., 4 – Aigerbach-Fm., 5 – quartzites of the Hochstegen-Fm., 6 – Hochstegen Marble.

in analogy to Liassic blackshales in Germany and Switzerland. It is overlain by only a few metres of brownish sandy calcite marbles, which may be attributed to the Middle Jurassic. On top follows the bluish-grey, fetid Hochstegen Marble. The lower part locally contains boudins of dolomitic beds; in higher horizons cherty nodules are common. An ammonite (*Perisphinctes sp.)*, belemnites, sponge spiculae, radiolaria and various open-marine microfossils are described from the Hochstegen Marble (Klebelsberg 1940; Schönlaub et al. 1975; Kiessling 1992). In the equivalent Silbereck Marble of the Eastern Tauern Window also corals could be found (Höfer & Tichy 2005). A detailed description of the Hochstegen-Fm. was given by Kiessling (1992). He found radiolarian and sponge spiculae of Oxfordian and Tithonian ages and stressed the striking similarities to the South German Malm. An affinity to the Helvetic Quinten Limestone of Eastern Switzerland was suspected by Thiele (1970). Frisch (1975b) made a comparative study with the Ultrahelvetic Grestener Zone in Austria.

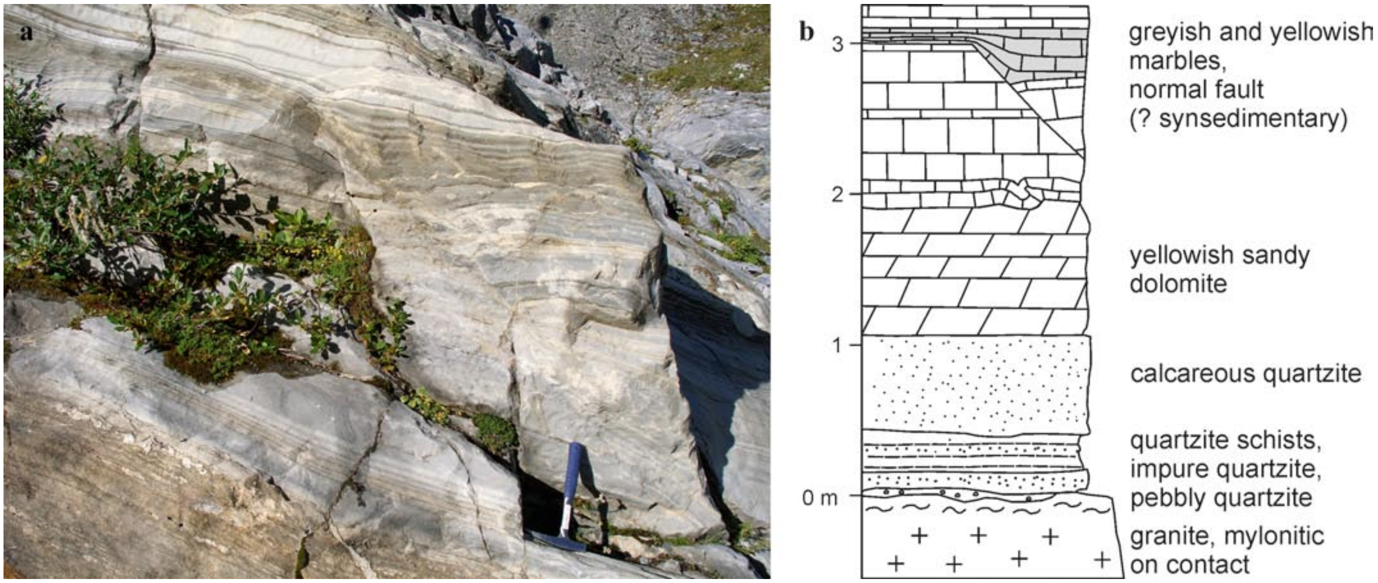


Fig. 12. a) The basal part of the Hochstegen-Fm. with ? synsedimentary normal fault, outcrop Grosser Kunerbach (11° 39' 38" E, 47° 05' 06" N). Fig. 12b) Detailed profile of basal units of Hochstegen-Fm., the same outcrop as Fig. 12a).

The Upper Jurassic carbonates overly in the Tauern Window post-Variscan sediments in the basins and granites or other basement rocks in the horst areas. A notable feature is the mylonitic shear deformation of the “Zentralgneise” at some contacts while the Hochstegen Marble is much less deformed. This implies that the sediments transgressed over a tectonically exhumed basement, which reminds of a Basin-and-Range-like situation. Continuing extensional processes during deposition of the Hochstegen Limestone are visible from synsedimentary normal faults (Fig. 12).

Interpretation: A coastal plain depositional environment with organic-rich sands and mudstones is inferred for the quartzites and the kyanite-schists. The local massive light quartzites may represent fluvial sand bodies or sandy deltaic horizons. A short episode of submergence is documented by the single calcite marble horizon. The more finely laminated quartzite and graphite-bearing schists resemble a fan-delta environment with succession of mudstones and sandstones. The overlying brownish sandy calcite marbles mark the widespread marine transgression during the Middle Jurassic which can be traced far to the north under the Molasse basin (Lemcke 1988). The deposition of the Hochstegen Marble took place under shallow water conditions in the lower parts (dolomitic horizons), but the higher horizons are attributed to deeper water conditions. Kiessling (1992) proposed an outer shelf environment under semi-reducing conditions because of a frequent H_2S content and microfossils which were pyritized during early diagenetic processes.

The well exposed Wolfendorn section is a matter of debate since decades. Tollmann (1963) proposed a Palaeozoic age of the graphite-bearing quartzites (? Lower Jurassic) and, consequently, assumed a thrust plane here. Because the quartzites apparently rest also over the Hochstegen Marble, due to a recumbent isoclinal fold (Fig. 11), he drew another thrust. Tollmann (1963) and Frisch (1975 a) describe both carbonates as Hochstegen Marble. The present authors, on the contrary, attribute the lowest carbonates to the Aigerbach-Fm. because of the remnants of Windtal-Fm. beneath and the sedimentary contact to the Hochstegen-quartzite of presumed Early Jurassic age above which was already recognized by Frisch (1975a).

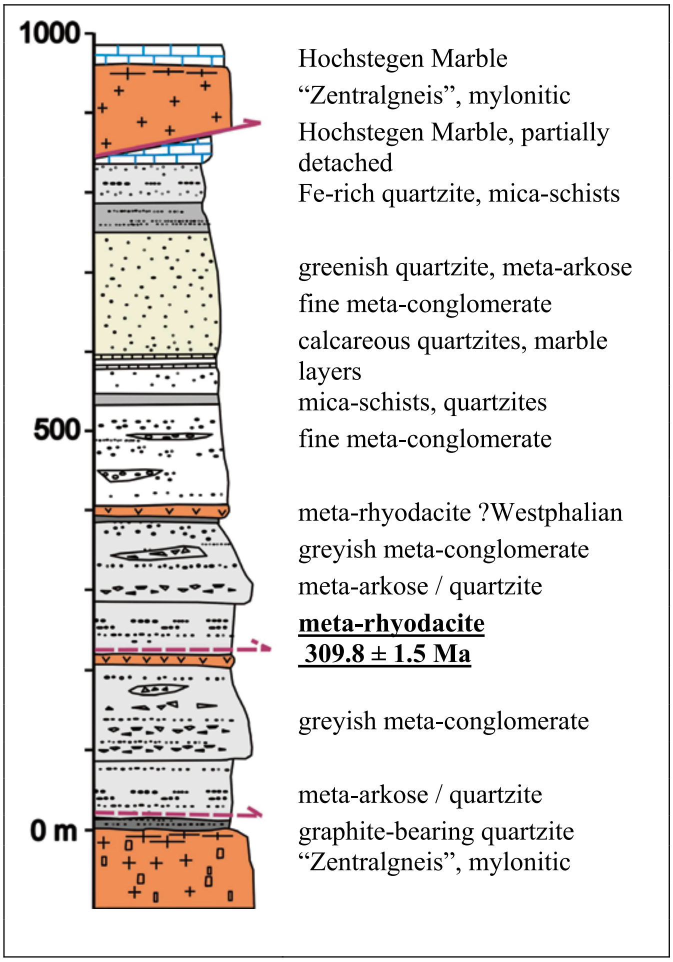
Other occurrences of post-Variscan sediments

The well exposed Riffler-Schönach Basin forms an elongate belt between the Ahorn- and Tux Gneisses. Detailed descriptions are already given by Thiele (1974), Sengl (1991) and Veselá et al. (2008). Therefore we present here only a new age datum from a meta-rhyodacite of Westphalian age (309.8 ± 1.5 Ma, Table 1) from the Hoher Riffler area and show its position in the stratigraphic column (Table 3).

Around Mayrhofen, the “Porphyrmaterialschiefer Series” frames as a thin ribbon the northern Tauern Window and represents the northern continuation of the Tux Gneiss thrust sheet (Veselá et al. 2008). It contains layers of meta-rhyolites with porphyritic textures. In addition, graphite-bearing phyllites, quartzites, arcoses and amphibolites occur. The Porphyrmaterialschiefer is unconformably covered by calcite marbles which are attributed to the Hochstegen-Formation. Deformation of the rocks is too severe for detailed sedimentological investigation (e.g. Dietiker 1938; Beil-Grzegorczyk 1988). A layer of rhyolitic to andesitic metavolcanic rocks has been dated at 284 +2/-3 Ma (Söllner et al. 1991, Table 1). The Lower Permian meta-rhyolites cover directly the Tux Gneiss at several locations in the western Tauern Window (e.g. the Venntal meta-rhyolite gives an age of about 293 Ma, F. Söllner pers. comm). It documents Early Permian subaerial volcanic activity after the exhumation of the Tux Gneiss and the age maximum of the Porphyrmaterialschiefer Series. The Porphyrmaterialschiefer Series forms a thrust sheet which is sometimes described as “Porphyrmaterialschieferschuppe” (Frisch 1968, 1974; Thiele 1974). Because of the unspeakable name, Thiele (1976) proposed to rename it Torhelm nappe, after the Torhelm (2452 m), a mountain east of Mayrhofen (Fig 2).

The Maurerkees Basin is situated on the southern margin of the Tauern Window and it is a part of the so-called “Mi-

Table 3. Lithostratigraphy of the Riffler-Schönach Basin, Hoher Riffler area



caschist unit", which is folded into the migmatic basement rocks ("Old Gneiss Series") (Schmidegg 1961; Raith et al. 1980). It comprises graphite-garnet schists, quartzites, meta-arkoses and meta-conglomerates. The sedimentary succession displays characteristics of an anastomosing river system and a shallow lacustrine depositional environment, where peat deposits developed. Although the metamorphism reached amphibolite facies, the graphitic schists yielded plant fossils proving Stephanian to Early Permian age (Franz et al. 1991; Pestal et al. 1999).

In the Eisbruggjoch area (Ponte di Ghiaccio) meta-sediments have been found between the two lamellae of the Upper Jurassic Hochstegen Marble. The marbles were folded and internally thrust, so that the subjacent chlorite-schists, banded mica-schists and quartzite-schists are emplaced in between. All these rocks are characterized by a varying amount of finely disseminated ankerite. Thin marble horizons are intercalated and Baggio et al. (1982) report also meta-conglomerates with amphibolite- clasts and lenses within this layer. The age of the meta-sediments is unknown. However, considering the presence of basement-derived rocks (amphibolite) and carbonate horizons, a Permian-Triassic age can be presumed.

The stratigraphic position of the Kaserer Series is still debated due to the complete lack of datable fossils. A Cretaceous age was deduced from apparent conformable contacts to the Hochstegen marble by Frisch (1974), Thiele (1974) and Rockenschaub et al. (2003). In contrast, a Permo-Triassic age was suspected by Dietiker (1938), Tollmann (1963), Fenti & Friz (1974), Lammerer (1998) and Veselá et al. (2008). The older age is supported by the occurrence of sheared anhydrite (of ? Triassic age) within the Kaserer Series and along the contact to the Upper Jurassic Hochstegen Marble which was found in drill cores from the Brenner base tunnel project (Brandner et al. 2007, 2008). In addition, there is an apparent oscillating sedimentary transition to the Middle Triassic carbonates of the Schöberspitzen. The Kaserer Series is composed of a variegated succession of fluvial sediments and shallow marine deposits with evaporites, coarse- to fine-grained quartzites, arkoses, meta-conglomerates, black phyllites, mica-schists and dolomites. In our interpretation, the Kaserer Basin represents the southernmost rift-related trough, which evolved later to the Penninic Ocean. Several serpentinite lenses which are incorporated into the Kaserer metasediments indicate that the once shallow basin lost its substratum by large-scale low-angle extensional faults and came into contact with mantle rocks. During the Alpine convergence phase, the sediments of the Kaserer Basin were stacked and thrust together with a basement slice of a Cambrian meta-gabbro over the Tauern area together with the whole stack of the Penninic Bündnerschiefer nappes of the Outer Tauern Window (Veselá et al. 2008).

Conclusions

In spite of the metamorphic overprint, the tentative interpretation of the sedimentary history of the Carboniferous to Jurassic strata gives a reasonably consistent picture which fits into the geodynamic history of the Alps. The metasediments of the Tauern Window exhibit striking similarities with coeval non-metamorphic deposits within the Germanic Basin. The study area is therefore considered to have been part of the Vindelician Land until the Middle Jurassic.

The earliest post-Variscan sediments of the western Tauern Window could be dated into the Westphalian. These are greyish conglomerates and minor blackschists, which cover the undated but almost certainly Upper Carboniferous Ahorn Gneiss and are topped by metavolcanics of Westphalian age (309.8 ± 1.5 Ma, Moscowian stage after Gradstein et al. 2004). These deposits are interpreted as sediments of alluvial fans and braided rivers. The blackschists, which locally contain plant fossils, reflect formation of peat deposits within a low energy environment of anastomosing rivers. Together with the rhyodacitic and rhyolitic lava flows, they mark periods of accelerated tectonic subsidence in the basin at the end of Carboniferous and beginning of Permian. The relatively short time span between the intrusion of the granitoids and the onset of the basin formation requires fast uplift rates and active tectonic exhumation. In the Pfitsch-Mörchner Basin, the volcanic activity lasted until the Artinskian stage of Early Permian, accompanied by the formation of fanglomerates. The sedimentary fill nicely documents the stepwise denudation of the Variscan orogen and concomitant subsidence of the basins.

The Mesozoic history of the basins may be interpreted as follows: The increasing amount of playa-lake deposits in Late Permian and Early Triassic times documents the lowering of the continental relief. Carbonates and cargneuls are attributed to the ? Middle- and Upper Triassic. They document that the elevation of the basin floors was close to sea level where even a small relative sea-level rise led to flooding of vast areas. A coastal to deltaic depositional environment prevailed but sediment delivery from continental sources persisted until the Jurassic. In response to continued crustal extension and relative sea-level rise, marine conditions were established from the ? Middle Jurassic which is contemporaneous to the break-up of the Penninic-Ligurian Ocean (e.g. Bill et al. 2001) leading to rapid subsidence and the submergence of the adjacent continental margins. The Late Jurassic Hochstegen-Fm. was deposited when the entire area (or at least most parts) of the Tauern Window was drowned and, locally, even deeper marine conditions established. Unambigeously dated Cretaceous sediments are not known from the Inner Tauern Window, but are debated for the Kaserer Serie. On the other hand, there is no need for a continuous sedimentation because an erosional surface on top of Upper Jurassic strata is widespread also in the Molasse foreland.

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