Post-Variscan to Early Alpine sedimentary basins in the Tauern Window (eastern Alps)

P. VESELÁ[1], B. LAMMERER[1], A. WETZEL[2], F. SÖLLNER[1] & A. GERDES[3]

[1]*Department of Earth and Environmental Sciences; Ludwig-Maximilians-Universität, Luisenstr. 37, D-80333 München, Germany (e-mail: petra.vesela@iaag.geo.uni-muenchen.de)*

[2]*Geologisch-Paläontologisches Institut, Universität Basel, Bernoullistrasse 32, CH-4056 Basel, Switzerland*

[3]*Institute of Geosciences, Petrology & Geochemistry, Johann Wolfgang Goethe-Universität, Senckenberganlage 28, D-60054 Frankfurt am Main, Germany*

Abstract: The crystalline basement of the Tauern Window is locally covered by Palaeozoic to Mesozoic sediments that experienced Alpine tectonometamorphism. The sedimentary cover has been subdivided into mappable lithological units. The correlation of these units, the use of some dated marker intervals and independent palinspastic restoration provide evidence that the depositional area was differentiated into basins and swells. At the end of the Variscan orogeny, during the Carboniferous and Permian, intermontane basins formed in basement rocks and mainly continental clastics accumulated in elongate troughs. Later, probably during the Triassic, there was levelling of the previous relief and subsidence of the basins, but continental sedimentation still prevailed although interrupted by some marine transgressions. Thereafter, probably during the Jurassic, the area was progressively flooded and the sedimentation became increasingly calcareous. The Upper Jurassic carbonates document complete submergence. In some areas, the Upper Jurassic carbonates directly rest on crystalline basement indicating renewed tectonic stretching. The sedimentary cover shows striking similarities with coeval deposits within the Germanic Basin and the study area is therefore considered to have been part of the southern European continental margin of the Tethys (the so-called Vindelician Land).

In addition to the classical ocean floor magmatic rocks and the overlying deep-marine deposits, mountain belts consist of continental margin and shelf deposits and their basement (e.g. Coward & Dietrich 1989). The latter especially store valuable information about the pre-orogenic palaeogeographical situation and the early history of an evolving continental margin. This is true for the Alps. However, where the continental crust and its sedimentary cover have experienced a strong tectonometamorphic overprint, deciphering the pre-orogenic history is far from straightforward.

Continental margins are characterized by deep-rooted faults and even the adjacent shelf areas may be affected by block-faulting. For instance, fault systems developed during the Late Palaeozoic (e.g. Arthaud & Matte 1977) became re-activated during the Mesozoic rifting of the central Atlantic and Tethys Oceans (e.g. Benammi & El Kochri 1998; Bouaziz *et al.* 1999). Such reactivated faults are known to influence the lithological development of the sedimentary cover (e.g. Faerseth 1996; Keeley 1996; Wetzel *et al.* 2003). It appears that pre-existing Late Palaeozoic faults and associated grabens strongly affected the tectonosedimentary development in that part of the Alps which is exposed today in the Tauern Window (Lammerer *et al.* 2008). It is the purpose of this paper to unravel the relationships between the Late Palaeozoic tectonic structures, including grabens, and the Mesozoic sediments.

Geological setting

Numerous small, elongated basins are known from the Alpine area and its northern foreland which formed at the end of the Variscan orogeny during the Late Palaeozoic as intermontane, fault-bounded basins (e.g. von Raumer 1998). Examples are the Permo-Carboniferous basins of northern Switzerland (Matter 1987), the Lake Constance and Landshut–Neuötting Basins (Lemcke 1988) continuing to basins within the Zentrale Schwellenzone in Austria (Kröll *et al.* 2006) which are only known from drilling and seismic imaging. Within the Alps, well-exposed examples are the Salvan-Dorénaz Basin in the Aiguille Rouge Massif (Capuzzo *et al.* 2003; Capuzzo & Wetzel 2004) and the basins within the Aar–Gotthard Massif (Franks 1966; Oberhänsli *et al.* 1988; Schaltegger & Corfu

From: SIEGESMUND, S., FÜGENSCHUH, B. & FROITZHEIM, N. (eds) *Tectonic Aspects of the Alpine-Dinaride-Carpathian System.* Geological Society, London, Special Publications, **298**, 83–100.
DOI: 10.1144/SP298.5 0305-8719/08/$15.00

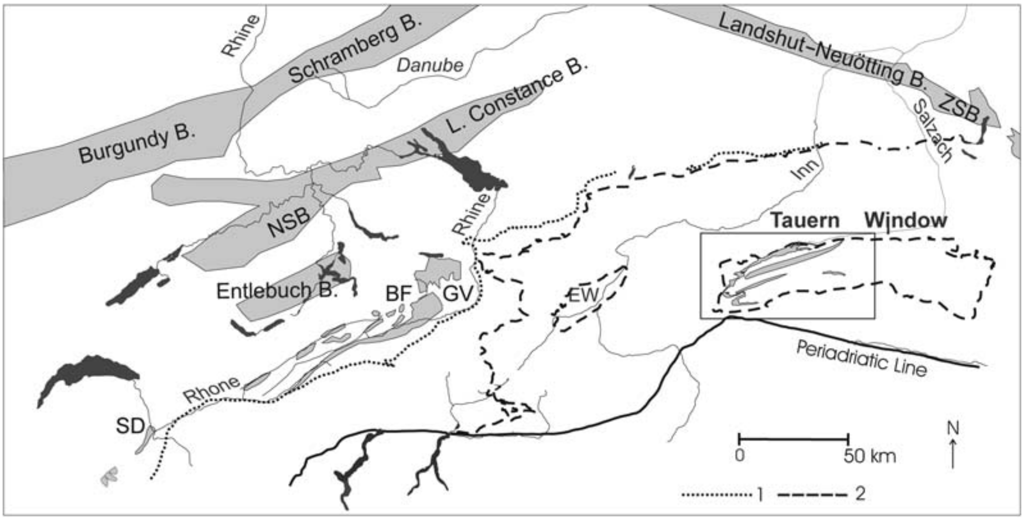


Fig. 1. Post-Variscan basins in Central Europe and Alpine realm (modified after Lemcke 1988; Ménard & Molnar 1988; Kröll *et al.* 2006; McCann *et al.* 2006). 1, Penninic-Helvetic thrust plane; 2, Austroalpine-Penninic thrust plane; SD, Salvan-Dorénaz Basin; NSB, Northern Swiss Permo-Carboniferous Basin; BF, Bifertengrätli Basin; GV, Glarner Verrucano Basin; EW, Engadine Window; ZSB, Zentrale Schwellenzone Basins. The inset frame shows the position of Figure 2.

1995). Besides the sediment fill with continental clastics and some volcaniclastic material, these basins share the similarity of being emplaced within basement rocks, mostly of Late Variscan age (Fig. 1).

In the eastern Alps, the European basement is exposed only in the Inner Tauern Window. Therefore, it represents an important link between the basement outcrops of central Europe and the Tisza Block in the Pannonian Basin (Haas & Péró 2004).

Post-Variscan sediments in the Tauern Window

The basement rocks of the Tauern Window consist of Variscan granitic plutons (locally called Zentralgneise) now metamorphosed and deformed which intruded into Lower Palaeozoic and older host rocks including amphibolites and graphite-bearing metasediments (e.g. Finger *et al.* 1993). Together they form a huge duplex structure, which has been uplifted along a deep-reaching ramp (Lammerer *et al.* 2008).

Within the Inner Tauern Window, four Late Palaeozoic to Mesozoic elongate, trough-like basins have been identified. Three of these, the Riffler–Schönach Basin, the Pfitsch–Mörchner Basin and the Maurerkees Basin, are separated by tectonic horsts consisting of basement rocks (Ahorngneiss Horst, Tux Gneiss Horst and Zillertal Gneiss Horst). The fourth basin, the Kaserer Basin, represents, in our interpretation, the southernmost rift-related trough, which developed during the Pangea break-up event that formed the Penninic Ocean. The sediments were detached and overthrust at the base of the Bündnerschiefer (Penninic) Nappes stack (Fig. 2).

The stratigraphically youngest post-Variscan unit that formed within the whole area is the Upper Jurassic Hochstegen Marble (Schönlaub *et al.* 1975; Kiessling 1992). It represents the eastern continuation of the Quinten Limestone of the Helvetic realm in Switzerland. The Hochstegen Marble covers both the former graben and horst areas and varies from between 20 and 400 m in thickness.

The age dating of metasediments which formed prior to the Hochstegen Marble is subject to some uncertainty, because metamorphism and deformation has destroyed almost all fossil material. A lower limit is given by the youngest age of the basement, which is 295 ± 3 Ma (Cesare *et al.* 2001) and an upper limit by the Hochstegen Marble, which began to be deposited in the Oxfordian at 160 Ma (Kiessling 1992). Lower Permian quartz porphyries (Söllner *et al.* 1991) and Anisian deposits with crinoids (Frisch 1975) represent further time markers. Plant fossils have been found so far only in the small Maurerkees Basin, proving a Late Carboniferous

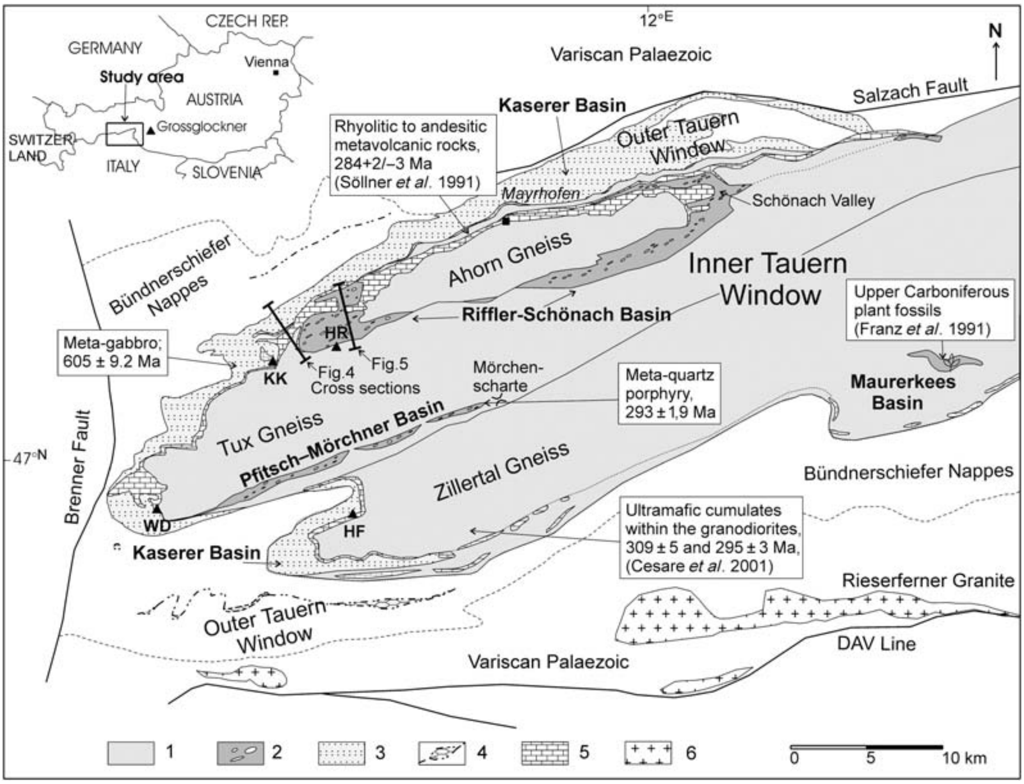


Fig. 2. Geological sketch map of the Tauern Window and the position of the post-Variscan basins. 1, Palaeozoic rocks and Variscan granites; 2, post-Variscan clastic sediments (Upper Carboniferous–Lower Jurassic); 3, Triassic clastic sediments and carbonates at the base of the Bündnerschiefer; 4, limestones, dolomites and cargneuls (Anisian); 5, Hochstegen Formation (Jurassic); 6, Alpine granites (Oligocene); HR, Hoher Riffler (3231 m); HF, Hochfeiler (3510 m); KK, Kleiner Kaserer (3039 m); WD, Wolfendorn (2776 m); DAV Line, Defereggen-Antholz-Vals Fault.

to Early Permian age (Franz *et al.* 1991; Pestal *et al.* 1999).

To unravel the post-Variscan history, the rock successions covering the Palaeozoic basement have been subdivided into mappable lithological units which can be correlated within the study area. Although these units fulfil the requirements of lithostratigraphical formations, their definition as such is beyond the scope of this paper. The most continuous succession is exposed in the Riffler–Schönach Basin and it is used as standard section within this paper. Various lithofacies associations have been distinguished on the basis of lithological changes and vertical succession, dominant grain size or grading. Due to the folding and metamorphism (which reached amphibolite facies), in most instances it has not been possible to classify the internal geometry of the beds, the detailed characteristics of any bounding surfaces or the palaeocurrent patterns. The mineral paragenesis reflects the composition of the protolith. In some instances, rock colour proved to be a useful criterion.

In view of these limitations, the reconstruction of the sedimentary environment and evolution of the basins is not an easy task, but field geology in the very well-exposed Alpine area has provided much new information and revealed some surprising findings. The purpose of this work is to define the lithostratigraphical units constituting the basin fill and to decipher the basin evolution. The stratigraphical scheme presented in this paper is based not just on the geochronological data and lithological changes but also on the correlation with units in the western Alps, southern Germanic Basin and the Bohemian Massif under the Bavarian and Austrian Molasse Basin.

Pfitsch–Mörchner Basin

The Pfitsch–Mörchner Basin extends from the Pfitsch Valley (Italy) in a SW–NE direction over

20 km to the Mörchenscharte (Austria). Its sediments are tightly folded into a syncline which plunges to the west and wedges out at the Mörchenscharte (2872 m) (Fig. 2). The clastic series of the basin fill starts with conglomerates and breccias (Fig. 3a) intercalated with volcaniclastics. The geochronological analysis of a volcanic extrusion from a locality near to the Mörchenscharte was carried out. As described below, zircons from meta-quartz porphyry cutting old basement rocks and covered

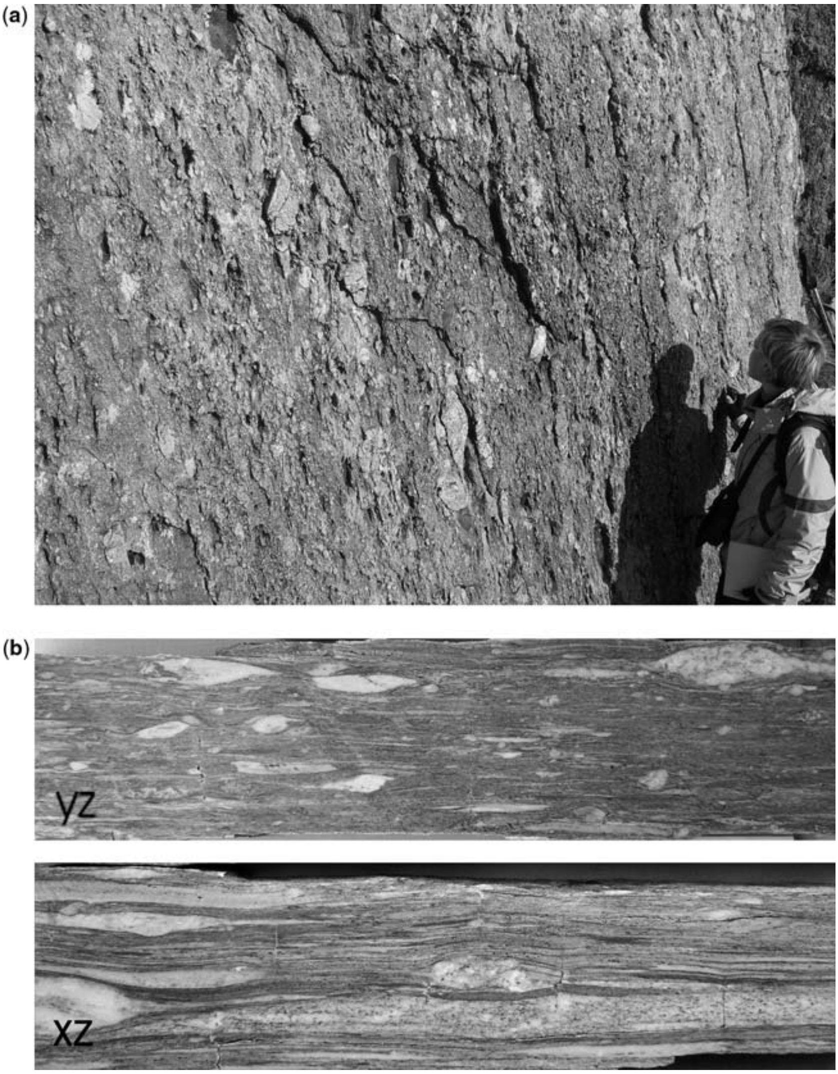


Fig. 3. (**a**) Metaconglomerates. Texturally immature and poorly sorted coarse-grained polymict matrix-supported metaconglomerates representing the proximal part of an alluvial fan (Unit I). Angular to subangular clasts and boulders up to 30 cm in size are predominantly granitic in origin, but also some amphibolites, graphite-bearing schists, marbles and very rare serpentinite clasts occur. The greyish matrix is of sand and silt size. Pebbles show relatively low prolate strain in a tectonically protected area at the Pfitscher Joch, Langsee, 2240 m (Austrian/Italian border). (**b**) Polished sections of a metaconglomerate from the Pfitscher Joch cut in x–z and y–z directions of the strain ellipsoid. Pebbles of aplites, granites and quartzites show strong flattening strain in an outcrop 500 m to the south of that shown in (a). Long axes of the specimens are 28 cm. (**c**) Same specimens as in (b) but the z-axis was stretched twice and the x-axis was shortened to $\frac{1}{2}$ by optical methods in order to partially remove the natural strain. The original angular shape of the more competent pebbles and the poor sorting is fairly good visible in the y–z cut. In the x–z direction, the natural strain is too high to provide a satisfactory result.

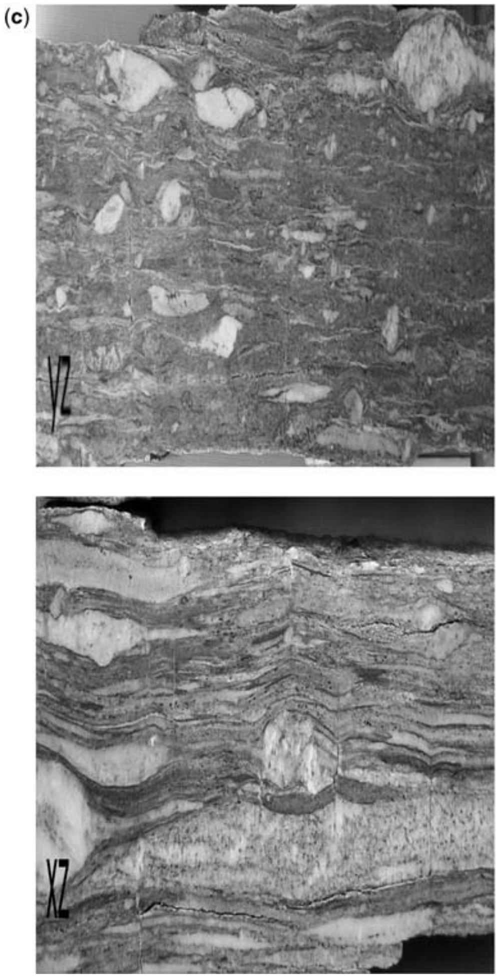


Fig. 3. (*Continued*)

by a meta-conglomerate provide a Late Carboniferous age (293 ± 1.9 Ma) of the magma extrusion. This documents a volcanic activity during initial phases of the basin formation along deep normal faults. The unconformably overlying meta-conglomerates are thus Early Permian or younger in age. Above this, the sediments grade into metapelites and quartzites. Although this fining-upwards succession is about 250 m thick, the geometric analysis of the stretched and flattened pebbles, however, suggests an original thickness in the range of 1 kilometre (Lammerer & Weger 1998) (Fig. 3b, c).

These clastic sediments are overlain by limestones, dolomites and cargneuls of the Aigerbach Formation, which is Middle to Late Triassic in age (Brandner *et al.* 2007). Later fine-grained clastic sediments were deposited; these are supposedly Late Triassic to Early Jurassic in age. To the west, the succession continues upward into the Upper Jurassic Hochstegen Marble. When tracing the Hochstegen Marble to the Wolfendorn area farther to the west, its substrate changes. There, the marble rests only on a thin veneer of Triassic rocks which in turn rest on the basement consisting of Variscan granitoids of the Tux Gneiss. This geometry suggests the onlapping of the basinal sediments onto an elevated area in the north which we interpret as a graben-horst geometry. The basement of the Pfitsch–Mörchner Basin consists of Early Variscan metamorphic rocks like amphibolites and graphite schists (Greiner Schists). These easily erodable rocks formed the graben floor, while the horst positions were made by more resistant granitoids.

The Kaserer Basin

We interpret the fill of the Kaserer Basin as being deposited in a basin that was situated to the south of the Tauern Window and which developed during the Pangean break-up into the Penninic Ocean. These beds form the base of the Penninic Bündnerschiefer and together they were thrust over the European basement as a nappe stack which forms the Outer Tauern Window. Kaserer Basin comprises of sediments of the so-called Kaserer Series, Seidlwinkel Formation and Aigerbach Formation (Middle to Upper Triassic marbles, dolomites and cargneuls) and the so-called Wustkogel Series.

We consider the complex structure of the Outer Tauern Window as an internal thrust and folded sediment stack. The evidence for this is the way that Middle to Upper Triassic carbonate rocks and evaporitic deposits (and other evaporite horizons of uncertain age) occur at several tectonic levels: at the base, within and on the top of the Kaserer and Wustkogel Series and also within the Bündnerschiefer Nappes. These evaporitic sediments presumably served as detachment horizons during the thrusting of the nappes.

Kaserer Series. The substrate of the Kaserer Series was initially formed by Palaeozoic and older basement rocks. During the Mesozoic, these rocks became extensively stretched and boudinaged and, finally, mantle-derived rocks have been emplaced at the basin floor during deposition of the sediments. This is documented by serpentinite bodies, which are incorporated into the Kaserer Series north of Mayrhofen (Thiele 1974) and by a meta-gabbro of Cambrian age (534 ± 9.4 Ma) exposed along a thrust plane in the Tuxer Joch area (Fig. 4). Geochronological data and dating methods of the

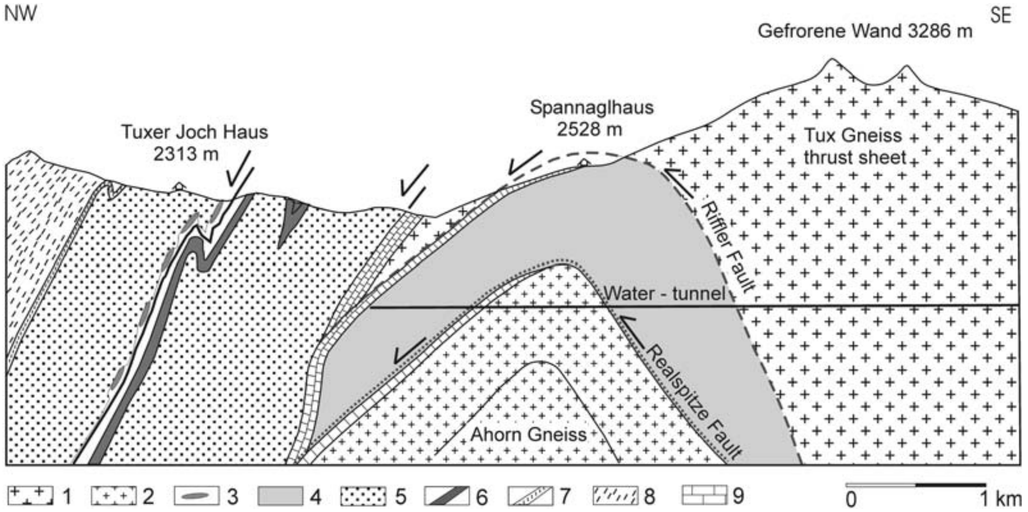


Fig. 4. Cross-section through the Tuxer Joch–Kaserer area. 1, Variscan granites, Ahorn Gneiss; 2, Variscan porphyric granite, Tux Gneiss; 3, Cambrian meta-gabbro within the thrust plane; 4, post-Variscan clastics of the Riffler–Schönach Basin; 5, Permo-Triassic Kaserer Series; 6, Triassic marbles; 7, cargneuls and quartzite, Upper Triassic; 8, Bündnerschiefer Series (Lower Jurassic–Upper Cretaceous); 9, Hochstegen Formation (Upper Jurassic).

meta-gabbro are presented in a separate section below (Figs 8a, b). Similar ages of metabasites occur in other positions within the Tauern Window basement and the Austroalpine basement more to the east (e.g. Kebede *et al.* 2005).

The basal deposits of the Kaserer Series consist of so far undated quartzites, meta-arkoses and mica- and graphite-bearing schists. Occasionally, these rocks exhibit graded bedding. They are well exposed at the Kleiner Kaserer (3091 m) where they have been thrust onto the Jurassic Hochstegen Marble. A succession, more than 100 m thick, with thin horizons of dolomitic marbles, marbles and cargneuls in the upper part of the Kaserer Series (Schöberspitzen), represents a correlative of the dated Anisian rocks (Frisch 1975) in the Wolfendorn area. The nature of the underlying strata and the correlation with the Wolfendorn deposits suggest that the Kaserer Series ranges in age from Late Permian to Early Triassic age, respectively.

Wustkogel Series. In the northern Tauern Window, the so-called Wustkogel Series overlies the Middle Triassic carbonates and form the immediate base of the Bündnerschiefer. The series consists of equigranular greenish quartzite, impure feldspar-rich meta-arenites and meta-arkoses and metaconglomerates showing thin-bedded variations in composition. The gradual transition to the Bündnerschiefer exhibits several coarsening-upward cycles with laterally persistent horizons of cargneuls and limy graphite-bearing schists intercalated into the quartzites. These beds are interpreted to represent fluvial- and delta-systems prograding into a progressively subsiding basin, where evaporitic conditions prevailed. This sequence is very well exposed in the Tuxer Joch and Gerlos area.

Stratigraphic Issues. The stratigraphy and the structure of the Outer Tauern Window is a still a matter of debate. Dietiker (1938), who mapped the area around Mayrhofen and Gerlos, proposed a Permo-Triassic age for the rocks of the Kaserer Series and saw a nappe contact with the Hochstegen Marble. On the contrary, Thiele (1974) presumed that the ‘Kaserer Series’ lay in sedimentary contact with the Hochstegen Marble and proposed an Early Cretaceous age, whilst noting that a definite stratigraphic position awaited fossil findings. Later workers accepted Thiele’s opinion of a Cretaceous age due to an apparent conformable contact in the Wolfendorn area (Frisch 1974, 1980; Lammerer 1986; Rockenschaub *et al.* 2003).

Our more recent field observations, on the other hand, pose some strong arguments against a conformal position:

(1) At the type locality, the Kleiner Kaserer (3096 m), a tectonic horizon exists, as the Hochstegen Marble is parallel to the smooth Zentralgneiss surface, while the Kaserer Series beds are strongly folded. A tectonic horizon within the Kaserer Series is further documented by several bodies of serpentinite near Mayrhofen.

(2) There is a clear sedimentary oscillatory transition from the Kaserer Series to the overlying

Schöberspitzen limestones and dolomites which lie in the same horizon as the carbonates from the Kalkwandstange in which Frisch (1974) found Anisian crinoids. However, he supposed a tectonic contact with the underlying Kaserer Series, but outcrops are poor at that critical position.

(3) In drillings for the Brenner base tunnel, sheared anhydrite was encountered between Hochstegen Marble and the Kaserer Series (Brandner *et al.* 2007). This is uncommon in Cretaceous deposits of that area, but common for the Permo-Triassic series and for thrust horizons.

For all these reasons, we preliminarily suggest a ?Permo-Triassic age for the Kaserer Series.

A second debatable unit is the so-called Wustkogel Series. Here, we prefer to use a stratigraphically more neutral term, the 'Green Meta-arkoses Series' proposed by Thiele (1970). A Permo–Scythian age is generally assumed for this because of its affinity with the Gröden Sandstone Formation and the Buntsandstein. The term the Wustkogel Series refers to the Seidlwinkel Formation which is Middle Triassic in age, and its subjacent strata (Frasl 1958; Frisch 1968; Höck 1969). Thiele (1970) however doubted this stratigraphic position because the 'Green Meta-arkoses Series' lies on top of the Anisian carbonate rocks and grades into the Jurassic Bündnerschiefer' and so he proposed a Late Triassic age. We support this correlation but recognize its provisional nature. The Stubensandstein of Central Europe can be seen as an equivalent. Feldspar-rich sands were supplied to the Germanic Basin from uplifted areas in the south, the so-called Vindelician Land (Ziegler 1990). The same area might have delivered sediment at its southern side to the south European continental margin.

The Riffler–Schönach Basin

The Riffler–Schönach Basin is a well-exposed Variscan basin which today forms an elongate, SW–NE trending belt. This follows the general strike of the Ahorn Gneiss Horst and dips about 10°–16° to the southwest as well to the east under the Tux Gneiss thrust sheet (Fig. 2). The south-eastern part is known as the 'Schönachmulde', (literally 'the Schönach syncline', see Thiele 1974; Miller *et al.* 1984; Sengl 1991). This term, with its suggestion of a syncline, is misleading, as the sediments dip uniformly to the south and are in upright position. The mesoscale asymmetric folds are all north-verging due to shearing and thrusting.

In the Hoher Riffler area, a section about 800 m thick is exposed; the lowermost part is internally thrust, doubling about 170 m of rocks (Fig. 5; Table 1). The clasts in the metaconglomerates are flattened and stretched in the E–W direction. The minimal original thickness of the basin fill is

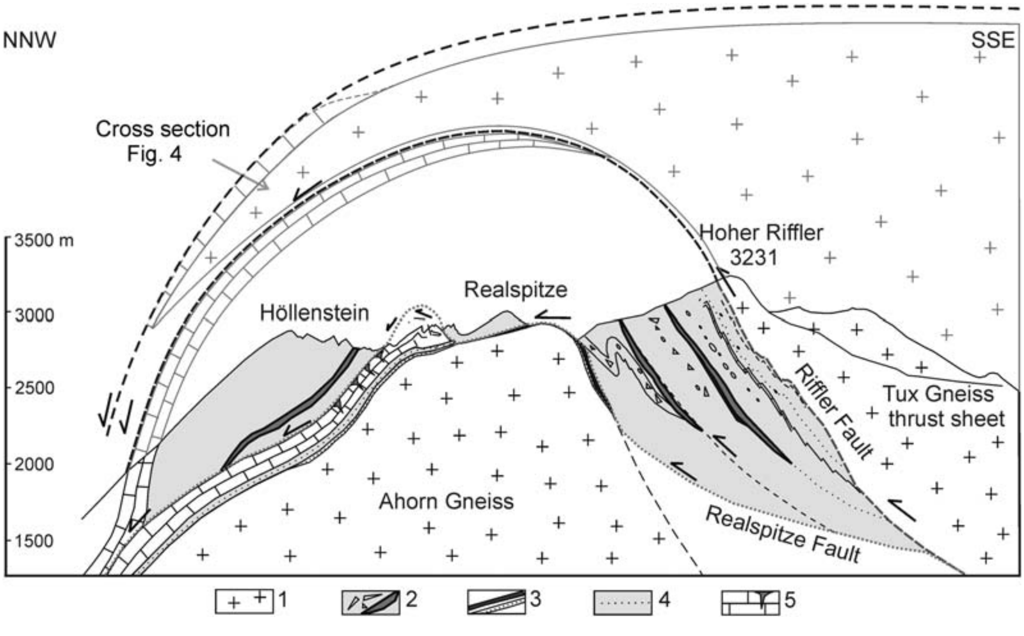
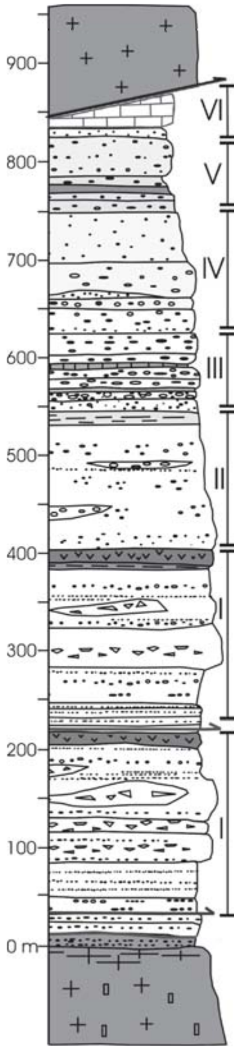


Fig. 5. Cross-section through the Hoher Riffler area. 1, Variscan granites and Palaeozoic basement rocks; 2, post-Variscan clastic sediments and meta-rhyodacite of the Riffler–Schönach Basin; 3, graphite-bearing schists and quartzites (? Lower Jurassic); 4, sandy marble (? Middle Jurassic); 5, Hochstegen Marble (Upper Jurassic) with karstification, in grey colour projected the situation from the Tuxer Joch, Kaserer area in the west (Fig. 4).

Table 1. *Lithofacies associations of the Riffler–Schönach Basin, W and NE from Hoher Riffler*



Lithofacies – short description	Interpreted original composition of the protolith	Interpretation of depositiona processes and environment
"Zentralgneise", mylonitic	granites	
"Hochstegen Marble" – partially detached	lime, sandy lime and dolomite	gradual ingression of the sea
white and brown Fe-rich quartzite	sand, partially pebbly	channel sandstone
greyish schists and quartzite with marble layers	laminae of sand, mud and marl	fining upward cycles, fan delta-near environment
greenish quartzite/ meta-arkose, micaceous lenses/metaconglomerate	feldspar-rich sand, partially pebbly mud, silt	stream reworked outer part of alluvial fans/ sheet flood and stream channel deposits
quartzites, marble nodules, marble layers	calcareous sand marly and limy deposits	? periodical sea ingression events
calcareous quartzites	sand	
mica-schists	mud	floodplain, crevasse splays
white and greyish quartzite/ metaconglomerate and -arkose	feldspar-rich fine to coarse sand, partially pebbly, mud clasts	meandering river
meta-rhyodacite	rhyodacite	subaerial lava flow
graphite-bearing schists	carbonaceous mud, coal	plant and mud films, vegetated swamp deposits
greyish metaconglomerate/ meta-arkose/quartzite	massive, matrix-supported gravel, crudely bedded sand, pebbly	upper to middle part of wet alluvial fan, partially stream reworked
brownish quartzite		
meta-rhyodacite	rhyodacite	subaerial lava flow
greyish metaconglomerate/ meta-arkose/quartzite	massive, matrix-supported gravel, crudely bedded sand, pebbly	upper to middle part of wet alluvial fan, partially stream reworked
greyish quartzite/ meta-arkose		
brownish quartzite, strongly deformed	sand, partially pebbly	anastomosing river
graphite-bearing schists and quartzites- ? "Hochstegen Quartzite"	mud, sand carbonaceous mud	vegetated swamp deposits, crevasse splay
"Zentralgneise", mylonitic	granites	

estimated between two and three times of the present value—up to 1.9 km. The restoration of the geological section by use of balancing software (2DMove) gives a half-graben structure, about 2 km in depth and 7 km in width (Fig. 6). The true original extension cannot be reconstructed, because the basin is not fully exposed. The uniform lithology, except terrigenous clastic material at the base, and the wide extent of the Hochstegen Marble on the top suggest a rather low-relief landscape during Late Jurassic time.

The Ahorn Gneiss and Tux Gneiss initially formed granitic horsts bounding the half-graben of the Riffler–Schönach basin. The Hochstegen Marble covered the entire unit as a post-rift sediment. During Alpine convergence, the Tux Gneiss and its Hochstegen cover was thrust along the Realspitze Fault over the Riffler–Schönach basin which, in turn, was thrust along the Riffler Fault over the Ahorn gneiss forming now a duplex structure (Figs 5 and 6). By this stacking, the Hochstegen Marble occurs threefold within one section: twice

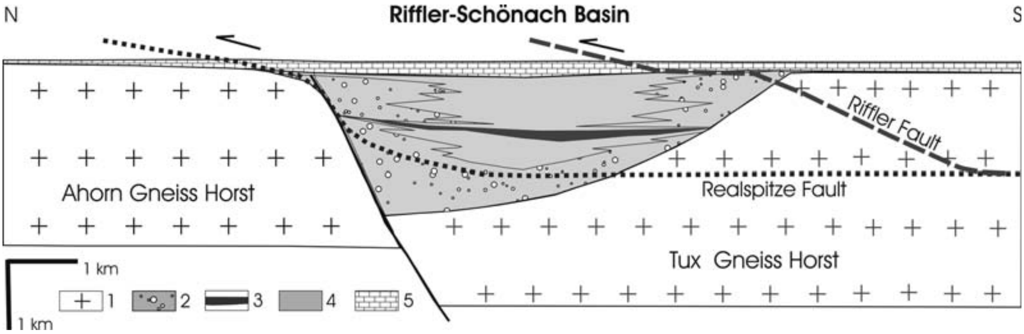


Fig. 6. Restoration of the original situation of the Riffler–Schönach Basin (W part). 1, Variscan granites and Palaeozoic basement rocks; 2, coarse post-Variscan clastics; 3, rhyodacite; 4, fine-grained post-Variscan clastics; 5, Hochstegen Formation (Jurassic).

covering granitic basement, once covering the metasediments of the Riffler–Schönach basin. The third Hochstegen Marble layer rests on top of the Tux Gneiss thrust sheet in the section further to the west (Fig. 4). The tip of the thrust sheets dips with about 50°–60° to the north. An analogous situation occurs in the eastern part of the Riffler–Schönach Basin, where in the Kirchspitze area the Ahorn Gneiss Horst is overthrust by basinal deposits (Thiele 1974, 1976).

The Hochstegen Formation in the Hoher Riffler area

The Hochstegen Formation covers the Tux Gneiss basement and the Riffler–Schönach basinal metasediments. At the base of the Formation, thin layers of graphite-bearing schists and graphite-bearing bedded or massive quartzites occur. An Early Jurassic age for this so-called ‘Hochstegenquarzit’ has been proposed (Frisch 1968). It is overlain by brownish sandy marbles (?Middle Jurassic). On the top, the main part of the formation is made up by bluish-grey, sulphide-bearing Hochstegen Marble which is locally at the base dolomitic (Oxfordian) and contains in higher horizons (Lower Tithonian) cherty nodules (Kiessling 1992).

Interpretation. The Hochstegen Formation in the Tauern Window overlies basinal sediments as well as the basement rocks (Figs 5 and 6). A notable feature is the shear deformation of the basement rocks (Zentralgneise) at the contact with the Hochstegen Marble, where the Zentralgneise locally become mylonites. This implies that the sediments rest on a tectonically exhumed and erosionally truncated basement. Extensional processes in formerly thickened continental crust could have caused a Basin-and-Range-like situation. The deposition of sand, silt, mud, coal and carbonates on the granitic basement implies considerably rapid tectonic subsidence and attendant erosion.

The lowest part of the Hochstegen Formation is composed of quartzite and graphite-bearing schists and displays characteristics of floodplain deposits with organic-rich mudstones formed in swamps, transected by low-gradient channels. The massive quartzites may represent fluvial sand bodies incised into the coastal plain deposits. The presence of overlying yellowish and brownish sandy marbles up to ten metres thick suggests a marine transgression followed abruptly. Above them, dolomites and greyish marbles document a marine environment as they contain various open-marine microfossils proving a Late Jurassic age (Kiessling 1992).

Lithostratigraphy of the Riffler–Schönach Basin fill

Six lithostratigraphical units constituting the basin fill have been defined. In the present paper, the description is restricted to the western part of the basin, which is very well exposed. The lithostratigraphy is however also applicable to the eastern part.

Unit I: Coarse clastics and volcanics

This unit is composed of greyish metaconglomerates, quartzites, meta-arkoses and meta-rhyodacites. The lowest part of the unit consists of very coarse matrix- to clast-supported polymictic metaconglomerates arranged in coarsening-upward successions. They are massive or crudely bedded, with weak grading. The matrix is sandy to pelitic; angular to subangular boulders of mostly granitic provenance are up to 30 cm in size. In the upper part, pebbles of vein-quartz clasts, gneisses, mudstones and graphite-bearing schists occur as stretched prolate bodies. In the Rötschneidkar (northwest of the Hoher Riffler), carbonate-rich rocks with greenish calc-silicate-rock pebbles occur in addition. In the upper part of Unit I, the amount of medium- to fine-grained sandy material increases. On top of the interval, very fine graphite-bearing micaschists, up to 8 m thick, are overlain by a dark-grey 15 to 30 m thick porphyritic meta-rhyodacite. The interval laterally extends for about 2 km and represents, thus, a good stratigraphical marker. The boundary to the underlying sandy and pebbly deposits is sharp.

Interpretation. The coarse clastics at the base suggest a wet alluvial fan depositional environment having predominantly plutonic and metamorphic rocks exposed in the catchment area. Coarse-grained, clast-supported beds (up to 2 m thick) may represent sieve deposits. Disorganized sediment gravity flows have been partially reworked through stream floods and in braided river systems in gravel and sandy bedforms in the middle and lower part of the fan. Lenses of fine sand and mud accumulated at decreasing flow velocities. The mud and coaly material accumulated in a marginal vegetated part of the fan away from the channels. The formation of alluvial fans implies considerable relative uplift (e.g. rising fault scarps) in tectonically active areas. Coarsening-upward conglomerates are overlain by unsorted debris-flow deposits while the fan prograded. The rhyodacitic lava flow documents subaerial volcanism during the initial phase of the basin formation. The volcanic layer was protected from erosion and preserved within the low-gradient fluvial system within a subsiding basin. The age of the volcanics is presumably Late Carboniferous–Early Permian, the age of many other volcanic and volcanoclastic deposits in the Alpine realm (e.g. Bonin *et al.* 1993; Capuzzo & Bussy 2000).

Unit II: Quartzites, metaconglomerates and mica-schists

This unit is about 150 m thick and comprises white and greyish Fe-rich quartzites, metaconglomerates and mica-schists. Unit II exhibits an overall fining-upward trend. Metaconglomerate lobes up to 3 m thick are intercalated into dm- to m-bedded quartzites. Pebbles, up to 10 cm in diameter, occur within a sandy, feldspar-rich matrix. The stretched pebbles are of vein-quartz, granitic and pelitic composition. Channel-like quartzite bodies with erosional lower bounding surfaces can be recognized. The quartzites contain <2 cm thick, very fine magnetite-rich heavy mineral layers and lenses. Up sequence, the proportion of fine mica-schists significantly increases.

Interpretation. The laterally persistent, m-thick sands alternating with pelites indicate a meandering-river depositional environment. Channels filled with graded sands overlying pebbly basal lags typically occur. Unfortunately, internal structures like ripple- or cross-bedding have been obliterated by metamorphism. A red colour of the original sandstones is very likely and both the enrichment by iron and the deeply oxidized deposits point to a warm climate (e.g. Ollier 1969). Further up the sequence, fine sands interbedded with mudstones are suggestive of a wide, muddy flood plain. Several metres of quartzite with high amount of mudstone pebbles and mudstone lenses indicate vertical aggradation of the flood plain severely affected 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. German Basin, Hauschke & Wilder 1999).

Unit III: Marbles and calcareous quartzites

This unit comprises quartzite, meta-arenites, calcareous quartzite and marble layers. It is about 60 m thick and extends laterally for about 1.5 km. The transition to underlying and overlying units is gradual. Metaconglomerate beds are intercalated into dm- to m-bedded quartzites. Feldspar-rich beds are common. Within the lower interval of this unit, layered marble nodules within the quartzite occur. Towards the top, they form continuous, 2 to 40 cm thick marble layers.

Interpretation. The increasing carbonate content, seen in nodules (due to boudinage of layers) and thin persistent layers first and an accumulation of carbonate in distinct beds later point to recurrent short periods of relative sea-level rise (e.g. Fürsich *et al.* 1991. A coastal plain setting is quite likely. During periods of lowered sea level, fluvial channels might have incised the plain. Unit III represents a laterally persistent horizon and is hence a useful stratigraphical marker.

Such a depositional system documents erosion of continental areas and considerable subsidence of the basins, which is typical for the post-Variscan period (Henk 1993; Ziegler 1982). We suggest a Middle Triassic age for the calcareous horizons and consider that they can be ascribed to the sea-level fluctuations of the Tethys which repeatedly flooded the southern part of the European continent at this time.

Unit IV: Impure quartzites

Unit IV is composed of 100 m thick quartzites to meta-arkoses and metaconglomerates with a specific light-green colour caused by phengite.

The pebbles are of vein-quartz, aplitic and granitic origin. Individual angular to subangular granitic clasts and boulders up to 10 cm in size within a sandy matrix are rare. The quartzites are well sorted. Thin micaceous lenses of 5 to 50 cm length are common. In the lower part of the unit, deposits with abundant feldspar clasts or mica-rich meta-arenites occur. The boundary to the underlying unit with calcareous nodules and marble layers is gradual.

Interpretation. Unit IV documents clastic sediment supply into the basin, often by sheet floods reworking the middle and distal parts of alluvial fans. Wide and shallow braided channels formed during high-energy floods due to heavy rain showers. Such supercritical high-density flows may have transported even individual large boulders over a considerable distance. During the peak flow, the adjacent areas were flooded and sheets of well-stratified sand or fine gravel with little silt and clay formed. Ripples with silty lee sides might be the origin of fine micaceous lenses which resemble flaser bedding. The high amount of feldspar clasts indicates a warm climate, at least seasonally dry, favouring the physical disintegration of granite rocks. Ephemeral floods transported debris throughout the basin. The sediments show striking lithological similarities with ‘Green Meta-arkoses Series’ of the Kaserer Basin, which is supposed to be Late Triassic in age. As palaeogeographic equivalents to these beds, we assign the fluviatile feldspar-rich sand deposits of the Vindelician Keuper (so-called Stubensandstein) in the German Basin (e.g. Ziegler 1990; Beutler *et al.* 1999), being aware that this is speculative.

Unit V: Quartzites, meta-arenites, schists and marbles

Unit V consists of greyish, ribbon-like, fine-grained, calcareous, micaceous schists and mica-quartzites and meta-arenites to metaconglomerates with intercalated, laterally persistent brownish marble horizons. It is about 40 m thick. The boundary with the underlying Unit IV is fairly sharp. All these rocks are characterized by a varying amount of finely disseminated ankerite. In the outcrop east of the Tuxer Ferner House, banded mica-schists and graded meta-arenites occur. Above, several fining-upward cycles, 1 to 5 m thick, with sharp lower surfaces are present. Polymictic, coarse conglomerates are overlain by fine conglomerate and graded quartzite beds. The amount of carbonate (up to 10%), fine-grained quartzites, meta-arenites and schists increases towards the top of a cycle. Thin impure marble beds, 5 to 10 cm thick occur repeatedly. The top of this unit consists of brownish calcareous and limonite-rich quartzites and fine conglomerates.

Interpretation. The depositional environment of Unit V is inferred to have been an alluvial fan within a coastal plain that temporarily developed into a fan-delta complex in a shallow bay depending on the relative change of sea level. The fan-delta complex is characterized by a cyclic succession of finely laminated mudstones and graded sandstones. They were transected by fluvial channels, depositing coarse basal lags, sand and mud in fining-upward cycles. The channel fills are overlain by mudstones and thin carbonate beds. The sediments contain about 5% of disseminated carbonate and, in the upper sandy part, limonite as well. Alluvial fans may prograde into the coastal setting. Calcareous horizons within the mudstones represent phases of relative high sea level. The greyish colour in the lower part suggests reducing conditions because of preserved organic matter while the brownish colour implies oxidation. A change in climate and/or groundwater level is likely. The stratigraphic position of Unit V, below the Upper Jurassic Hochstegen Marble and well above the probable Middle Triassic, suggests an age in the range of Early to Middle Jurassic. This is comparable to the sections north and southwest of the Vindelician High which document increasing flooding during this time (e.g. Trümpy 1980).

Unit VI: Marbles—(Hochstegen Formation)

The Hochstegen Formation consists of yellowish sandy marbles, dolomitic and pure greyish marbles. It occupies a significantly wider area than the older units. It rests on the rocks of Unit V and the boundary is fairly sharp. Unit VI starts with yellowish sandy marbles up to 10 m thick and dolomites. The upper part is made up of monotonous greyish marbles, 20 to 400 m thick. Synsedimentary normal faults occur exhibiting up to several metres of throw and convolute bedding. A palaeontological study on radiolarian associations has proved an Oxfordian and Tithonian age for the upper part of the Hochstegen Formation (Kiessling 1992). The main reason for the preservation of fossils was the early diagenetic pyritization. In the Riffler area, the Hochstegen Formation is about 40 m thick and is overthrust by the Tux Gneiss sheet, which again carries the Hochstegen Formation.

Interpretation. The lower part of the Hochstegen Formation documents the transition from coastal conditions to an open marine environment. Sandy marbles and dolomites represent sand bars and deposits close to the coast. The synsedimentary faulting, the sharp boundary to the underlying clastics and the pronounced decline in clastic material point to a clear increase in relative sea level. When compared to other Tethyan settings, rapid subsidence during the Middle Jurassic appears to be quite likely following the break-up of the Tethyan Ocean during the Bajocian (e.g. Borel 1995; Ziegler 2005). The diversity of radiolarian fauna within the upper part of the formation indicates an establishment of deeper water conditions during the Late Jurassic (Kiessling 1992).

Tectono-sedimentary evolution of the Riffler–Schönach Basin

At the end of the Variscan orogeny, numerous elongate intermontane basins formed in response to both consolidation of the crust and strike-slip movements (e.g. Ziegler *et al.* 2006). However, there is an ongoing debate on whether some of the basins in the Variscan Internides are of strike-slip or rift origin (Henk 1993; Capuzzo & Wetzel 2004; McCann *et al.* 2006).

The sedimentary record of the Riffler–Schönach basin starts with supply of continental clastics. In addition, rhyodacitic rocks of a presumed Late Carboniferous–Early Permian age document subaerial volcanism during the initial phases of basin formation and deep-reaching faulting. The basin fill consists of debris flow deposits that dominate in the western part of the basin and were formed on the proximal parts of alluvial fans. The coarse grain-size indicates high transport competence and, hence, a pronounced relief. The conglomerates contain granitic boulders implying rapid uplift and denudation of the basement. Comparison with other such basins suggest that the sedimentary cover had probably been removed prior to basin formation (Capuzzo *et al.* 2003; Capuzzo & Wetzel 2004). Abundant granite, feldspar- and vein-quartz clasts point to subordinate chemical weathering within the catchment area (e.g. Ollier 1969).

Dark mudstones accumulated under a humid climate from distal alluvial fans within a flood plain. The thickness of the floodplain mudstones increases significantly towards the eastern part of the basin. There, in the Schönach valley, fine-grained mudstones intercalated with quartzites and volcaniclastics are almost 300 m thick and display characteristics of distal parts of alluvial fan floodplain and playa-lake deposits. The thick mudstones are suggestive of rapid differential basin subsidence lowering the river gradient (see Capuzzo & Wetzel 2004). The overall basin fill geometry suggests a palaeoflow to the northeast during the formation of Unit I.

A warm, seasonally dry climate with a concomitant change in sediment composition to feldspar- and Fe-rich deposits characterized the depositional environment of Unit II for which a meandering river system is inferred. Within the Unit III, carbonates of presumed Anisian age are exposed. Accumulation of carbonates in distinct beds within a sandy coastal plain indicates periods of relative sea-level rise (e.g. Fürsich *et al.* 1991).

Unit IV comprises distal alluvial fans prograding into a coastal plain during ephemeral floods. Uplift and erosion of the hinterland may have been intensified. Braided rivers deposited well-sorted, but impure, sands. High amounts of feldspar clasts within the sands indicate the persistence of a warm and at least seasonally dry climate.

Units V and VI represent fluvio-deltaic depositional and coastal plain settings respectively, which have been rapidly flooded as open marine conditions were established on the top of Unit VI. Alluvial fans may have prograded into the coastal plain and carbonates represent phases of relative high sea level and marine incursions. Middle Jurassic sandy marbles form a sharp transition to the neritic environment and document progressive subsidence. In Late Jurassic times, deep marine conditions were established.

In Cretaceous time, the extensional regime changed progressively to compressional tectonics giving wrench faulting and stress-induced buckling of the lithosphere, causing a relative low-stand in sea level. During the earliest Cretaceous, large parts of western and central Europe were uplifted and subjected to erosion (Ziegler 2005). The Jurassic marine sediments in the Tauern Window may have been at least partially exhumed. The subsequent erosion possibly accounts for the strongly varying thickness of the Hochstegen Marble over the entire Tauern Window. In the southeast, the marble thins out or is completely missing (Fig. 2). This corresponds to the Cretaceous and Palaeocene evolution farther to the north. There the strong intraplate compressional deformation caused the partial destruction of the Mesozoic sedimentary cover of the Bohemian Massif in the foreland of the eastern Alps (e.g. Ziegler 1990, 2005).

Geochronological data and methods

The age of the meta-quartz porphyry from the Pfitsch-Mörchner Basin

West of the Mörchenscharte, a 5 m to 25 m thick meta-quartz porphyry cuts serpentinites, amphibolites and fine-grained or medium-grained clastic metasediments and is unconformably overlain by metaconglomerates. For a geochronological analysis, a medium-grained meta-quartz porphyry (MO1) was sampled 700 m to the west of the Mörchenscharte at an altitude of 2700 m. Zircons were separated into grain-size fractions. They form a homogeneous population, subhedral in shape with slightly corroded surfaces, but clear-cut edges and pyramidal apices. Crystal types according to Pupin (1980, 1985) are characterized as P3 to P5, as well as S9 to S22 which point to a sub-alkaline or calc-alkaline type of magma. Large zircon fractions 1 and 2 (150–180 μm) were assorted according to these criteria, respectively.

Conventional U–Pb analyses were performed in the laboratory at the Department of Earth and Environmental Sciences at the Ludwig-Maximillians-Universität (LMU). The data were plotted in a Tera & Wasserburg diagram, and calculations were made with the ISOPLOT program (Ludwig 2003). Data points of coarse grain-size fractions 1 and 2 are concordant; finer grain-size fractions show loss of radiogenic lead. The calculated discordia intersects the concordia at 293.0 ± 1.9 Ma and at the origin (Fig. 7). The age is interpreted as the time of zircon crystallization in the melt which is, within limits of error, identical with the extrusion age of the quartz porphyry magma.

The age of the meta-gabbro horizon from the Kaserer Basin

A fine-grained meta-gabbro (sample RAK) was sampled for age determination from the peak of the Rauhe Kopf (2150 m, Schmirntal, Brenner area). A MORB character was determined for this rock by Frisch (1984) using chemical characteristics. He assumed a Cretaceous age for the host rocks, the so-called Kaserer Series, and hence also for the intrusion. This age, however, was already questioned by field studies, as the Kaserer Series is in sedimentary contact with overlying Anisian carbonate rocks (Lammerer 2003).

Zircons of the meta-gabbro RAK were separated into two different types. Cathodo-luminescence investigations on type-1-zircons display predominantly only a single growth phase. An asymmetric inherited core is rarely developed. Zircon growth was uniform and displays irregularly cloudy luminescence. Type-2-zircons are of heterogeneous composition and display a three-phase growth history. A detrital core is surrounded by the volumetrically dominant main growth phase which contrasts in luminescence and is characterized by weakly developed oscillatory zoning. The anhedral

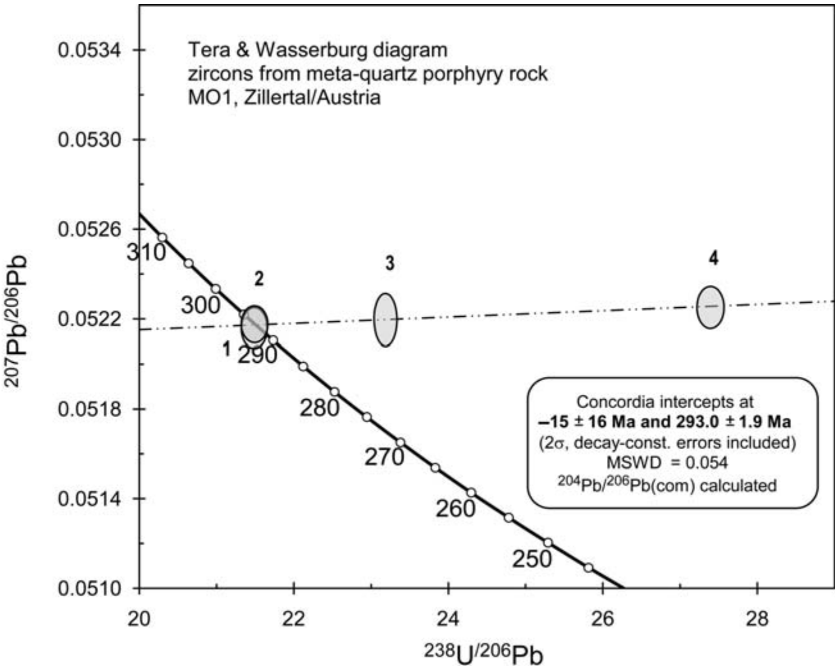
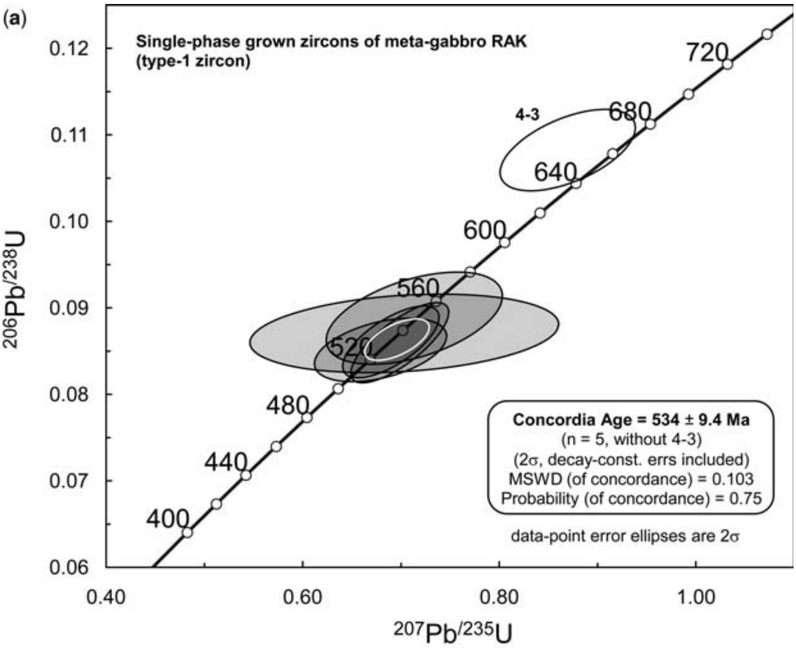


Fig. 7. Tera & Wasserburg diagram depicting zircon grain–size fractions from meta-quartz porphyry rock MO1 (Mörchenscharte/Zillertal, Austria). Large grain–size fractions 1 and 2 (150–180 μm) are, independent of their crystal type, concordant at 293 ± 1.9 Ma. Loss of radiogenic lead, possibly due to the enhancement of surface corrosion effects, is visible in smaller-sized zircon fractions 3 (80–100 μm) and 4 (42–53 μm). The age reflects the time of superficial extrusion of the precursor volcanic rocks.



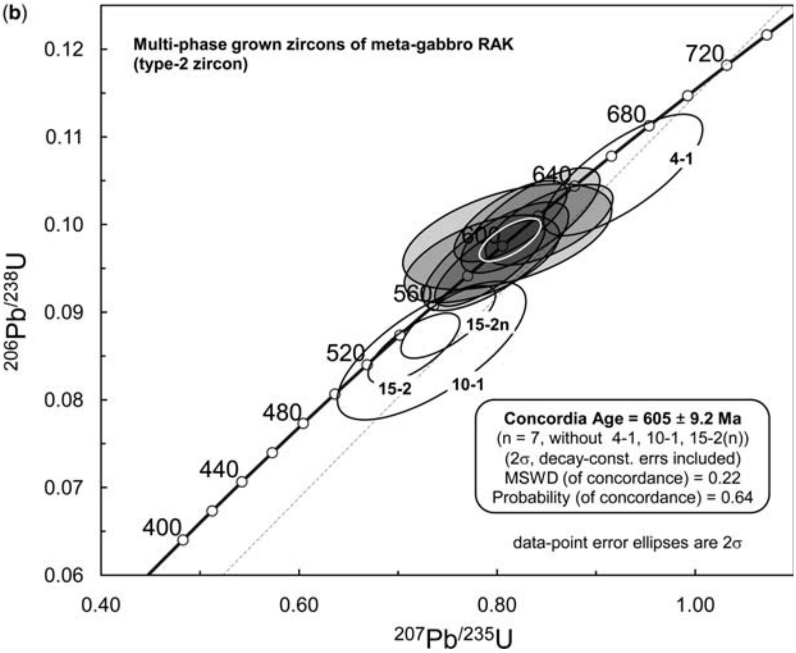


Fig. 8. (**a**) Concordia diagram of U–Pb single spot analyses with LA-ICP-MS on type-1-zircons from meta-gabbro RAK (Schmirntal/Brenner, Austria). Cathodoluminescence images reveal a simple growth history of this zircon type, which started occasionally at detrital cores. The main zircon growth has been dated at 534 ± 9.4 Ma. This age is interpreted as the time of zircon growth and suggests simultaneous crystallization of the gabbroic precursor rock. (**b**) Concordia diagram of U–Pb single spot analyses with LA-ICP-MS on type-2-zircons from meta-gabbro RAK (Schmirntal/Brenner, Austria). Complex moulded zircons, indicated by cathodoluminescence images reveal a main zircon growth phase at 605 ± 9.2 Ma. Older inherited cores (about 716 Ma, upper intercept of discordia line) and an outer rim of subsequent zircon overgrowth are visible. Zircons of this type seem to be overtaken into the gabbroic melt and had experienced marginal zircon overgrowth.

outer shape of this zone can be explained by dissolution during a succeeding heating phase. In addition, a marginal domain of light and homogeneous luminescence is developed and may correspond to the similar-looking main growth zone in type-1 zircons. Unfortunately, this rim was too small to give reliable age results. As both zircon types originate from the same rock, a complex zircon growth history can be inferred.

Zircon grains were analysed for U, Th and Pb isotopes by Laser Ablation Inductive Coupled Plasma Mass Spectrometry (LA-ICP-MS) techniques at the Institute of Geosciences, Johann Wolfgang Goethe-University Frankfurt, using a Thermo-Finnigan Element II sector field ICP-MS coupled to a New Wave UP213 ultraviolet laser system. Data were acquired in peak jumping mode during 30 s ablation with a spot size of 20 and 30 μm, respectively. A common-Pb correction based on the interference- and background-corrected ^{204}Pb signal and a model Pb composition (Stacey & Kramers 1975) was carried out if necessary. The necessity of the correction is judged on whether the corrected $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ lies outside of the internal errors of the measured ratios. Reported uncertainties (2σ) were propagated by quadratic addition of the external reproducibility (2 s.d.) obtained from the standard zircon GJ-1 during the analytical session and the within-run precision of each analysis (2 s.e.). Concordia diagrams (2σ error ellipses) and concordia ages with 2σ uncertainty were produced using Isoplot/Ex 2.49 (Ludwig 2003). For further details on the method, see Gerdes & Zeh (2006).

U–Pb analyses were made of inherited cores and the main growth phases of both zircon types. The age of the main zircon growth phase in type-1 zircons is dated at 534 ± 9.4 Ma (Fig. 8a) and can be interpreted as the phase of dominant zircon growth in the gabbroic melt. Discordant data point 4-3 suggests to have suffered uranium loss. The main growth phase in type-2 zircons is significantly older and of Precambrian age (605 ± 9.2 Ma; Fig. 8b). Two ages of inherited cores in type-2 zircons are discordant (4-1 and 10-1) because of the loss of radiogenic lead. A crystallization age of about 716 Ma (including the origin) can be inferred from the upper intercept of the regression line.

The different ages of the dominant growth phases in both zircon types are explained by their different growth history. The single-phase of type-1 zircons developed in the gabbroic melt, whereas type-2 zircons are considered to have been overtaken into the melt as older assimilated components. Only the outermost, small rim belongs perhaps to the stage of gabbroic melt formation at 534 ± 9.4 Ma.

Conclusions

Sedimentary basins exposed in the Tauern Window are part of the network of post-Variscan basins in western and central Europe. The Tauern Window exposes European continental crust which was drowned during the Late Jurassic, but which includes several small, elongate sedimentary basins which formed from the Late Palaeozoic as intermontane graben structures. The basins can be traced over 20 km or more wherein more than 1 to 2 km of sediments accumulated. As elongate belts, they run parallel to the Alpine tectonic strike and might have affected the orientation of Alpine compressive structures.

The onlap of sediments onto crystalline basement (well exposed in the Pfitsch–Mörchner Basin) demonstrates that the Late Palaeozoic basins were separated by highs. The sedimentary fill documents a rapid uplift, denudation of the Variscan orogenic belt and concomitant subsidence of the basins. The fault-bounded nature of these narrow basins is also evidenced by the existence of abrupt variations in the stratigraphic thickness. The facies pattern of the west Tauern Window suggests that three horsts experienced erosion for a prolonged period while the basins in between trapped sediments (Fig. 9). The sediments rest on a tectonically exhumed and erosionally truncated basement as the floor of the basin is made up of Variscan granitoids and Palaeozoic metamorphic rocks. Mylonitic zones occur within the basement rocks along steeply dipping normal faults. Basin-and-range-like extensional processes could have caused such a situation (Ménard & Molnar 1988).

In the representative, well-exposed basins like the Pfitsch–Mörchner or Riffler–Schönach Basins, no clear evidence for hiatus horizons within the sediments are seen. This absence is due to the Alpine folding and metamorphic overprint, as discordances between the strata are presumed to exist. Nevertheless, in some protected locations, major structures are still well preserved, so that lithostratigraphical correlation of the rock successions is feasible. The post-Palaeozoic history can be analysed, but only in part. The stratigraphic concept of more or less successive sedimentary evolution of the basins is, in part, contrary to previous interpretations. Our interpretation and the attempt to reconstruct the post-Variscan sedimentary evolution in the Tauern Window is based on the evidence that the area was exposed to prolonged erosion and experienced tectonic stretching until the Late Jurassic, when the area was flooded.

During the initial stages of the basin formation, subaerial volcanism was active. Major sediment delivery from continental sources, particularly by attendant erosion of the Variscan orogen, persisted

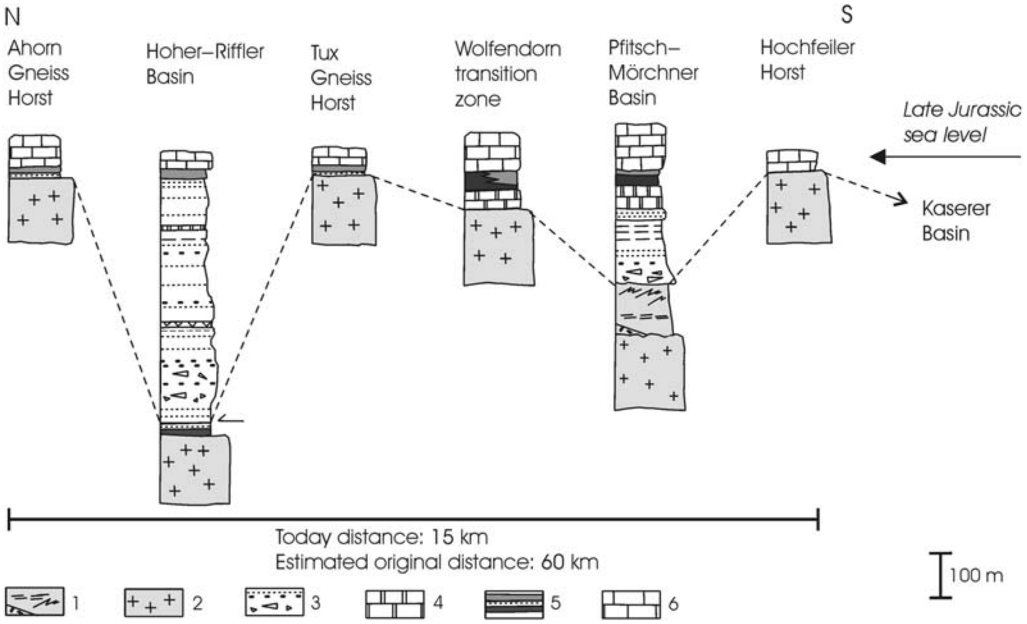


Fig. 9. Correlation of sections in the western Tauern Window. 1, pre-Variscan basement rocks; 2, Variscan granites; 3, post-Variscan clastic sediments; 4, Anisian carbonates; 5, graphitic schists and quartzites, sandy marbles (Early-Middle Jurassic); 6, Hochstegen Marble (Upper Jurassic).

until the Jurassic. The basin fill started with an overall fining-upward series of coarse clastic sediments which represent alluvial fans, fluvial sediments of meandering rivers and playa-lakes in pre-Middle Triassic times. Triassic marbles and cargneuls document that topography of the basin floors was close to sea level. Relative sea-level rise led to repeated flooding of the smooth surface of the southern European continental area. Above this calcareous horizon, fine-grained and well-sorted clastics were deposited by sheet floods and braided rivers until the Middle Jurassic. At this time, a transition from the coastal to deltaic conditions occurred. In response to continued crustal extension and relative sea-level rise, marine conditions were established from the Middle Jurassic, probably due to the break-up of the Tethys leading to rapid subsidence and the drowning of the continental margin. The Late Jurassic Hochstegen Formation was deposited mainly under deeper marine conditions when the entire area of the Tauern Window was submerged.

We thank Yvonne Legath (Munich) for laborious selection of the few zircons from the gabbro, Chris Walley (Swansea) for reading the manuscript and providing the final touches to the English, Horst Rass and Heinz Nyvelt from the Verbund Austria Hydropower in Mayrhofen for permission and support in visiting the water tunnels. This paper benefited from the engaged and encouraging reviews by Hilmar von Eynatten (Göttingen) and Wilfried Winkler (Zürich). The Deutscher Akademischer Austauschdienst (DAAD) financially supported Petra Veselá.

References

Arthaud, F. & Matte, P. H. 1977. Late Paleozoic strike-slip faulting in southern Europe and northern Africa. *Geological Society of America Bulletin*, **88**, 1305–1320.

Benammi, M. & El Kochri, A. 1998. Ouverture du rift atlasique: mise en évidence d'une paléofaille de transfer orientée N120. *Comptes Rendus de l'Académie des Sciences, Paris, Sciences de la terre et des planetès*, **327**, 845–850.

Beutler, G., Hauschke, N. & Nitsch, E. 1999. Faziesentwicklung des Keupers im Germanischen Becken. *In*: Hauschke, N. & Wilde, V. (eds) *Trias. Eine ganz andere Welt. Mitteleuropa im frühen Erdmittelalter*. Verlag Dr. Friedrich Pfeil, München, 129–174.

Bonin, B., Brändlein, P., Bussy, F. *et al.* 1993. Late Variscan magmatic evolution of the Alpine Basement. *In*: von Raumer, J. F. & Neubauer, F. (eds) *Pre-Mesozoic Geology in the Alps*, Springer-Verlag, Berlin, 171–201.

Borel, G. 1995. Préalpes médianes romandes: courbes de subsidence et implications géodynamiques. *Bulletin de Société de Vaudois de Science Naturelle*, **83**, 293–315.

Bouaziz, S., Barrier, E., Turki, M. M. & Tricart, P. 1999. La tectonique permo-mésozoïque (anté-Vraconien) dans la marge sud téthysienne en Tunisie méridionale. *Bulletin de la Société géologique de France*, **170**, 45–56.

Brandner, R., Reiter, F. & Töchterle, A. 2007. Geologische Prognose des Brenner Basis-tunnles-ein Überblick. *In*: Schneider, E., John, M. & Brandner, R. (eds) *BBT 2007, Internationales Symposium Brenner Basistunnel und Zulaufstrecken*. Innsbruck University Press, 13–23.

Capuzzo, N. & Bussy, F. 2000. High-precision dating and origin of synsedimentary volcanism in the Late Carboniferous Salvan Dorénaz basin (Aiguilles-Rouges Massif, Western Alps). *Schweizerische Mineralogische und Petrographische Mitteilungen*, **80**, 147–167.

Capuzzo, N. & Wetzel, A. 2004. Facies and basin architecture of the Late Carboniferous Salvan-Dorenaz continental basin (Western Alps, Switzerland/France). *Sedimentology*, **51**, 675–697.

Capuzzo, N., Handler, R., Neubauer, F. & Wetzel, A. 2003. Post-collisional rapid exhumation and erosion during continental sedimentation: the example of the Late Variscan Salvan-Dorenaz basin (Western Alps). *International Journal of Earth Sciences*, **92**, 364–379.

Cesare, B., Rubatto, D., Hermann, J. & Barzi, L. 2001. Evidence for Late Carboniferous subduction type magmatism in mafic – ultramafic cumulates of the Tauern window (Eastern Alps). *Contributions of Mineralogy and Petrology*, **142**, 449–464.

Coward, M. & Dietrich, D. 1989. Alpine tectonics — an overview. *In*: Coward, M. P., Dietrich, D. & Park, R. G. (eds) *Alpine Tectonics*. Geological Society Special Publication, **45**, 1–29.

Dietiker, H. 1938. *Der Nordrand der Hohen Tauern zwischen Mayrhofen und Krimml (Gerlostal, Tirol)*. PhD Thesis, ETH Zürich.

Faerseth, R. B. 1996. Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea. *Journal of the Geological Society London*, **153**, 931–944.

Finger, F., Frasl, G., Haunschmid, B. *et al.* 1993. The Zentralgneise of the Tauern Window (Eastern Alps)—insight into an intra-Alpine Variscan batholite. *In*: Neubauer, J. F. & von Raumer, J. F. (eds) *The Variscan Basement in the Alps*. Springer Verlag, 375–391.

Franks, G. D. 1966. The development of the limnic Upper Carboniferous of the eastern Aar Massif. *Eclogae Geologicae Helvetiae*, **59**, 943–950.

Franz, G., Mosbrugger, V. & Menge, R. 1991. Carbo-Permian pteridophyll leaf fragments from an amphibolite facies basement, Tauern Window, Austria. *Terra Nova*, **3**, 137–141.

Frasl, G. 1958. Zur Seriengliederung der Schieferhülle in den mittleren Hohen Tauern. *Jahrbuch der geologischen Bundesanstalt, Wien*, **101**, 323–472.

Frisch, W. 1968. Geologie des Gebietes zwischen Tuxbach und Tuxer Hauptkamm bei Lanersbach (Zillertal, Tirol). *Mitteilungen der Geologie und Bergbaustudenten*, **18**, 287–336.

Frisch, W. 1974. Die stratigraphisch-tektonische Gliederung der Schieferhülle und die Entwicklung des penninischen Raumes im westlichen Tauernfenster (Gebiet Brenner – Gerlospaß). *Mitteilungen der Österreichischen Geologischen Gesellschaft*, **66/67**, 9–20.

Frisch, W. 1975. Ein Typ-Profil durch die Schieferhülle des Tauernfensters: Das Profil am Wolfendorn (westlicher Tuxer Hauptkamm, Tirol). *Verhandlungen der Geologischen Bundesanstalt*, Wien 1974/**2-3**, 201–221 .

Frisch, W. 1980. Post-Hercynian formations of the western Tauern window: sedimentological features, depositional environment, and age. *Mitteilungen der Österreichischen Geologischen Gesellschaft*, **71/72**, 49–63.

Frisch, W. 1984. Metamorphic history and geochemistry of a low-grade amphibolite in the Kaserer Formation (marginal Buendner Schiefer of the western Tauern Window, the Eastern Alps). *Schweizerische Mineralogische und Petrographische Mitteilungen, Bulletin Suisse de Mineralogie et Petrographie*, **64**, 193–214.

Fürsich, F. T., Oschmann, W., Jaitly, A. K. & Singh, I. B. 1991. Faunal response to transgressive-regressive cycles: example from the Jurassic of western India. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **85**, 149–159.

Gerdes, A. & Zeh, A. 2006. Combined U-Pb and Hf isotope LA-(MC-)ICP-MS analyses of detrital zircons: Comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany. *Earth and Planetary Science Letters*, **249**, 47–62.

Haas, J. & Péró, C. 2004. Mesozoic evolution of the Tisza Mega-unit. *International Journal of Earth Sciences (Geologische Rundschau)*, **93**, 297–313.

Hauschke, N. & Wilde, V. (eds) 1999. *Trias, eine ganz andere Welt: Mitteleuropa im frühen Erdmittelalter*. Verlag Dr. Friedrich Pfeil, München.

Henk, A. 1993. Subsidenz und Tektonik des Saar-Nahe-Beckens (SW-Deutschland). *Geologische Rundschau*, **82**, 3–19.

Höck, V. 1969. Zur Geologie des Gebietes zwishchen Tuxer Joch und Olperer (Zillertal, Tirol). *Jahrbuch der Geologischen Bundesanstalt, Wien*, **112**, 153–195.

Kebede, T., Kloetzli, U., Kosler, J. & Skiold, T. 2005. Understanding the pre-Variscan and Variscan basement components of the central Tauern Window, Eastern Alps, Austria; constraints from single zircon U-Pb geochronology. *International Journal of Earth Sciences*, **94**, 336–353.

Keeley, M. L. 1996. The Irish Variscides: problems, perspectives and some solutions. *Terra Nova*, **8**, 259–269.

Kiessling, W. 1992. Palaeontological and facial features of the Upper Jurassic Hochstegen Marble (Tauern Window, Eastern Alps). *Terra Nova*, **4**, 184–197.

Kröll, A., Meurers, B., Oberlercher, G. *et al.* 2006. *Erläuterungen zu den Karten Molassezone Salzburg–Oberösterreich*. Geologische Bundesanstalt, Wien.

Lammerer, B. 1986. Das Autochton im westlichen Tauernfenster. *Jahrbuch der Geologischen Bundesanstalt, Wien*, **129**, 51–67.

Lammerer, B. & Weger, M. 1998. Footwall uplift in an orogenic wedge; the Tauern Window in the Eastern Alps of Europe. *Tectonophysics*, **285**, 213–230.

LAMMERER, B. 2003. The Tauern Window, key to the understanding of the Eastern Alps. *Memorie di Scienze Geologiche*, *Padova*, **54**, 183–184.

LAMMERER, B., GEBRANDE, H., LÜSCHEN, E. & VESELÀ, P. 2008. A crustal-scale cross-section through the Tauern Window (eastern Alps) from geophysical and geological data. *In*: SIEGESMUND, S., FÜGENSCHUN, B. & FROITZHEIM, N. (eds) *Tectonic Aspects of the Alpine-Dinaride-Carpathian System.* Geogical Society, London, Special Publications, **298**, 219–229.

LEMCKE, K. 1988. *Geologie von Bayern 1: Das bayerische Alpenvorland vor der Eiszeit*. Schweizerbart'sche Verlagsbuchhandlung.

LUDWIG, K. R. 2003. *Users manual for isoplot/ex rev. 2.49: a geochronological toolkit for Microsoft Excel*. Berkeley Geochronology Center, Special Publication, **1a**, 1–56.

MATTER, A. 1987. Faziesanalyse und Ablagerungsmilieus des Permokarbons im Nordschweizer Trog. *Eclogae Geologicae Helvetiae*, **80**, 345–367.

MCCANN, T., PASCAL, C., TIMMERMAN, M. J. *ET AL.* 2006. Post-Variscan (End Carboniferous – Early Permian) basin evolution in Western and Central Europe. *In*: GEE, D. G. & STEPHENSON, R. A. (eds) *European Lithosphere Dynamics*. Geological Society London, Memoirs, **32**, 355–388.

MÉNARD, G. & MOLNAR, P. 1988. Collapse of Hercynian Tibetan Plateau into a Late Palaeozoic European Basin and Range province. *Nature*, **334**, 235–237.

MILLER, H., LEDOUX, H., BRINKMEIER, I. & BEIL, F. 1984. Der Nordwestrand des Tauernfensters—stratigraphische Zusammenhänge und tektonische Grenzen. *Zeitschrift der Deutschen Geologischen Gesellschaft*, **135**, 627–644.

OBERHÄNSLI, R., SCHENKER, F. & MERCOLLI, I. 1988. Indications of Variscan nappe tectonics in the Aar Massif. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **68**, 509–520.

OLLIER, C. D. 1969. *Weathering*. Oliver and Boyd, Edinburgh.

PESTAL, G., BRUEGGEMANN-LEDOLTER, M., DRAXLER, I. *ET AL.* 1999. Ein Vorkommen von Oberkarbon in den mittleren Hohen Tauern. *Jahrbuch der Geologischen Bundesanstalt, Wien*, **141**, 491–502.

PUPIN, J. P. 1980. Zircon and granite petrology. *Contributions to Mineralogy and Petrology*, **73**, 207–220.

PUPIN, J. P. 1985. Magnatic zoning of Hercynian granitoids in France based on zircon typology. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **65**, 29–56.

ROCKENSCHAUB, M., KOLENPRAT, B. & NOWOTNY, A. 2003. Das westliche Tauernfenster. *In*: ROCKENSCHAUB, M. (ed.) *Arbeitstagung der Geologische Bundesanstalt*. Wien, 7–38.

SCHALTEGGER, U. & CORFU, F. 1995. Late Variscan "Basin and Range" magmatism and tectonics in the Central Alps: evidence from U-Pb geochronology. *Geodinamica Acta*, **8**, 82–98.

SCHÖNLAUB, H. P., FRISCH, W. & FLAJS, G. 1975. Neue Fossilfunde aus dem Hochstegenmarmor (Tauernfenster, Österreich). *Neues Jahrbuch für Geologie und Paläontologie*, 1975/**2**, 111–128.

SENGL, F. 1991. *Geologie und Tektonik der Schönachmulde (Zillertaler Alpen, Tirol)*. PhD Thesis, Ludwig-Maximilians-Universität München.

SÖLLNER, F., HÖLL, R. & MILLER, H. 1991. U-Pb-Systematik der Zirkone in Meta-Vulkaniten ("Porphyroiden") aus der Nördlichen Grauwackenzone und dem Tauernfenster (Ostalpen, Österreich). *Zeitschrift der deutschen geologischen Gesellschaft*, **142**, 285–299.

STACEY, J. S. & KRAMERS, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, **26**, 207–221.

THIELE, O. 1970. Zur Stratigraphie und Tektonik der Schieferhülle der westlichen Hohen Tauern. *Verhandlungen der geologischen Bundesanstalt, Wien*, 230–244.

THIELE, O. 1974. Tektonische Gliederung der Tauernschieferhülle zwischen Krimml und Mayrhofen. *Jahrbuch der Geologischen Bundesanstalt, Wien*, **117**, 55–74.

THIELE, O. 1976. Der Nordrand des Tauernfensters zwischen Mayrhofen und Inner Schmirn (Tirol). *Geologische Rundschau*, Stuttgart, **65**, 410–421.

TRÜMPY, R. 1980. *Geology of Switzerland – a guide book*. Wepf, Basel, New York.

VON RAUMER, J. F. 1998. The Paleozoic evolution in the Alps: from Gondwana to Pangea. *Geologische Rundschau*, **87**, 407–435.

WETZEL, A., ALLENBACH, R. & ALLIA, V. 2003. Reactivated basement structures affecting the sedimentary facies in a tectonically "quiescent" epicontinental basin: an example from NW Switzerland. *Sedimentary Geology*, **157**, 153–172.

ZIEGLER, P. A. 1982. Triassic Rifts and Facies Patterns in Western and Central Europe. *Geologische Rundschau*, **71**, 747–771.

ZIEGLER, P. A. 1990. *Geological Atlas of Western and Central Europe*. 2nd edn. Shell Internationale Petroleum Maatschappij, The Hague.

ZIEGLER, P. A. 2005. Permian to Recent Evolution. *In*: SELLEY, R. C., COCKS, L. R. & PLIMER, I. R. (eds) *The Encyclopedia of Geology*. Elsevier, World Wide Web Address: http://www.encyclopediaofgeology.com/samples/europe2.pdf

ZIEGLER, P. A., CLOETINGH, S., CORNU, T. & BEEKMAN, F. 2006. Neotectonics and intraplate continental topography of the northern Alpine Foreland. *Earth-Science Reviews*, **74**, 127–196.