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The Tauern Window (Eastern Alps, Austria): a new tectonic map, with cross-sections and a tectonometamorphic synthesis

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Abstract We present a tectonic map of the Tauern Window and surrounding units (Eastern Alps, Austria), combined with a series of crustal-scale cross-sections parallel and perpendicular to the Alpine orogen. This compilation, largely based on literature data and completed by own investigations, reveals that the present-day structure of the Tauern Window is primarily characterized by a crustal-scale duplex, the Venediger Duplex (Venediger Nappe system), formed during the Oligocene, and overprinted by doming and lateral extrusion during the Miocene. This severe Miocene overprint was most probably triggered by the indentation of the Southalpine Units east of the Giudicarie Belt, initiating at 23–21 Ma and linked to a lithosphere-scale reorganization of the geometry of mantle slabs. A kinematic reconstruction shows that accretion of European lithosphere and oceanic domains to the Adriatic (Austroalpine) upper plate, accompanied by high-pressure overprint of some of the units of the Tauern Window, has a long history, starting in Turonian time (around 90 Ma) and culminating in Lutetian to Bartonian time (45–37 Ma).

Keywords Alpine tectonics · Metamorphism · Age dating · Orogenesis · Lithosphere dynamics

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1 Introduction

The Tauern Window of the Eastern Alps exposes exhumed parts of Europe-derived crust that were accreted to the base of an Adria-derived upper plate, represented today by the Austroalpine nappes (e.g., Schmid et al. 2004). Spectacular surface geology (e.g., Lammerer et al. 2008), together with the results of deep seismic reflection measurements (e.g., Lüschen et al. 2006) offers a unique opportunity to understand crustal-scale collisional accretion in the Alps. Accretion was followed by Late Alpine indentation, crustal-scale folding, orogen-parallel extension and lateral extrusion. This led to the final exhumation of a high-grade metamorphic Cenozoic nappe stack that pierced the Austroalpine orogenic lid by a combination of tectonic and erosional unroofing (e.g., Ratschbacher et al. 1991; Rosenberg et al. 2007).

We present a newly compiled tectonic map of the Tauern Window and surrounding units with the aim of replacing the still widely used nomenclature based on traditional terms such as “Zentralgneise”, “Altes Dach”, “untere Schieferhülle”, “obere Schieferhülle” and “Nordrahmenzone” (e.g., Thiele 1980). This better reflects the progress made in geology over the past 100 years and allows for a better understanding of orogenic processes in a modern geodynamical framework. To our knowledge, Kurz et al. (1996, 1998) were the first to introduce a modern nomenclature for the tectonic units of the Tauern Window and their work was influential in our own compilation. We make use of the tectonic map for constructing new cross-sections that help visualize the complex three-dimensional geometry of the tectonic units, including important along-strike changes in the structure of the Tauern Window. Finally we discuss the kinematics and dynamics of deformation, as well as the metamorphic evolution of this area, which forms a first-class natural laboratory for studying orogenic processes.

This contribution is largely based on literature data. Most of the published articles and maps used will be cited below in their proper context. At this stage, we only mention the most important references: Pestal and Hejl (2005) was used for a large part of the map. In addition, the most important references were: Exner (1962a), van Bemmelen and Meulenkamp (1965), Becker (1993), Egger et al. (1999), Frisch (1980a), Häusler (1988), Kurz et al. (1998), Lammerer and Weger (1998), Schmid et al. (2004), Pestal et al. (2009), Veselá and Lammerer (2008), Veselá et al. (2008) and Töchterle (2011). Numerous regular 1:50′000 map sheets available from the Geologische Bundesanstalt (http://www.geologie.ac.at/de/GEOMARKT/karten.html) were also extremely helpful. These literature data were completed by intensive field investigations by the authors of this presentation and other members of the tectonics group at FU Berlin in parts of the Tauern Window (e.g., Rosenberg and Schneider 2008; Rosenberg and Garcia 2011; Scharf 2013; Scharf et al. 2013), focusing on the western and eastern margins of the Tauern Window, and additionally, by reconnaissance work of the authors in other parts of the Tauern Window.

We will first describe the major tectonic units within and around the Tauern Window, including a compilation of the lithostratigraphy of the Subpenninic units, followed by a brief description of the major Late Alpine fault zones in the area. This part of the present contribution serves as an explanatory text accompanying the tectonic map presented in Fig. 1. Thereby Table 1 facilitates the correlation of tectonic units from west to east. This will be followed by an analysis of the large-scale structure of the Tauern Window based on a series of across and along strike cross-sections. Finally, we will address the tectonic evolution of the Tauern Window and conclude by also briefly mentioning the most important unanswered questions.

2 Major tectonic units of the Tauern Window derived from the distal European margin (Subpenninic nappes)

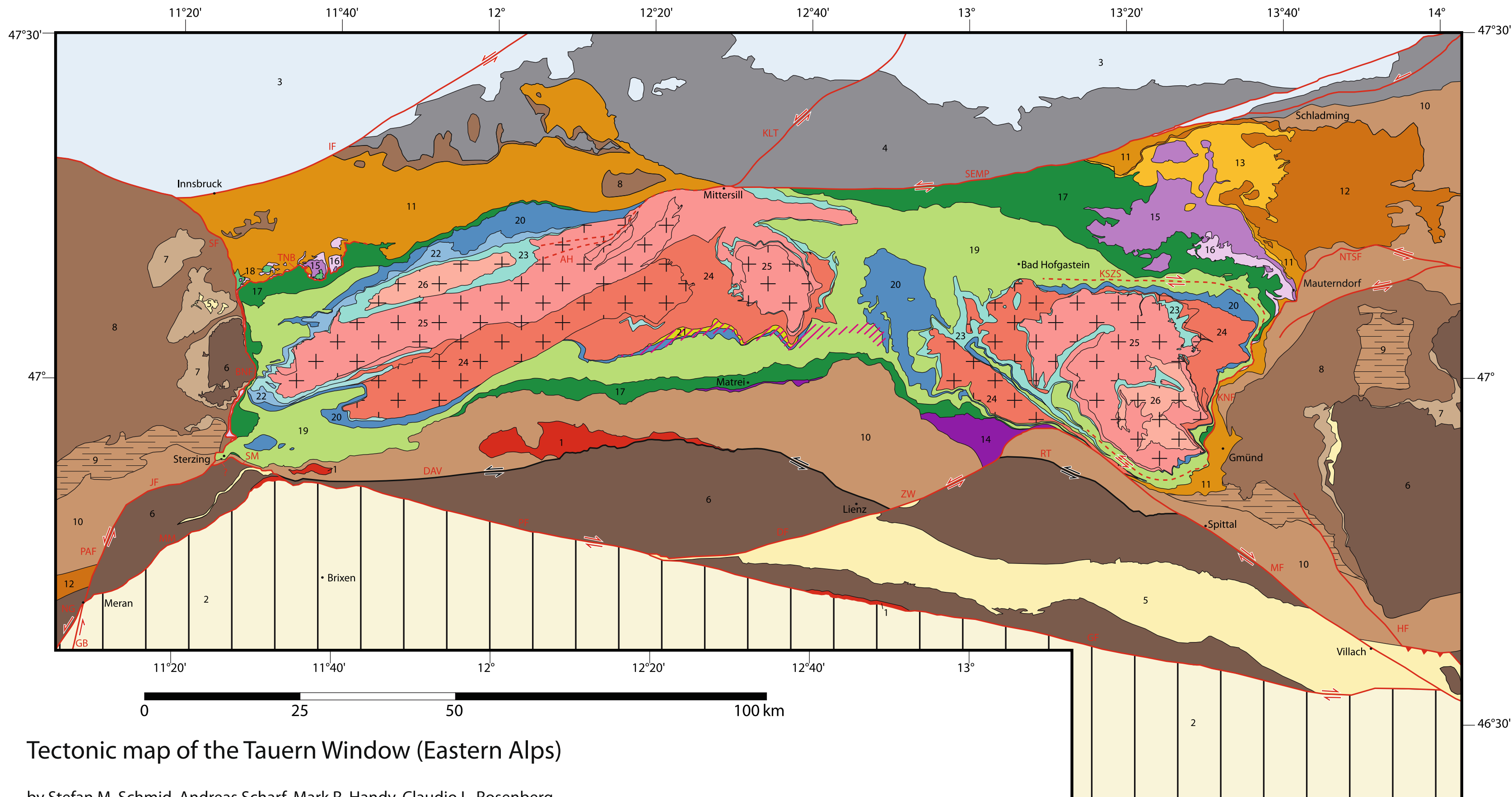
2.1 Subpenninic nappes of the Venediger Duplex (or Venediger Nappe system)

We refer to these nappes as Subpenninic based on their interpretation as deriving palaeogeographically from the European margin (Milnes 1974; Schmid et al. 2004). In the classical nomenclature (e.g., Thiele 1980), these units were referred to as (1) "Altes Dach" (*Variscan basement* of Fig. 1), (2) the "Zentralgneise" (*Permo-Carboniferous intrusions* of Fig. 1), and (3) the *post-Variscan cover* (Fig. 1). The latter partly corresponds to what is often referred to as the "Untere Schieferhülle". In our compilation, the post- Variscan cover comprises not only the Mesozoic cover of units 1 and/or 2, but also continental, volcanodetrital and volcanic rocks of Late Carboniferous to Triassic age. These include Late Carboniferous (post-310 Ma) to Permo-Triassic clastic continental sediments, intercalated with meta-volcanic layers that were deposited in small basins (Veselá and Lammerer 2008; Veselá et al. 2011), as well as a series that is generally referred to as "Jungpaläozoikum" (Pestal et al. 2009; see Sect. 2.3 for details). These deposits are topped by the Wustkogel Formation (Frasl 1958; note that throughout the text we use the term formation in an informal way). We suspect that all these sediments experienced only one phase of metamorphism and deformation of Alpine age. Hence such deposits are of great importance for tracing Alpine nappe boundaries.

What is traditionally referred to as Venediger "Nappe" or "Complex" (Frisch 1976, 1977; Kurz et al. 1998) is a duplex structure that consists of a folded stack of nappes arranged in a horse-like manner between a roof thrust and a floor thrust, as first recognized by Lammerer and Weger (1998; see also Lammerer et al. 2008, their Fig. 8). The floor thrust is not exposed at the Earth's surface, whereas the roof thrust is found at the base of rather thin continental basement slices (gneiss lamellae) and/or their former post-Variscan cover, including an eclogitic sliver of sedimentary and magmatic (mafic) origin ("units in the hangingwall of the Venediger Duplex" of Fig. 1), also derived from the distal European margin. In many places the tectonic contacts between individual nappes of the Venediger Duplex are clearly seen to abut against this roof thrust.

The *Ahorn and Göss nappes* (26) of the western and eastern Tauern Window, respectively, are the structurally

Fig. 1 Tectonic map of the Tauern Window (Eastern Alps). The ▶ abbreviations used for the Late Alpine faults are as follows: AH Ahorn Fault; BNF Brenner Normal Fault; DAV Defereggen-Antholz-Vals Fault; DF Drautal Fault; GB dextrally transpressive Giudicarie Belt; GF Gailtal Fault; HF Hochstuhl Fault; IF Inntal Fault; JF Jaufen Fault; KNF Katschberg Normal Fault; KSZS Katschberg Shear Zone System; KLT Königsee-Lammertal-Traunsee Fault; MF Mölltal Fault; MM Meran-Mauls Fault; NTSF Niedere Tauern Southern Fault; NG North Giudicarie Fault; PF Pustertal Fault; PAF Passeier Fault; RT Ragga-Teuchl Fault; SEMP Salzach-Ennstal-Mariazell-Puchberg Fault; SF Silltal Fault; SM Sterzing-Mauls Fault; TNB Tauern Northern Boundary Fault; ZW Zwischenbergen-Wöllatratten Fault (A high-resolution version of this figure appears as Electronic Supplementary Material with the online version of the article and can be found as a fold-out at the back of the printed issue)



Tectonic map of the Tauern Window (Eastern Alps)

by Stefan M. Schmid, Andreas Scharf, Mark R. Handy, Claudio L. Rosenberg

1 Periadriatic plutons (Oligocene)
2 Southern Alps

Upper Austroalpine - far-travelled cover nappes
3 Northern Calcareous Alps (Mesozoic)
4 Grauwackenzone (Paleozoic)

Upper Austroalpine - basement and cover nappes
Drauzug-Gurktal Nappe System
5 Mesozoic cover (Blaser Nappe, Mauls Triassic, Drauzug)
6 Basement complexes (Steinach Nappe, South Deferegg Units, Gurktal Nappe)

Ötztal-Bundschuh Nappe System
7 Mesozoic cover (Brenner Mesozoic, Stangalm Mesozoic)
8 Variscan basement

Koralpe-Wölz Nappe System
9 Schneeberg-Radenthein Units
10 Texel-Millstatt-Wölz Units

Silvretta-Seckau Nappe System
11 Innsbruck-Wagrain-Katschberg Quartzphyllite Units
12 High-grade Variscan basement (Campo and Schladming nappes)
13 Schladming Nappe - overturned Permo-Mesozoic cover

Lower Austroalpine nappes
14 Lower Austroalpine unit south of the Tauern Window
15 Reckner Nappe including Main Nappe Group of Radstatt Tauern
16 Hippold Nappe including Hochfeind Nappe

Ophiolite-bearing units (Penninic nappes)
17 Matrei Zone (mélange of units derived from Piemont-Liguria Ocean and Austroalpine blocks)
18 Reckner Ophiolitic Complex (Piemont-Liguria Ocean)
19 Glockner Nappe System (prasinites and calcschists, Valais Ocean

Units derived from the distal European margin (Subpenninic nappes)
Units in the hangingwall of the Venediger Duplex
20 Modereck Nappe System
21 Eclogite Zone
22 Wolfendorn Nappe

Venediger Duplex
23 Post-Variscan cover (Permo-Carboniferous and Mesozoic) of nappes in the Venediger Duplex
Permo-Carboniferous intrusions into Variscan basement
24 Zillertal-Riffl, Sonnblick-Romate and Mureck-Storz nappes
25 Tux-Granatspitz and Hochalm nappes
26 Ahorn and Göss nappes

Area of eclogite-facies overprint within the Tauern Window
First-order Mio- Pliocene fault; ductile and brittle; thrusts
First-order Mio- Pliocene fault; ductile
Major Oligocene-age ductile fault

Table 1 Nappe correlations (see text for further details)

General tectonic setting	Number	West	Central	East
Periadriatic Plutons	1	Rensen Pluton	Rieserferner Pluton	–
Southern Alps	2	Southern Alps (Adriatic Indenter)	Southern Alps (Adriatic Indenter)	Southern Alps (Adriatic Indenter)
Upper Austroalpine:	3	Northern Calcareous Alps	Northern Calcareous Alps	Northern Calcareous Alps
far travelled cover nappes	4	Grauwackenzone	Grauwackenzone	Grauwackenzone
	5	Blaser Nappe, Mauls Triassic	Drauzug	Drauzug, Mesozoic Gurktal Nappe
	6	Steinach Nappe, Mauls-Meran basement	South Deferegg Units, Strieden Complex	Basement Gurktal Nappe
	7	Brenner Mesozoic	–	Stangalm Mesozoic
	8	Ötztal Nappe	–	Bundschuh Nappe
Upper Austroalpine:	9	Schneeberg Unit	–	Radentheim Unit
basement-cover nappes	10	Texel Nappe	North Deferegg Unit, Schober Unit, Polinik-Prijakt Unit	Millstatt Nappe, Wölz Nappe
	11	Innsbruck Quarztphyllite	–	Wagrain and Katschberg Quartzphyllite Units
	12	Campo Unit	–	Schladming Nappe
	13	–	–	Overturned Permo-Mesozoic cover
	14	–	Sadnig-Group	–
Lower Austroalpine nappes	15	Tarntal Nappe	–	Main Nappe Group/Lantschfeld Nappe/Pleisling Nappe
	16	Hippold Nappe	–	Hochfeind Nappe
	17	Nordrahmen Zone north of Tauern Window	Matrei Zone south of Tauern Window	Nordrahmen Zone north of Tauern Window
Ophiolite-bearing units	18	Reckner Ophiolitic Complex	–	–
	19	Glockner Nappe system	Glockner Nappe system	Glockner Nappe system
Units derived from the distal European margin above Venediger Duplex	20	Eisbrugg-slice, Geroldstein Mesozoic	"Glimmerschieferlamelle", Seidlwinkl-Rote Wand Nappe	Murtörl-Schrovin Unit
	21	–	Eclogite Zone	–
	22	Wolfendorn Nappe	–	–
	23	includes "Junglaläozoikum", Hochstegenkalk & Kaserer Serie	includes "Jungpaläozoikum", Maurertal Fm. & Murtörl Fm.	includes "Jungpaläozoikum", Silbereck Series & Draxel Complex
Units derived from the distal European margin: Venediger Duplex	24	Zillertal Nappe	Riffl Nappe, Sonnblick-Romate Nappe	Mureck gneissic slice and Storz Nappe
	25	Tux Nappe	Granatspitze Nappe	Hochalm Nappe
	26	Ahorn Nappe	–	Göss Nappe

The numbers given in the second column correspond to those given in the figure legend of Fig. 1 and used for mapping the 26 different tectonic units over the area of the entire Tauern Window

lowest nappes of the Venediger Duplex. In view of very substantial along-strike changes in structure, however, it is unlikely that they represent lateral equivalents that connect via the subsurface in a cylindrical fashion. The Ahorn Nappe can easily be separated from the overlying Tux-Granatspitz Nappe based on post-Variscan cover sequences that include continental deposits of the Late Carboniferous-Permian Riffler-Schönach Basin (Veselá et al. 2008). The contact of the Göss Nappe with the overlying Hochalm Nappe is more difficult to trace because of the frequent absence of an intervening post-Variscan cover. We follow Exner (1980) who emphasised that a clear separation between the gneissic core of the Göss dome and the overlying Permo-Carboniferous gneisses is locally provided by the Draxel Complex (mostly garnet micaschist pointing to a flysch-type protolith and considered part of the "Jungpaläozoikum", Schuster et al. 2006). Where this "Jungpaläozoikum" is missing, the nappe contact is defined by migmatitic gneisses that include amphibolites formed during Variscan metamorphism, separating Late Carboniferous to Permian gneiss cores.

The *Tux-Granatspitz and Hochalm nappes* (25) occupy an intermediate structural position within the Venediger Duplex and hence are similarly located in the eastern and western parts of the Tauern Window, respectively. Their lateral continuity across the central Tauern Window is also questionable. The highest nappes within the duplex are the *Zillertal-Riffl Nappe* (24) of the western Tauern Window, the *Sonnblick-Romate Nappe* (24) of the eastern-central area and the *Mureck-Storz Nappe* (24) of the easternmost Tauern Window. These nappes are all directly overlain by the roof thrust and must hence be considered as structural equivalents even though they are separated from each other in map view. The Mureck-Storz Nappe has a separate mylonitic orthogneiss slice at its base (Mureck-Gneis or -Decke of Exner 1982).

The rocks of the Venediger Duplex reached temperatures of 500 to 600 °C during Alpine Barrow-type metamorphism (Oberhänsli et al. 2004; Schuster et al. 2004 and references therein). In the case of the southwestern Tauern Window (Selverstone et al. 1984, Selverstone 1985, 1988, 1993) the pressure maximum of 1.0–1.1 GPa predated the attainment of peak temperature conditions of 550 °C, at 0.7 GPa around 30 Ma ago (Christensen et al. 1994). Garnet growth under decreasing pressures (Selverstone 1993; Christensen et al. 1994) was pulse-like during the interval of 30–20 Ma (Pollington and Baxter 2010). The *Eclogite Zone* (21) of the Central Tauern Window was thrust onto the Venediger Duplex after the end of a first phase of decompression ending at about 32 Ma, and then was re-heated at around 30 Ma (Kurz et al. 2008; their Fig. 4). Hence, equilibration of the Venediger Duplex under Barrow-type conditions ("Tauernkristallisation") probably occurred around 30–28 Ma in the Tauern Window (see also Inger and Cliff 1994; Cliff et al. 1998). Rapid cooling during contemporaneous orogen-parallel stretching and orogen-perpendicular shortening started around 20 Ma (von Blanckenburg et al. 1989; Fügenschuh et al. 1997; Luth and Willingshofer 2008; Scharf et al. 2013).

2.1.1 Variscan basement

We restrict the term "Variscan" to metamorphic formations that predate most of the typically 310–270 Ma plutonic rocks referred to as "Zentralgneise" (Finger et al. 1993, 1997; Eichhorn et al. 2000; Veselá et al. 2011). Only the 335 Ma Ahorn Gneiss is known to be older (Veselá et al. 2011), but outcrops that would expose its contact with the country rocks are missing. Shortening related to Variscan Orogeny probably ended by Early Westphalian time (about 310 Ma ago) and was followed by a period of high heat flow related to extensional collapse and/or magmatic underplating. This was associated with widespread magmatic activity (Finger et al. 1997; Schuster and Stüwe 2008) typical for Late Carboniferous and Permian times all over Central Europe (e.g., Burg et al. 1994; Ziegler 1992). In the traditional literature, the term "Altes Dach" denotes those parts of the pre-Mesozoic metamorphic basement that show clear intrusive contacts with the "Zentralgneis" whereas "Altkristallin" denotes pre-Late Carboniferous basement in general (Pestal et al. 2009). The pre-Alpine metamorphic grade of this Altkristallin ranges from greenschist-facies (i.e. Habachphyllite of the northernmost central Tauern Window; Frasl 1958) to amphibolite-facies including migmatites ("Komplex der Alten Gneise" of the Riffl Nappe further south; Frasl and Frank 1966).

Radiometric dating has also revealed pre-Variscan tectono-metamorphic events. A reworked block of metagabbro found within the Mesozoic Kaserer Series (see Sect. 2.3) from the western Tauern Window yielded zircon with ages of 534 ± 9.4 Ma (Veselá et al. 2008). Pre-Variscan ages (Eichhorn et al. 2001; Kebede et al. 2005) were also found for a part of the so-called and poorly defined "Habach Series" of the central part of the Tauern Window (Frasl 1958; Höck 1993), specifically for the Lower Habach Formation or Lower Magmatic Sequence as defined by Kebede et al. (2005). This is a meta-ophiolitic association that comprises mafic and ultramafic series belonging to the Tux-Granatspitz Nappe of the central Tauern Window (Fig. 1).

Another large pre-Variscan basement complex in the central part of the Tauern Window (see Kebede et al. 2005 for a compilation of radiometric ages) is the "Old Gneiss Series" (="Komplex der Alten Gneise" of Frasl and Frank 1966). This series consists of Pre-Cambrian to Ordovician amphibolite, biotite gneiss and micaschist. These contain younger migmatitic layers and anatectic granites that formed during the Variscan event, i.e., in Early Carboniferous time (Schermaier 1991; Eichhorn et al. 1999, 2000). Elongate layers of strongly deformed Early Carboniferous granitoids (e.g., the Felbertauern Gneiss Lamellae; Eichhorn 2000) form the base of a thrust sheet of this "Serie der Alten Gneise", also described as Riffl Nappe in the literature (Frisch 1980a). However, in contrast to Frisch (1980a), we suspect that this Riffl Nappe (Zillertaler-Riffl Nappe of Fig. 1) is of Alpine age (see below). Where post-Variscan series are only locally preserved or missing, we mapped the boundary between Tux-Granatspitz Nappe and Zillertaler-Riffl Nappe in the central Tauern Window on the basis of distinctions in basement lithology. The basement complex of the Zillertaler-Riffl Nappe (mostly "Serie der Alten Gneise") is lithologically very distinct from the tectonically underlying series of the Tux-Granatspitz Nappe (pre-Variscan Lower Magmatic Sequence and Variscan Basisamphibolit; Kebede et al. 2005). The "Storz

Komplex" (Exner 1971a), also part of the Zillertaler-Riffl Nappe, makes up much of the high-grade parts of the Mureck-Storz Nappe in the easternmost Tauern Window (Table 1 and Fig. 1) and is a pre-Variscan basement complex lithologically similar to the "Komplex der Alten Gneise". The part of the Greiner Group (Lammerer 1986) that is intruded by the "Zillertaler Zentralgneis" in the western Tauern Window is probably also of pre-Variscan age.

Pre-Mesozoic series overlying the Lower Habach Formation of the Tux-Granatspitz Nappe of the central Tauern Window (Obere Magmatitabfolge and Habach Phyllites) correspond to the Habach Group as defined and mapped by Pestal and Hejl (2005). These series are typical for structurally higher parts of the Tux-Granatspitz Nappe preserved in synclines, which also include series that lack a pre-Variscan overprint, amongst them calc-alkaline volcanites often interpreted in terms of an island-arc environment (e.g., Vavra and Frisch 1989) and related sediments, the Habach Phyllites (Pestal et al. 2009 and references therein). Some of these volcanites yield Early Carboniferous to Permian ages (Kebede et al. 2005 and references therein) whereas the age of sedimentation of at least some of the Habach Phyllites is Neoproterozoic (Reitz and Höll 1988; Reitz et al. 1989). In the absence of clear age criteria we group the series of the Habach Group with the rest of the Variscan basement although some of the volcanites probably have a Late Carboniferous to Permian (i.e., post-Variscan) age.

2.1.2 *Permo-Carboniferous intrusions*

We regard the "Zentralgneise" of the Göss, Tux-Granatspitz, Hochalm, Zillertal-Riffl, Sonnblick-Romate and Mureck-Storz nappes, whose ages typically vary between 310 and 270 Ma (Finger et al. 1993, 1997; Eichhorn et al. 2000; Veselá et al. 2011), as post-Variscan in the sense that these intrusions post-date the Variscan tectonometamorphic event, although most authors refer to them as "Late Variscan". Here we prefer to refer to them as post-Variscan because they discordantly intrude Variscan and/or older metamorphic fabrics and hence, are only affected by Alpine deformation. For simplicity, we also put the "Zentralgneis" of the Ahorn Nappe in the same category although its Early Carboniferous age (Veselá et al. 2011) indicates that it must have intruded during rather than after Variscan orogeny.

2.1.3 *Post-Variscan cover*

The cover of suspected Late Carboniferous to Permian age that post-dates Variscan metamorphism, i.e., the *Post-Variscan cover* (23), plays a particularly important role in tracing nappe boundaries where Mesozoic strata are missing. Pestal and Hejl (2005) mapped such meta-sedimentary formations (e.g., Murtörl Formation and Draxel Complex, interpreted as "Jungpaläozoikum") at several locations with the same signature. Despite remaining uncertainties regarding their exact age, we interpreted these occurrences to represent cover in the sense that their age of deposition most probably post-dates Variscan tectonometamorphism.

The Murtörl Formation (Murtörlserie of Exner 1971a) was originally defined within a tectonic slice of the eastern Tauern Window that structurally overlies the Venediger Duplex (so-called Murtörl-Schrovin-Schuppe discussed later), but the term was also used for other occurrences of the same formation by Pestal et al. (2009), e.g., for the so-called "Woiskenschiefer" (Exner 1956, 1957) that separate the Sonnblick-Romate Nappe (uppermost structural level within the Venediger Duplex) from the underlying Hochalm Nappe (see Table 1 for correlations of structural units). The rocks of the Draxel Complex (Exner 1971b, 1980, 1982) define the thrust contact between Göss Nappe and overlying Hochalm Nappe. Unfortunately, both Murtörl Formation and Draxel Complex remain undated. Some workers have resorted to using the character of their contacts with magmatic bodies, including dykes that are considered part of the "Zentralgneis", as a criterion for determining the age of the sediments of the "Jungpaläozoikum"; meta-sediments injected by dykes (Schuster et al. 2006) were interpreted to also have experienced Variscan tectonometamorphism. Unfortunately, this criterion would only pertain if the "Zentralgneise" were indeed Variscan. As mentioned earlier, however, we regard the "Zentralgneise" as post-Variscan in the sense that they only suffered Alpine deformation. Recent studies in the Tauern Window have shown that sedimentation and magmatic activity were contemporaneous in Late Carboniferous to Permian times (Veselá et al. 2008, 2011) and there is increasing evidence for the existence of a separate post-Variscan, i.e., Permian, thermal event in the Alps in general (Schuster and Stüwe 2008).

Following Pestal et al. (2009) we also considered the so-called "Zwischenelendschiefer" (Lerchbaumer et al. 2010) of the cover of the Hochalm Nappe, the "Schiefer mit Biotitporphyroblasten" (Cornelius and Clar 1939) of the Granatspitz area (Tux-Granatspitz Nappe of the central Tauern Window) and the "Furtschaglschiefer" (Lammerer 1986) of the cover of the Zillertal-Riffl Nappe in the western Tauern Window as parts of this post-Variscan cover. Radiometric dating has so far only yielded "maximum ages" inferred from detrital zircons: 356 ± 2 Ma for the "Furtschaglschiefer" (Klötzli unpubl. as quoted in Lerchbaumer et al. 2010); 362 ± 6 and 368 ± 17 Ma for the "Biotitporphyroblastenschiefer" (Kebede et al. 2005) and 360 ± 13 Ma for the "Zwischenelendschiefer"

(Lerchbaumer et al. 2010). These data merely indicate that the Variscan rocks must have contained latest Devonian to earliest Carboniferous detrital zircons. The data set is remarkable for its lack of detrital zircons shed from the "Zentralgneise". Moreover, the "Biotitporphyroblastenschiefer" of the Felbertal and Amertal transgress directly onto the so-called "Basisamphibolit" (an amphibolite horizon forming the base of the "Obere Magmatitabfolge" and the frame of the "Zentralgneis" intrusion in the Granatspitz area; Kebede et al. 2005 and references therein). The protolith-age of this "Basisamphibolit" is 343 ± 1 Ma (Early Carboniferous) based on U–Pb zircon data (Kebede et al. 2005). The overlying "Biotitporphyroblastenschiefer" yields detrital zircons with 362 ± 6 Ma (Kebede et al. 2005), i.e., zircons that are older than the underlying "Basisamphibolit" and hence, of detrital origin. In summary, all these data suggest that the above-discussed series are post-Variscan in age.

The following formations fall into the post-Variscan and Pre-Mesozoic age range with certainty: (1) the Maurertal-Formation overlying the "Altkristallin" of the Zillertal-Riffl Nappe dated with fossils as Westphalian to Stephanian in age (312–299 Ma; Franz et al. 1991; Pestal et al. 1999) and (2) the so-called "Porphyrmaterialschiefer" comprising volcanites dated at around 283 Ma based on U–Pb zircon ages (Söllner et al. 1991; Loth et al. 1997). The latter are widespread in higher tectonic units (Wolfendorn Nappe; Frisch 1973/74) but also occur, together with Triassic marbles, in the Upper Palaeozoic cover of the Tux-Granatspitz Nappe near the contact to the Glockner Nappe system (Frank et al. 1987).

Summarizing, there are good reasons to group the post-Variscan Permo-Carboniferous cover with the Mesozoic cover. This provides an effective tool for separating Alpine tectonic units within the Venediger Duplex. The Mesozoic strata will be discussed in a separate chapter that also considers the palaeogeographic position of the Subpenninic units, including those in the hangingwall of the Venediger Duplex (Sect. 2.3). Where present, the Mesozoic strata provide unambiguous lithostratigraphic criteria for tracing Alpine nappe contacts.

2.2 Subpenninic nappes in the hangingwall of the Venediger Duplex

Two observations provide a key for distinguishing between units of the Venediger Duplex and the overlying Subpenninic nappes: firstly, Frank (1969) recognized a large isoclinal fold (his Seidlwinkl fold nappe) that is neither part of the Venediger Duplex nor of the Glockner Nappe system. Instead, it is part of what we call the Modereck Nappe system, described below (Sect. 2.2.3). Together with thin basement slices, this fold roots south of and in the hangingwall of the Venediger Duplex. Secondly, it was found that the Eclogite Zone in the central southern part of the Tauern Window occupies a structural position above the Venediger Duplex but below a lateral equivalent of the Seidlwinkl Nappe. The envelope of the Seidlwinkl Nappe that is in contact with the Glockner Nappe system is also locally overprinted by high-pressure metamorphism (Kurz et al. 1996, 1998a, 2008). Taken together, these facts point to a tectonic and metamorphic evolution of the Eclogite Zone and parts of the Seidlwinkl Nappe (Modereck Nappe system) that is distinct from that of the underlying Venediger Duplex. The northwestern part of the Tauern Window exposes a third Subpenninic slice that lacks high-pressure overprint: the Wolfendorn Nappe (Frisch 1973/74). Weakly metamorphosed units such as the Eisbrugg Slice and Gerlosstein Mesozoic in the southwestern Tauern Window are also part of the Modereck Nappe system (Rockenschaub et al. 2003a; Oehlke et al. 1993), as well as the Murtörl-Schrovin Unit of the northeastern Tauern Window (see Table 1).

2.2.1 *Wolfendorn Nappe*

The *Wolfendorn Nappe* (22) of the northwestern Tauern Window overthrusts two imbricates of the Venediger Duplex: the Tux-Granatspitz Nappe and Ahorn Nappe. This thin nappe was defined by Frisch (Frisch 1973/74) who realized that it has a pre-Triassic substratum (the Late Palaeozoic "Porphyrmaterialschiefer"; see Fig. 2) that substantially differs from the basement of the underlying Venediger Duplex. However, at the type locality of the Wolfendorn Nappe (a mountain peak of the same name) the Porphyrmaterialschiefer (see Sect. 2.1) is missing, and the base of the Wolfendorn Nappe contains only a thin band of Triassic strata separating the Upper Jurassic Hochstegen Marble of the Venediger Duplex (cover of the Tux-Granatspitz Nappe) from the Hochstegen Marble of the Wolfendorn Nappe (Frisch 1973/74). The latter is stratigraphically overlain by the Kaserer Series of suspected Cretaceous age (Frisch 1973/74, 1980b; Lammerer 1986; Rockenschaub et al. 2003a), a formation that is typical for the Wolfendorn Nappe (Fig. 2). In our compilation, we share the view of Frisch (1973/74) and Rockenschaub et al. (2003a), being aware that the structure of the Wolfendorn area and the age of the Kaserer Series is still highly controversial (see Veselá and Lammerer 2008; Lammerer et al. 2008, 2011; Töchterle 2011 for differing views).

2.2.2 *Eclogite Zone*

The *Eclogite Zone* (Fig. 1) occupies a tectonic position above the Venediger Duplex and below the Modereck Nappe system (2.2.3). Eclogite-facies conditions of

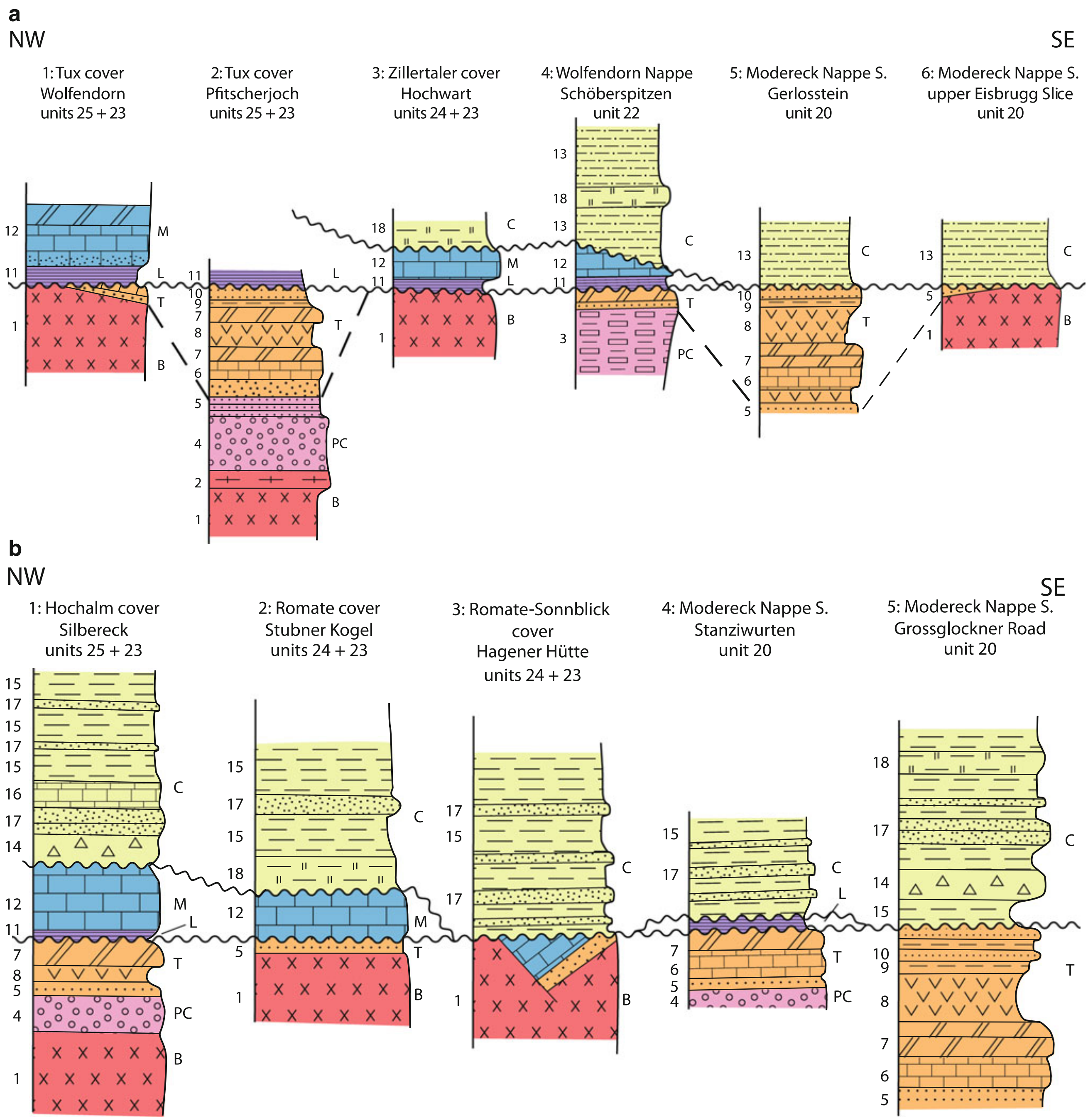


Fig. 2 Lithostratigraphic columns of the late Palaeozoic and Mesozoic cover of the Subpenninic nappes. **a** Western Tauern Window, **b** Eastern Tauern Window. The columns within the individual Fig. 2a, b are arranged according to the inferred palaeographical position going from NW (*left*) to SE (*right*). The stratigraphical logs were largely compiled from data by Alber (1976), Brandner et al. (2008), Exner (1982), Frisch (1975, 1980b), Frasl and Frank (1966), Höfer and Tichy (2005), Klebelsberg (1940), Kurz (2006), Kurz et al. (1998), Lammerer (1986), Lemoine (2003), Rockenschaub et al. (2003a), Thiele (1970), Veselá and Lammerer (2008), Veselá et al. (2008). Partly they are based on own observations. The lithologies are indicated with *numbers*, as follows: *1* granite gneiss; *2* Variscan basement; *3* Porphyrmaterialschiefer; *4* conglomerates; *5* Permo-Skythian quartzites; *6* limestones; *7* dolomites; *8* evaporites; *9* chloritoid schists; *10* Keuper quartzites; *11* Liassic black schists and sandstones; *12* Hochstegen Marble; *13* Kaserer Series in general; *14* dolomite breccias; *15* black phyllites; *16* slaty limestones; *17* Brennkogel quartzites; *18* calcschists. *Capital letters* indicate the geological age of the different formations, as follows: *B* Variscan basement; *PC* Upper Carboniferous to Permian; *T* Triassic; *L* Lower and Middle Jurassic; *M* Upper Jurassic; *C* Cretaceous (Brennkogel Formation and Kaserer Series). *Wavy lines* indicate the base Liassic and base Cretaceous unconformities, respectively

1.9–2.2 GPa and 600–630 °C (Hoschek 2001) were reached at 45–40 Ma (Zimmermann et al. 1994; Ratschbacher et al. 2004; Kurz et al. 2008), followed by a first stage of decompression lasting to 32 Ma. Later, reheating to amphibolite-facies conditions (Tauernkristallisation) affected the entire nappe stack including the Venediger Duplex (see Glodny et al. 2008 for a differing view regarding timing).

The eclogite-facies metamorphism during Early Cenozoic time indicates subduction of the most distal European passive continental margin to a depth of at least 80 km (Ratschbacher et al. 2004; Schuster et al. 2004; Thöni 2006; Kurz et al. 2008). The Eclogite Zone comprises felsic and carbonatic rocks (quartzites, paragneisses, garnet-micaschists, calcites, marbles, and siliceous dolomites; Franz and Spear 1983) and contains layers and lenses of mafic eclogites. These lithologies are part of a volcano-sedimentary sequence of the distal continental slope (Miller et al. 1980, 2007). The mafics probably represent intrusions into the most distal European margin at the continent-ocean transition. Possibly, parts of the Eclogite Zone may represent a tectonic mélange (Miller et al. 1980). Either way, it is unlikely that the Eclogite Zone is part of the oceanic Glockner Nappe system. In summary, we propose that the Eclogite Zone is derived from the most distal European margin, analogous to the Adula Nappe of the Central Alps in Switzerland (Schmid et al. 2004).

2.2.3 *Modereck Nappe system*

The term "Modereck Nappe" was coined by Kober (1922) and Hottinger (1935) to denote the structurally highest basement slice in the Sonnblick area that is occasionally also referred to as the Rote Wand Nappe or Rote Wand—Modereck Nappe (e.g., Kurz et al. 2008). We use the term *Modereck Nappe system* (20) to denote all the units in a similar structural position immediately below the Glockner Nappe. The Seidlwinkl Nappe, an isoclinal fold nappe whose extent is limited to the central Tauern Window (Frank 1969), finds its root at the Rote Wand and Stanziwurten localities found in the southwestern flank of the Sonnblick dome. This fold nappe has a gneissic core ("Gneislamelle 4" of Exner 1962a; Alber 1976) that comprises mostly the Permo-Triassic Wustkogel Formation. Parts of the Modereck Nappe system located in the Grossglockner area are, together with the adjacent Eclogite Zone, affected by eclogite-facies metamorphism (Fig. 1).

Following Kurz et al. (1996), we also consider the Murtörl-Schrovin Schuppe (Schuppe = thin nappe slice) in the eastern Tauern Window (Schuster et al. 2006) as a part of the Modereck Nappe system. This slice consists essentially of the Late Palaeozoic Murtörl Formation (Exner 1971a) overlain by the Wustkogel and Seidlwinkl formations (Schrovin-Gruppe of Exner 1971a). Slivers attributed to the Modereck Nappe system are also found in the Matrei area of the southern central Tauern Window where they occur as basement lamellae (so-called "Glimmerschieferlamelle" consisting of quartz-rich muscovite bearing micaschists) that are associated with Triassic marbles and the Cretaceous Brennkogel Formation. These slivers separate the underlying Eclogite Zone from the tectonically higher Glockner Nappe system (Spear and Franz 1986; Kurz et al. 1998.

Gneiss and amphibolite slivers, accompanied by Mesozoic marble and the Kaserer Series, a lateral equivalent of the Brennkogel Formation (Fig. 2), are also found south of and around the southwestern tip of the basement of the Zillertal-Riffl Nappe (Lower and Upper Eisbrugg Lamella of Oehlke et al. 1993). They tectonically overlie a thin veneer of Hochstegen Marble belonging to the Venediger Duplex. Thin Mesozoic slivers of the Modereck Nappe system are also exposed around the southern, western and northwestern margins of Ahorn and Tux-Granatspitz nappes (Modereck Nappe of Rockenschaub et al. 2003a, Rockenschaub et al. 2011; Decker et al. 2009). These slivers lie above the Wolfendorn Nappe and consist predominantly of Permo-Skythian clastics, evaporite-bearing Triassic carbonates and Keuper quartzites in the Seidlwinkl facies (Rockenschaub et al. 2003a; "Triassic base of the Upper Schieferhülle" of Töchterle et al. 2011). It is possible that some of the overlying meta-sediments (mostly calcschists referred to as "Bündnerschiefer") that we group with the Glockner Nappe system in fact represent the stratigraphic cover of Permo-Triassic strata belonging to the Modereck Nappe system (Decker et al. 2009; Rockenschaub et al. 2011; Töchterle 2011; Töchterle et al. 2011). However, we regard the majority of the calcschists of the northwestern Tauern Window to be in tectonic contact with the Seidlwinkl-Rote Wand Nappe and we therefore group them with the Glockner Nappe system.

3 Stratigraphical and palaeogeographical considerations regarding the Mesozoic cover of the Subpenninic nappes

The Mesozoic sediments of the Subpenninic nappes remain undated due to their strong metamorphic overprint. An exception is the Hochstegen Marble, an outer shelf deposit whose Late Jurassic age is documented by fossils (Klebelsberg 1940; Kiessling 1992; Höfer and Tichy 2005). Hence, dating these meta-sediments relies almost entirely on lithostratigraphic comparisons with well-dated series elsewhere in the Alps and its foreland. The facies of the Hochstegen Marble was taken either as typical for the Briançonnais palaeogeographical domain (e.g., Frisch

1979; Tollmann 1987), or alternatively, for the European (Helvetic) margin (e.g., Lammerer 1986; Trümpy 1992; Froitzheim et al. 1996). The answer to this dilemma has profound implications for the eastward lateral extent of the Briançonnais continental fragment separating the Piemont-Liguria and Valais oceanic domains, the origin of the Rhenodanubian flysch (north or south of the Subpenninic units), and thirdly and most importantly, the amount of Cenozoic N–S-shortening (see discussion in Kurz 2006).

Figure 2 shows lithostratigraphic sections for the Venediger Duplex, the Wolfendorn Nappe and parts of the Modereck Nappe system (see caption of Fig. 2 for references), arranged from north-west to south-east according to inferred palaeogeographical position for the western Tauern Window (Fig. 2a) and for the eastern Tauern Window (Fig. 2b), respectively. Occurrences of the Upper Jurassic Hochstegen Marble are restricted to the Venediger Duplex (columns 1 and 3 of Fig. 2a; columns 1–3 of Fig. 2b) and parts of the Wolfendorn Nappe (column 4 of Fig. 2a). We explain its absence practically everywhere in the Modereck Nappe system (columns 5 and 6 of Fig. 2a; columns 4 and 5 of Fig. 2b) as due to erosion below an unconformity at the base of the Brennkogel Formation of the eastern Tauern Window and its lateral equivalent, the Kaserer Series of the western Tauern Window. As proposed by Lemoine (2003), the dark calcschists and black shales of the Brennkogel Formation, with intercalations of quartzite beds and carbonatic breccias, is an association that is typical for the so-called "Gault-type" black shales found elsewhere in Mid-Cretaceous deposits of the Alps. These rocks were deposited in an oxygen-starved environment during one of the several Cretaceous global anoxic events (probably OAE1a; Takashima et al. 2006). Such lithologies are widespread in the Subbriançonnais units of eastern Switzerland (Schams, Tasna and Falknis nappes, e.g., Rück and Schreurs 1995), the Rhenodanubian Flysch Zone (e.g., Mattern and Wang 2008) and the Valaisan units of Switzerland and Savoie (e.g., Bertle 2004; Loprieno et al. 2011). The similarity of the sequences of the Seidlwinkl fold nappe (Modereck Nappe system) exposed along the Grossglockner road (Frasl and Frank 1966) and the External Valais Units of the Versoyen (Loprieno et al. 2011) is striking: a Cretaceous post-rift sequence directly transgresses a Germanic-type Triassic pre-rift sequence (see column 5 of Fig. 2b), the previously deposited Jurassic deposits having been completely eroded in submarine highs that formed during rifting associated with the opening of the Valais Ocean.

An older angular unconformity of Early Jurassic age (Frisch 1975) is responsible for the direct transgression of Early Jurassic quartzites and black shales onto the basement of the western tips of Tux-Granatspitz Nappe and the Zillertal-Riffl Nappe in the western Tauern Window (columns 1 and 3 of Fig. 2a). This indicates local erosion of previously deposited Triassic strata in the earliest Jurassic. The same graphite-rich formation, known as the Schwarzkopf Formation in the central and eastern Tauern Window (Pestal et al. 2009), was probably deposited during the Toarcian global anoxic event (Takashima et al. 2006) and locally overlays Upper Triassic Keuper beds (column 2 of Fig. 2a; column 4 of Fig. 2b). Frisch (1975) recognized the strong similarity of this formation with the so-called Gresten facies found in the Ultrahelvetic Grestener Klippenzone at the northern border of the Alps, a facies that extends into the Moravian Zone of the Bohemian Massif (Faupl 1975). This same Gresten facies is widespread all over the Europe-derived Tisza and Dacia Mega-Units of the circum-Pannonian area (Schmid et al. 2008). In our view, the presence of the Early Jurassic Gresten facies, together with the Germanic character of the Triassic deposits, strongly supports a European origin of the Subpenninic Units and virtually excludes their provenance within an eastern extension of the Briançonnais continental fragment. The latter ends eastward somewhere between the Engadine and Tauern windows.

Interestingly, the Brennkogel Formation is very similar to many of the meta-sediments of the Glockner Nappe system. This is particularly true for the profile across the Mesozoic cover of the Hochalm Nappe (Silbereckserie of Exner 1982, 1983; see column 1 of Fig. 2b) where the Brennkogel Formation, mapped as "Bündnerschiefer" (Häusler 1995), stratigraphically overlies marbles (Silbereckmarmor) recently dated as Late Jurassic (Höfer and Tichy 2005). This indicates that there must be a continuous transition from the Subpenninic Units that represent the distal European margin to the sediments of the Glockner Nappe system that were deposited largely on oceanic lithosphere (Valais Ocean, see below).

In conclusion, the Subpenninic nappes appear to originate from the distal European margin that faced the Valais oceanic domain. This points to a palaeogeographic origin of the Rhenodanubian flysch from south of the Tauern Window (Hesse 2011), which in turn indicates an amount of Cenozoic N–S-shortening across the Eastern Alps that is of the same order of magnitude as that reported for an Alpine transect across Eastern Switzerland (e.g., some 500 km, Schmid et al. 1996).

4 Ophiolite bearing units (Penninic units) of the Tauern Window

The palaeogeographic position of the most voluminous part of the ophiolite-bearing units of the Tauern Window, referred to as Glockner Nappe system, is controversial. While some authors (e.g., Frisch 1980b; Kurz 2006) attribute the Glockner Nappe system to the Piemont-Liguria

Ocean (PLO), others parallelize it with the calcschists and ophiolites of the Valais Ocean (VO) exposed in the Lower Engadine Window west of the Ötztal Nappe (e.g., Trümpy 1992; Schmid et al. 2004). At first sight, grouping it with one of the two oceans of Alpine Tethys (PLO or VO) would seem to be a semantic exercise considering that the intervening Briançonnais continental sliver wedges out between the Engadine and Tauern windows (Schmid et al. 2005; discussion above and in Kurz 2005). However, the following criteria allowed us to assign ophiolite-bearing units east of the Engadine window to one or the other of these oceanic domains: (1) age of rifting and passive margin formation regarding these two oceanic domains (Mid-Jurassic vs. Early Cretaceous; Frisch 1979), (2) presence (PLO) or absence (VO) of radiolarites and aptychus limestone deposited on exhumed mantle rocks, (3) presence of rock assemblages that are characteristic for an ocean-continent transition along either the Adriatic (PLO) or the European (VO) margins, (4) evidence for early accretion to either the Adriatic margin (PLO) during Cretaceous top-W nappe stacking in the Eastern Alps or Cenozoic accretion to the European margin (VO).

4.1 Glockner Nappe system

The term *Glockner Nappe system* (19) denotes a nappe pile with calcareous micaschist and subordinate meta-pelite (Glockner Nappe of Staub 1924) of probable Cretaceous age, often intercalated with prasinite or amphibolite, depending on grade of metamorphism (Pestal et al. 2009). In the northern central part of the Tauern Window, the meta-sediments of the Glockner Nappe system are often purely siliciclastic or carbonate-poor and phyllitic (so-called Fuscher Phyllit; Pestal et al. 2009). Fossils indicate a Hauterivian or younger age for a limestone formation found immediately north of these phyllites (Höck et al. 2006). The lithological association of the Glockner Nappe system is very similar to the Cretaceous Valais-derived calcschists of the Engadine Window and the Valais units of Savoie (Jeanbourquin and Burri 1991; Steinmann 1994; Loprieno et al. 2011). This series is distinguished from the Piemont-Liguria Ocean derived associations based on the criteria discussed above. The Cenozoic age of high-pressure metamorphism in the Glockner Nappe system (Fig. 1) indicates that parts of the Glockner Nappe system were subducted and exhumed during the Cenozoic Alpine orogeny, together with the most distal part of the European margin (Eclogite Zone). In summary, all this indicates that the Glockner Nappe system comprises relics of the Valais Ocean, together with the Rhenodanubian Flysch along the northern margin of the Eastern Alps (Schmid et al. 2004).

The Glockner Nappe system remains to be subdivided, for two main reasons. First, parts of the meta-sediments attributed to the Glockner Nappe, particularly those in the northern parts of the Tauern Window, may have been deposited on continental rather than oceanic lithosphere. Lenses of serpentinite, occasionally associated with metagabbro (Pestal et al. 2009 and references therein) are rather rare in this part of the Glockner Nappe system. Secondly, metamorphic grade varies from eclogite-facies (southern central part of the Tauern Window in vicinity to the Seidlwinkl fold nappe and the Eclogite Zone; Sturm et al. 1997; Dachs and Proyer 2001) to greenschist- or lower blueschist-facies conditions elsewhere (Schuster et al. 2004 in Oberhänsli et al. 2004). The maximum pressure and temperature determined for the Glockner Nappe system in the southern part of the central Tauern Window (Dachs and Proyer 2001) are only slightly less than those obtained for the adjacent Eclogite Zone.

4.2 Reckner ophiolitic complex

The *Reckner ophiolitic complex* (18) is a piece of exhumed subcontinental mantle with occurrences of ophicalcite, stratigraphically overlain by Jurassic radiolarites and younger pelagic sediments (Enzenberg-Praehauser 1967, 1976; Koller and Pestal 2003). This is typical for ophiolitic sequences derived from the Piemont-Liguria Ocean (Froitzheim and Manatschal 1996). This ophiolitic complex tectonically overlies the Lower Austroalpine Reckner and Hippold nappes (e.g., Rockenschaub and Nowotny 2009). All these three units (from top to bottom Reckner ophiolitic complex, Reckner Nappe, Hippold Nappe), tectonically overlie the Innsbruck Quartzphyllite Unit considered as an Upper Austroalpine unit, as will be discussed later. Moreover, all these three units were deformed under blueschist-facies conditions in Early Cenozoic time, as indicated by Ar/Ar white mica ages of 50–57 Ma for the Reckner ophiolitic complex (Dingeldey et al. 1997; Ratschbacher et al. 2004). Pressures obtained for Matrei Zone and Innsbruck Quartzphyllite Unit in the footwall of these three blueschist-facies units are distinctly lower (Dingeldey et al. 1997) and Alpine Ar/Ar ages are older (83–77 Ma; Heidorn et al. 2003) in case of the Innsbruck Quartzphyllite Unit. All this indicates younger, out-of-sequence thrusting of the Reckner ophiolitic complex, together with the underlying Hippold and Reckner nappes, onto the Innsbruck Quartzphyllite Unit.

4.3 Matrei Zone

The type locality of the *Matrei Zone* (17) is at the southern margin of the Tauern Window. Following Koller and Pestal (2003) and Pestal et al. (2009) we also include the so-called "Nordrahmenzone", defining the northern contact zone of the Tauern Window to the Austroalpine units, into this same tectonic unit. This Nordrahmenzone is lithologically very heterogeneous (Peer and Zimmer 1980); locally an Early Cretaceous age is indicated by palynomorphs (Reitz et al. 1990). The Matrei Zone s. str. is also lithologically very heterogeneous and represents an imbricate zone or mélange zone with huge blocks, up to several km wide. "Bündnerschiefer"-type sediments and subordinate ophiolitic lithologies (mafic–ultramafic rocks and/or their pelagic cover) are mixed with sediments of Permian to Jurassic age that are clearly derived from the Adriatic margin (Austroalpine). Some authors (e.g., Frisch 1987) prefer to interpret the Austroalpine blocks as olistoliths; others consider the Matrei Zone and lateral equivalents elsewhere as a tectonic mélange or imbricate zone (Arosa Zone, Valsertal Zone; Winkler and Bernoulli 1986). In any case, the setting of the Matrei Zone is that of an accretionary prism that formed during the subduction of the Piemont-Liguria Ocean in front and below the Austroalpine as a part of the Adria upper plate during Late Cretaceous times (Handy et al. 2010).

Little is known about grade and age of metamorphism in the Matrei Zone. Dingeldey et al. (1997) report 0.6–0.7 GPa and 400 °C for the Matrei Zone at the north-western margin of the Tauern Window while Koller and Pestal (2003) report blueschist overprint for the Matrei Zone at the southern rim of the Tauern Window. Dingeldey et al. (1997) report Eocene ages of metamorphism, indicating that the Matrei Zone was re-worked during Cenozoic orogeny, when the Glockner Nappe system was accreted to an upper plate that, apart from the Austroalpine, also included the previously accreted Matrei Zone.

5 Units derived from the Adriatic continental margin (Austroalpine nappes, Southern Alps) adjacent to the Tauern Window

5.1 Lower Austroalpine nappes

The Lower Austroalpine nappes comprise tectonic units originally located at the most distal passive margin of Adria (Froitzheim and Eberli 1990; Schmid et al. 2004). Drawing a clear boundary with the Upper Austroalpine units is difficult, particularly in the north-eastern and eastern corners of the Tauern Window. For example, we do not regard the Katschberg Zone Quartzphyllites, running parallel to the central part of the Katschberg Shear Zone (Scharf et al. 2013), as part of the Lower Austroalpine Nappe system for reasons discussed below. Mesozoic series with spectacular rift-related breccias that are typical for the Lower Austroalpine nappes appear at the northern margin of the Tauern Window in the Tarntal area south of Innsbruck, and in the Radstädter Tauern units at the north-eastern edge of the Tauern Window (Häusler 1988). Lower Austroalpine series have also been described from small areas south of the Tauern Window (Fuchs et al. 1996; Pestal and Hejl 2005; Fuchs and Linner 2005).

The Lower Austroalpine nappes around the Tauern Window suffered intense deformation and greenschist- or blueschist-facies overprinting, from the onset of subduction of the Piemont-Liguria Ocean in Late Cretaceous time to final closure of the Valais Ocean in Eocene time. The Ar/Ar white mica ages obtained for metamorphism in the Radstädter Tauern range between 80 and 50 Ma (Liu et al. 2001) but are younger in the Tarntal area (44–37 Ma, Dingeldey et al. 1997).

5.1.1 Hippold Nappe and Hochfeind Nappe

The breccious sediments of the *Hippold Nappe* (16) near the north-western corner of the Tauern Window are interpreted as base-of-fault-scarp breccias, shed from the south in Early and Mid-Jurassic times (Häusler 1988). These breccias are overlain by Upper Jurassic radiolarites (Enzenberg-Praehauser 1976). Representatives of the most distal part of the Austroalpine passive margin are also found in the form of the breccias of the *Hochfeind Nappe* (16) in the Radstädter Tauern near the north-eastern corner of the Tauern Window (Häusler 1988; Becker 1993). While the Hochfeind Nappe, as expected, immediately overlies the mélange of the Matrei Zone, the structural position of the Hippold Nappe on top of the Upper Austroalpine Innsbruck Quarzphyllite Unit is due to late-stage folding and thrusting.

5.1.2 Reckner Nappe and Main Nappe group

Reckner Nappe (15) is the traditional name (Häusler 1988) for the tectonically higher of the two Lower Austroalpine thrust sheets that tectonically overlie the Innsbruck Quartzphyllite Unit near the north-western corner of the Tauern Window ("Kalkwand Deckscholle" of Enzenberg-Praehauser 1976; "Tarntal Nappe" of Decker et al. 2009). The sediments of the Reckner Nappe are relatively poor in breccias, their facies being nearer to that of the Upper Austroalpine units. In terms of facies they can be compared to the Pleisling Nappe of the Radstädter Tauern (Häusler 1988). The Pleisling Nappe forms a large part of a pile of imbricates referred to as the *Main Nappe Group* (15) in the Radstädter Tauern (Becker 1993).

5.1.3 Lower Austroalpine south of the Tauern Window

The *Lower Austroalpine south of the Tauern Window* (14) consists of pre-Triassic basement and predominantly Permo-Skythian clastics (Pestal and Hejl 2005). A distinction of these units from Lower Austroalpine slivers, incorporated in the Matrei Zone, is often difficult (Fuchs et al. 1996; Fuchs and Linner 2005).

5.2 Upper Austroalpine basement-cover nappes

These nappes, also referred to as Central Austroalpine nappes (Froitzheim et al. 2008), occupy the central part of the Alpine orogen presently located south of the detached Grauwackenzone and Northern Calcareous Alps cover units and north of the Southern Alps. Most, but not all of these nappes are affected by Cretaceous (Eoalpine) metamorphism (Schuster et al. 2004; Oberhänsli et al. 2004; Schmid et al. 2004). Formerly they were subdivided into Middle and Upper Austroalpine Units, a subdivision now abandoned for various reasons (see discussions in Schuster and Frank 1999; Schmid et al. 2004). Their palaeogeographic relationship with the detached units of the Grauwackenzone and Northern Calcareous Alps is only partly understood. Nagel (2006) clearly showed that the so-called Phyllitgneiszone, regarded as the basement of the Lechtal Nappe (a part of the Bavarian nappes of the Northern Calcareous Alps), is an integral part of the Silvretta Nappe. Hence, a part of the Bajuvaric nappes represents the cover of one of these Central Austroalpine nappes. This is definitely not the case for the Grauwackenzone and the Tirolian and Juvavic nappes of the Northern Calcareous Alps that were detached from their substratum during the very early stages of Eoalpine orogeny (Schuster 2003; Schmid et al. 2004; Handy et al. 2010).

5.2.1 Silvretta-Seckau Nappe system

The Silvretta Nappe, including its Mesozoic cover, was thrust towards WNW and over the Lower Austroalpine units of eastern Switzerland during Eoalpine (Cretaceous) orogeny (Froitzheim et al. 1994), and is located west of the area covered by Fig. 1. The Seckau crystalline complex is located east of our tectonic map (Schmid et al. 2004). The Innsbruck Quartzphyllite Unit and the Schladming Nappe take up the largest area attributed to this nappe system within the area of Fig. 1.

For better understanding the transition zone between Lower and Upper Austroalpine units we mapped the *overturned Permo-Mesozoic cover of the Schladming Nappe* (13) separately from the overlying crystalline basement of the Schladming Nappe. These flat lying sediments, mostly consisting of phyllites and sericitic quartzites of Permian to Early Triassic age, were recognized as representing the overturned stratigraphic cover of the Variscan basement of the Upper Austroalpine Schladming Nappe by Slapansky and Frank (1987) and Becker (1993). Similar overturned cover is seen southeast of the locality Obertauern (north-northwest of Mauterndorf, see Fig. 1), but here in stratigraphic contact with Palaeozoic quartzphyllites (Fanning Phyllites of Exner 1989) rather than with the typical Schladming orthogneisses forming the basement of the Schladming Nappe NE of Obertauern. Exner (1989) parallelized the Fanning Phyllites with the Katschberg Quartzphyllites (quartzphyllites and phyllonites, Schuster et al. 2006). The latter is, however, commonly attributed the Lower Austroalpine Nappe system (e.g., Schuster et al. 2006). Since the overturned Mesozoic cover of the Schladming orthogneisses series can be traced along strike into the overturned cover of the Fanning Phyllites and the Katschberg Quartzphyllites (Pestal and Hejl 2005) we prefer to attribute the Fanning Phyllites and the Katschberg Quartzphyllites to the Silvretta-Seckau Nappe system, together with other quartzphyllites and/or phyllonitic series such as the Innsbruck Quartzphyllites Unit.

The *high-grade Variscan basement of Schladming and Campo nappes* (12) is mapped separately from the various phyllitic units of the Silvretta-Seckau Nappe system, although the separation between, for example, the Schladming high-grade orthogneisses and amphibolites from Fanning Phyllites, represents a lithological rather than an Alpine tectonic boundary. Only a thin and westernmost band of the Campo high-grade Variscan basement reaches our map in the Meran area (Fig. 1). There it is separated from the Texel Unit of the Koralpe-Wölz Nappe system by the Thurnstein Mylonite Zone to the north (Viola et al. 2001), and it borders the Drauzug-Gurktal Nappe system (Tonale Nappe; Viola et al. 2003) to the south.

The tectonic position of the *Innsbruck-Wagrain-Katschberg Quartzphyllite Units* (11) is controversial according to the literature. In the following we briefly explain the choice we made for our compilation. The Innsbruck Quartzphyllite Unit, besides quartzphyllites, also includes phyllonites (Patscherkofel Crystalline), schists (Steinkogel schists) and orthogneiss (Kellerjochgneis) lenses (Piber and Tropper 2003; Pestal et al. 2009). Some authors consider this unit as Lower Austroalpine (Tollmann 1977; Heidorn et al. 2003). However, according to recent mapping (Rockenschaub et al. 2003b; Rockenschaub and Nowotny 2009) the predominantly Palaeozoic (Silurian to Devonian) sedimentary series does not form the stratigraphic substratum of the Lower Austroalpine Mesozoic sediments exposed in the overlying Hippold Nappe. These rest above an out-of-sequence thrust over the Innsbruck Quartzphyllite Unit. Moreover, Alpine grade of metamorphism of the Innsbruck Quartzphyllite Unit is much lower (lower greenschist facies; Piber and Tropper 2003) than that of the Hippold Nappe (Dingeldey et al. 1997). In view of the low grade of Alpine metamorphism and its tectonic position underneath a klippe of Ötztal basement south of

Innsbruck (Patscherkofel), we consider the Innsbruck Quartzphyllite Unit as part of the Silvretta-Seckau Nappe system, following the tectonic scheme of Rockenschaub and Nowotny (2009). We do not follow the proposal by Pestal et al. (2009) that the Innsbruck Quartzphyllite Unit forms a part of the Koraple-Wölz nappe system; the latter has a much higher grade of Alpine metamorphism (Schuster et al. 2004). On the other hand, we followed Pestal et al. (2009) in parallelizing the Innsbruck Quartzphyllite Unit north of the Salzach-Ennstal-Mariazell-Puchberg (SEMP) Fault with the Wagrain Phyllite located south of this fault further east, where it tectonically overlies a thin sliver of the Schladming nappe (see Exner 1996, and Fig. 1, 25 km west-southwest of Schladming). This parallelization indicates a sinistral dislocation of the Wagrain Quartzphyllite with respect to the Innsbruck Quartzphyllite Unit along the SEMP Fault by some 60 km (see Fig. 1). As already discussed, we also included the Katschberg Quartzphyllites into the same group of phyllites. However, the Ordovician to Silurian Ennstal Phyllites (Priewalder and Schuhmacher 1976), parallelized with the Wagrain Quartzphyllite Unit by most authors (e.g., Pestal et al. 2009), are found in a much higher tectonic position: the steeply N-dipping Ennstal Phyllites tectonically overlie the high-grade Wölz Micaschists of the Koralpe-Wölz Nappe system (Fritsch 1953). Hence we mapped them as a part of the Grauwackenzone located south of two splays of the SEMP Fault (Fig. 1, east-southeast of Schladming).

5.2.2 Koralpe-Wölz Nappe system

The Koralpe-Wölz high-pressure Nappe system comprises a series of basement units characterized by significant Eoalpine metamorphic overprint (Schuster et al. 2001; Schuster 2003). It includes eclogitic MORB-type gabbros yielding Permian protolith ages (Miller and Thöni 1997) but lacks Mesozoic cover, detached early on and now located in the Northern Calcareous Alps (Froitzheim et al. 2008).

The Texel Unit of the *Texel-Millstadt-Wölz Unit* (10), located southwest of the Tauern Window, is known for its Cretaceous (ca. 90 Ma) eclogitic parageneses (Hoinkes and Thöni 1987; Habler et al. 2006; Thöni 2006). It is southerly adjacent to the Schneeberg Unit that forms the part of the *Schneeberg-Radenthein Unit* (9) located west of the Tauern Window, a unit consisting of amphibolite grade sequences of meta-pelites of Late Palaeozoic age that only suffered Alpine metamorphism (Krenn et al. 2011). The Schneeberg Unit, sandwiched between the northerly adjacent and structurally higher Ötztal Nappe and the southerly adjacent Texel Unit, was formerly interpreted as a N-dipping normal fault zone (Sölva et al. 2005). Recently, Pomella (2011) interpreted this N-dipping fault zone at the base of the Ötztal Nappe as an originally S-dipping nappe boundary that became overturned in Cenozoic times.

East of the Brenner and Jaufen faults, units of the Koralpe-Wölz Nappe system are extremely thinned out near Sterzing and can be followed further east into the northern Deferegger Alps and the Schober and Polinik-Prijakt crystalline units (Schuster et al. 2001; Schuster 2003; Schmid et al. 2004). There they are in a sub-vertical orientation and juxtaposed with the southerly adjacent and structurally higher Drauzug-Gurktal Nappe system along steeply inclined Late Alpine faults, such as the sinistral Defereggen-Antholz-Vals (DAV) Fault (Borsi et al. 1973; Mancktelow et al. 2001).

The Mölltal Fault dextrally offsets the eclogitic Polinik-Prijakt Crystalline Unit against its lateral equivalent to the east, the Millstatt Unit. The eclogite-facies Millstatt Unit is overlain by the amphibolite-grade Radenthein Unit of the Koralpe-Wölz Nappe system (Krenn et al. 2011). This configuration is analogous to that found west of the Tauern Window, which suggests that these configurations were adjacent to each other before orogen-parallel extension contemporaneous with the formation of the Tauern Window tore them apart (Frisch et al. 1998). East of the Tauern Window, the amphibolite grade Wölz Unit forms the northern part of the Texel-Millstadt-Wölz Unit, separated from the southern part by the klippe of the overlying Ötztal-Bundschuh Nappe system. This upper greenschist- to amphibolite grade Wölz Unit tectonically underlies the eclogite-facies equivalents of the Millstatt Unit. The Saualpe-Koralpe Unit is only found east of the area of the tectonic map of Fig. 1 (see Schuster et al. 2001; Schuster 2003; Schmid et al. 2004; Froitzheim et al. 2008, for more details).

5.2.3 Ötztal-Bundschuh Nappe system

The Ötztal-Bundschuh Nappe system occupies an intermediate tectonic position within the Cretaceous nappe stack, the unmetamorphosed or weakly metamorphosed Drauzug-Gurktal Nappe system in its hanging wall, and the Koralpe-Wölz high-pressure Nappe system in its footwall (Schmid et al. 2004). The Ötztal and the Bundschuh Nappe, located immediately west and east of the Tauern Window, respectively, are characterised by a strong field metamorphic gradient regarding Eoalpine metamorphism: the grade of metamorphism rapidly increases downwards and towards the contact with the higher grade Koralpe-Wölz Nappe system (Schuster et al. 2001; Schuster 2003). The effects of Miocene orogen-parallel stretching during E-directed lateral extrusion of the Austroalpine nappes towards the east (Ratschbacher et al. 1991) separated the Ötztal and Bundschuh nappes that originally were fairly close to each other.

The *Variscan basement* (8) of this nappe system is typically polymetamorphic (Thöni 1999). Its *Mesozoic cover* (7), preserved in the form of the Brenner Mesozoic (west of the Tauern Window) and the Stangalm Mesozoic (east of the Tauern Window) defines the nappe boundary in respect to the tectonically higher Drauzug-Gurktal Nappe system. The Stangalm Mesozoic formerly served as a proof for the "Middle Austroalpine" position of the Central Austroalpine nappe stack below the Drauzug-Gurktal Nappe system (Tollmann 1977).

5.2.4 Drauzug-Gurktal Nappe system

The Mesozoic cover of the highest nappe system within the Upper Austroalpine (Schmid et al. 2004, 2008), the Drauzug-Gurktal Nappe system, has close palaeogeographical affinities to the westernmost part of the Northern Calcareous Alps (Bechstädt 1978), parts of the adjacent Southern Alps, the Transdanubian Range in Hungary and the external Dinarides. Large parts of this nappe system were not metamorphosed at all; others at most reached lower greenschist facies during the Alpine cycle (Schuster et al. 2004; Oberhänsli et al. 2004). At present a large part of this nappe system is restricted to an area south of the southern border of Alpine metamorphism, referred to as SAM by Hoinkes et al. (1999), and immediately north of the Periadriatic Fault.

The following pre-Mesozoic *basement complexes* (6) belonging to this nappe system follow the Periadriatic Fault, from west to east: Tonale Nappe, Meran-Mauls Basement, Gailtal Basement, South Deferegger Alps and Strieden Complex (Schuster et al. 2001). At the western margin of the tectonic map (Fig. 1) the Palaeozoic of the flat-lying Steinach Nappe tectonically overlies the Mesozoic cover of the Ötztal Nappe (Brenner Mesozoic). This is analogous to the situation at the eastern margin of the map were the flat-lying Gurktal Nappe tectonically overlies the Mesozoic cover of the Bundschuh Nappe. The Graz Palaeozoic also belongs to this group of nappes but is restricted to an area east of the area covered by Fig. 1. The Palaeozoic of the Gurktal Nappe, locally including its Permo-Triassic cover, and the Graz Palaeozoic are un-conformably covered by Gosau Beds. The basement near the Periadriatic Line (Strieden Complex) is covered by non-metamorphic Mesozoic sediments, often in direct stratigraphic contact (Drauzug Mesozoic).

The *Mesozoic cover* (5) of this nappe system is principally preserved in the E–W elongated strip, the so-called Drauzug (van Bemmelen and Meulenkamp 1965). A thin isolated sliver of the Drauzug near Sterzing is referred to as the Mauls Mesozoic. This cover was formerly deposited onto the northerly and southerly adjacent basement complexes; some of the stratigraphic contacts still being locally preserved. Small klippen (Blaser Nappe) west of the Brenner Line represent the detached Mesozoic cover of the Steinach Nappe, detached during Late Cretaceous normal faulting (Fügenschuh et al. 2000). Analogous to this, Mesozoic cover of the Gurktal nappe at the eastern margin of Fig. 1 directly overlies the Ötztal-Bundschuh nappe and locally marks the base of the Gurktal nappe east of the Tauern Window, again due to Late Cretaceous normal faulting (Koroknai et al. 1999).

5.3 Upper Austroalpine: far travelled cover nappes

These nappes consist of Palaeozoic and Mesozoic cover units that started to detach from their crystalline substrate very early on, i.e. since the Valanginian (Faupl and Wagreich 2000). They were accreted at the front of the Cretaceous age orogenic wedge before their crystalline underpinnings were subducted and involved in Cretaceous (Eoalpine) metamorphism.

5.3.1 Grauwackenzone

The detached Ordovician to Carboniferous series of the *Grauwackenzone* (4) within the area of Fig. 1 belong to the Norian Nappe that forms the stratigraphic base of the southern edge of the Tirolian Nappe system of the Northern Calcareous Alps. These Palaeozoic sediments were metamorphosed under lower greenschist facies conditions during Cretaceous times. The Grauwackenzone is bordered to the south either by the sinistral SEMP (Salzach-Ennstal-Mariazell-Puchberg) Strike-Slip Fault Zone (central and eastern part of the map) or by a thrust contact with the structurally lower Innsbruck Quartzphyllite Unit (western part of Fig. 1). We also mapped the Ennstal Phyllites south of the SEMP Fault (ENE of Schladming, see Fig. 1) as a part of the Grauwackenzone.

5.3.2 Northern Calcareous Alps

Within the area covered by Fig. 1 most of the area mapped as *Northern Calcareous Alps 3* is part of the Tirolian Nappe system. This Tirolian Nappe system is underlain by the Bajuvaric Nappe system and overlain by the Juvavic Nappe system (Schmid et al. 2004), exposed in the extreme north-western and north-eastern parts of the map, respectively.

5.4 Southern Alps and Periadriatic Plutons

No geological or tectonic details have been mapped regarding the *Southern Alps* (2). East of the Giudicarie Line, they act as an indenter that triggered the uplift and exhumation of the Tauern Window (Ratschbacher et al.

1991; Rosenberg et al. 2004). Note, however, that the Southern Alps were internally deformed during the Miocene (e.g., Castellarin et al. 2006) and therefore represent a deformed indenter. The *Periadriatic Plutons* (1) align along the Periadriatic Fault and their emplacement is related to Oligocene transpression along the Periadriatic Fault system (Rosenberg 2004), transpression that predates dextral movements during the Miocene lateral extrusion of the Eastern Alps.

6 Major Late Alpine fault zones

In the following we use the term "fault" for simplicity and describe the nature of these faults briefly. Most of these Late Alpine faults (Fig. 1) accommodated substantial displacements that post-date nappe stacking. Describing them briefly we proceed from south to north.

Segments of the Periadriatic Fault define the northern edge of the South Alpine indenter (Ratschbacher et al. 1991; Rosenberg et al. 2007). The *North Giudicarie Fault* is a Miocene sinistral strike-slip zone that overprints Oligocene dextral strike-slip associated with a formerly straight Periadriatic Fault (Stipp et al. 2004; Pomella et al. 2011; see Viola et al. 2001, for a differing view). It forms the westernmost branch of a set of sinisitrally transpressive overthrusts defining a broader Giudicarie Belt located outside Fig. 1. At the southwestern edge of the map (Fig. 1) it bends into the SW-NE-striking *Meran-Mauls Fault* (Viola et al. 2001), an Oligocene ductile zone of dextral strike-slip faulting, changing in the Miocene to brittle top-SE thrusting (Pomella et al. 2011). Total sinistral offset of the Periadriatic Fault achieved by the Giudicarie Belt, including the Meran-Mauls Fault, amounts to 80 km (Frisch et al. 2000; Linzer et al. 2002). In the area north of the Meran-Mauls Fault kinematic interpretations are contradictory. According to Stöckli (pers. comm; version depicted in Fig. 1, with a question mark) a dextral mylonitic zone of Miocene age, that we term the *Sterzing-Mauls Fault*, kinematically links the southern end of the mylonites of the Brenner Normal Fault with the long WNW-ESE-trending *Pustertal* and *Gailtal faults*. The latter faults are parts of the Periadriatic Fault system and accommodated, after an Oligocene sinistral precursor, Miocene brittle dextral strike-slip (Mancktelow et al. 2001). According to others (S. Schneider pers. comm.), however, the area west of Mauls is instead characterized by sinistral mylonites, an observation that severely challenges a kinematic link between the Brenner mylonites and the Periadriatic Fault.

These segments of the Periadriatic Fault spatially and kinematically interact with a series of faults located north of, and branching off the Periadriatic Fault system. In the west the Miocene *Passeier Fault* branches off the North Giudicarie Fault and accommodates some 15 km of sinistral strike-slip motion under ductile to brittle conditions (Müller et al. 2001; Viola et al. 2001). At its northern tip it kinematically interacts with the *Jaufen Fault*, a complex fault zone that was repeatedly active (Viola et al. 2001). In Cretaceous times it acted as a thrust that brought the Mauls-Meran basement complex on top of the eclogitic Texel Unit. In Miocene times this old tectonic contact became overturned due to tight folding of the Mauls-Meran basement complex during late Alpine, N-directed indentation of the Southern Alps (Pomella 2011). Finally, it acted as a steeply N-dipping sinistrally transtensional fault zone, kinematically linked with the southern end of the Brenner Normal Fault (Selverstone 1988; Fügenschuh et al. 1997; Rosenberg and Garcia 2011). The western end of an Oligocene mylonite zone, the sinistral *DAV (Defereggen-Antholz-Vals) Fault* (Borsi et al. 1973; Kleinschrodt 1987), is overprinted by younger dextral mylonites of the previously described Sterzing-Mauls Fault (Mancktelow et al. 2001). Since the DAV Fault follows the boundary between the Koralpe-Wölz and the Drauzug-Gurktal Nappe systems it very likely has a long history going back into Cretaceous times (see discussion in Mancktelow et al. 2001). Much of its activity is, however, temporarily linked to the emplacement of the Rieserferner pluton and hence of Oligocene age (Wagner et al. 2006). The *Drautal Fault* is a brittle sinistral transpressive strike-slip fault of Miocene age (Heinisch and Schmidt 1984) that spatially and kinematically interferes with the Pustertal dextral strike-slip fault. We propose that the Drautal Fault represents a conjugate fault in respect to the Pustertal Fault, delimiting, together with its north-eastward continuation, referred to as the *Zwischenbergen-Wöllatratten Fault* (Exner 1962b), the western edge of a triangular block whose tip indents the Tauern Window during the Miocene, squeezing the western termination of the Sonnblick Dome (Scharf et al. 2013). We propose that the eastern termination of the sinistral DAV Fault near Lienz was sinistrally offset by the Miocene Drautal and Zwischenbergen-Wöllatratten faults. Thereby, the *Ragga-Teuchl Fault* (Hoke 1990), defining the boundary between the Koralpe-Wölz and the Drauzug-Gurktal Nappe systems, would represent the easternmost continuation of the Oligocene DAV Fault, cut by the younger Mölltal Fault in the east. The dextral and brittle Miocene *Mölltal Fault* is a stretching fault (Kurz and Neubauer 1996; Scharf et al. 2013) that delimits the eastern end of this triangular block, offsetting the southern margin of the Tauern Window by about 25 km. The *Hochstuhl Fault*, another dextral brittle fault located east of the Mölltal Fault also offsets the Gailtal Line east of the area of Fig. 1. This fault is kinematically linked with Late Miocene to recent dextral transpression in the Karawanken

(Polinski and Eisbacher 1992); it dies out northwestward and is unrelated to exhumation of the Tauern Window.

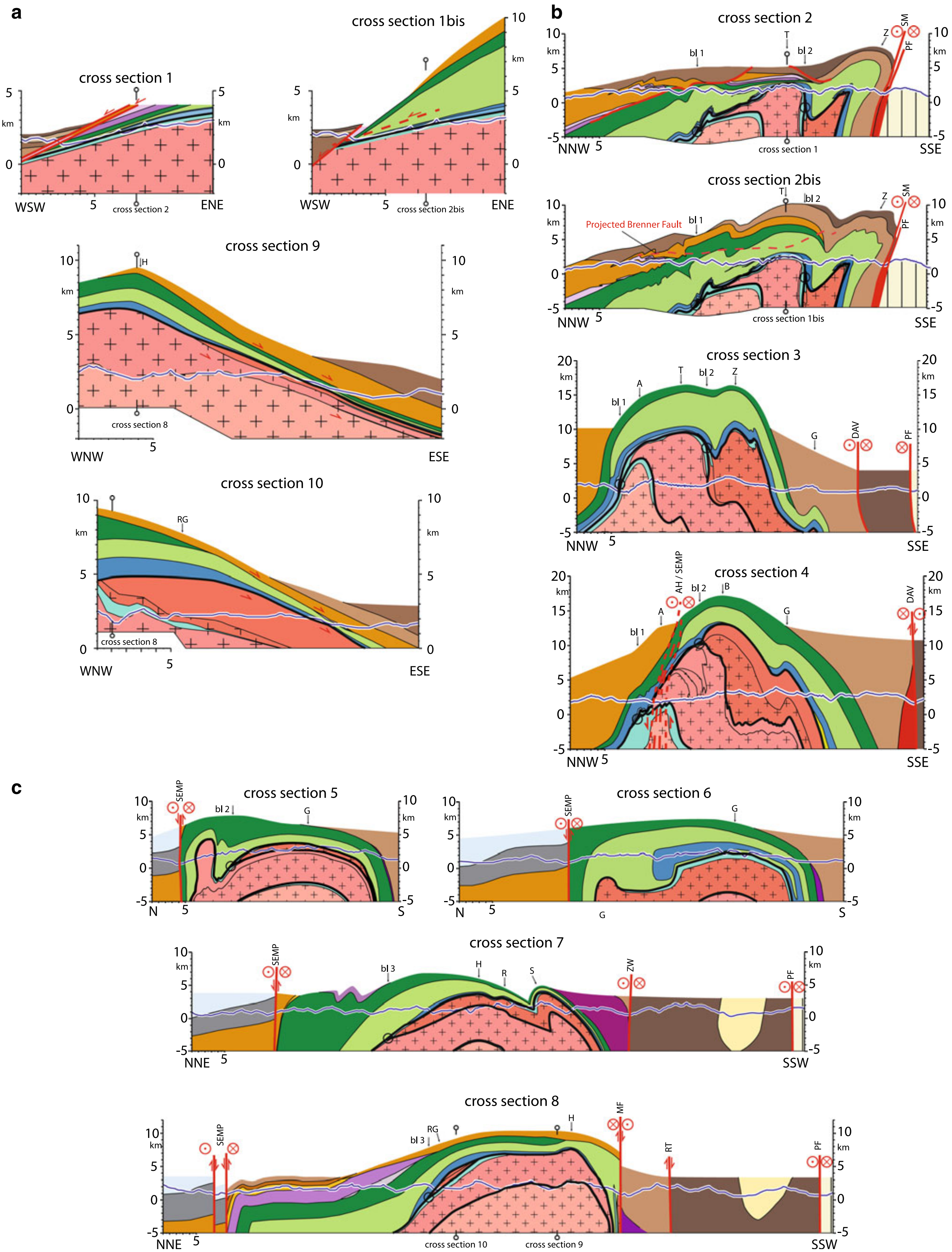
Two Miocene normal fault zones that accommodate orogen-parallel extension are characterized by a broad mylonitic zone with a brittle lid and delimit the western and eastern termination of the Tauern Window. The *Brenner Fault* in the west represents a normal fault with a substantial amount (at least some 44 km) of orogen-parallel extension according to some authors (Axen et al. 1995; Fügenschuh et al. 1997, 2012). Others, emphasising the effects of substantial amounts of N–S compression only observed east of the Brenner Fault, propose much smaller (2–14 km) estimates (Rosenberg and Garcia 2011, 2012). In any case, all authors agree that N–S-compression by folding of the Subpenninic nappe stack and E–W extension are contemporaneous. The southern termination of the ductile mylonite belt that accompanies the Brenner Fault is also a matter of debate. Some authors (Stöckli pers. comm.; Fügenschuh et al. 2012) propose that the ductile Brenner mylonites find their continuation in the dextral Sterzing-Mauls Fault while the brittle late-stage parts of the Brenner Normal Fault join the Jaufen Fault. Others (Rosenberg and Garcia 2012) propose that the extensional displacements of the Brenner Fault reduce to zero south of Sterzing and hence that this fault does not have a southern continuation. Similarly, there is a controversy about the existence or non-existence of the *Tauern Northern Boundary Fault*, proposed to represent the transformation of the displacements across the Brenner ductile normal fault mylonites into sinistral strike-slip motion by Töchterle et al. (2011) and Fügenschuh et al. (2012). Thereby, the *Silltal Fault* would split off the ductile Brenner mylonites and only represent the northern continuation of late-stage and brittle normal faulting across the Brenner Fault. Rosenberg and Garcia (2012), on the other hand, reject this interpretation, based on the lack of structural and petrological evidence; they suggest that both the ductile and brittle components of extensional displacement continue northward into the Silltal Fault.

The *Katschberg Fault* (Genser and Neubauer 1989) represents a ductile normal fault at the eastern termination of the Tauern Window that formed contemporaneously with N–S shortening that started in Early Miocene times; its lateral ends swing around the north-eastern and south-eastern edges of the Tauern Window as part of the Late-Alpine Katschberg Shear Zone System (Scharf et al. 2013) which results in ductile dextral and sinistral strike-slip shearing in the calcschists of the Glockner Nappe system at the northern and southern terminations of the Katschberg Normal Fault. In our view, the sinistrally transtensional *Niedere Tauern Southern Fault* (Wölfler et al. 2011) does not represent the northeastern continuation of the Katschberg Normal Fault: it rather developed during a later stage of lateral extrusion, i.e. after ductile deformation ceased due to falling temperatures. The age of the basin fill (Tamsweg Neogene) located between the two branches of the Niedere Tauern Southern Fault and its relationships with faulting indicate that this brittle phase initiated at around 17 Ma ago (Strauss et al. 2001), whereas the cooling history in the area of the Katschberg Fault indicates activity of this essentially ductile normal fault long before 17 Ma (Scharf et al. 2013).

The *Salzach-Ennstal-Mariazell-Puchberg (SEMP) Fault* represents, after the dextral Periadriatic Fault, the second-most important Miocene Alpine strike-slip fault zone. Sinistral offset of the Innsbruck-Wagrain-Katschberg Quartzphyllite Unit amounts to some 60 km. Both these strike-slip zones are conjugate and were active coevally during the Miocene, producing substantial E–W extension (Ratschbacher et al. 1991). Rosenberg and Schneider (2008) convincingly demonstrated that the western termination of the SEMP Fault has to be looked for along the *Ahorn Fault*, a broad deformation belt within the Ahorn Nappe, where deformation along the SEMP Fault becomes increasingly transpressive and entirely ductile. Westward, sinistral strike-slip is gradually transformed into late stage N–S shortening by upright folding (Rosenberg and Schneider 2008; Töchterle et al. 2011). The *Königsee-Lammertal-Traunsee Fault* splays off the western end of the SEMP Fault and accommodates some 10 km sinistral displacement (Decker et al. 1994). The Oligo- Miocene sinistral *Inntal Fault* is located further northwest and accommodates some 20–40 km (Ortner et al. 2006) or 50 km (Linzer et al. 2002) sinistral strike-slip offset.

7 Large scale structure of the Tauern Window

The cross-sections of Fig. 3 illustrate the large-scale architecture of the Tauern Window. In the case of two particular profiles in the westernmost Tauern Window two alternative solutions are shown regarding the extrapolations above the Earth's surface. Profiles 1 and 2 (Fig. 3a, b, respectively) depict such extrapolations based on the views expressed in Fügenschuh et al. (2012), while profiles 1bis and 2bis (Fig. 3a, b, respectively) are constructed according to the interpretation by Rosenberg and Garcia (2011, 2012). Cross-section 1 (Fig. 3a) depicts two flat-lying brittle normal-fault offsets at the base and the top of the Hippold Unit, squeezed between Matrei Zone and Upper Austroalpine basement; Matrei Zone and units below, down to the top-part of the Subpenninic basement, are mylonitized due to ductile shearing related to normal faulting. Based on the work of Töchterle (2011) later-stage high-angle brittle faulting is regarded as relatively insignificant and hence not shown in cross-section 1. Cross-


a
cross section 1
WSW
ENE
cross section 2
cross section 1bis
cross section 2bis
cross section 9
WNW
ESE
cross section 8
cross section 10
RG
b
cross section 2
NNW
SSE
bl 1
bl 2
T
Z
SM
PF
cross section 1
cross section 2bis
Projected Brenner Fault
cross section 1bis
cross section 3
A
G
DAV
cross section 4
AH / SEMP
B
c
cross section 5
N
S
SEMP
cross section 6
cross section 7
NNE
SSW
bl 3
H
R
ZW
cross section 8
MF
RT
cross section 10
cross section 9

◀ **Fig. 3** *Orogen-perpendicular* and *-parallel cross-sections* illustrating the upper crustal structure of the Tauern Window. Large parts of cross-sections 2 and 2bis (**b**) follow a profile published by Brandner et al. (2008) and data from Töchterle (2011); all others are constructed according to published and unpublished maps of the Geologische Bundesanstalt of Austria, as well as own data that include extrapolations based on contouring of the most important tectonic boundaries (Scharf 2013). Note that the scale of the cross-sections in Fig. 3a differs from that of Fig. 3b, c. See Fig. 4 for the cross-section traces. **a** Orogen-parallel sections; cross sections 1 and 1bis represent alternatives discussed in the text. **b** Orogen-perpendicular sections across the western Tauern Window; cross-sections 2 and 2bis represent alternatives discussed in the text. **c** Orogen-perpendicular sections across the central and eastern Tauern Window

section 1bis depicts the top of the Brenner mylonites that primarily accommodate differential folding of the Tauern window with respect to the Austroalpine west of the Brenner Fault (broken red line) as well as a steeper brittle fault (solid line) as contoured in Rosenberg and Garcia (2011). The thickness of the Glockner nappe is obtained by projecting upward the 40° west-dip of the contact Matrei Zone to Glockner Nappe system that can be contoured immediately NNE of Sterzing (Fig. 1).

All orogen-perpendicular cross-sections (Fig. 3b, c) show a re-folded duplex structure. In profiles 2 to 4 (Fig. 3b), located in vicinity to the TRANSALP seismic cross-section (Lüschen et al. 2006), the amount of post-duplex N–S shortening (referred to as D5 later on) can only roughly be assessed since the exact initial geometry of the roof thrust and the exact mechanism of folding are unknown. Assuming conservation of line length of an originally horizontal roof thrust, located at some 12 km depth before D5 folding (depth of the Sub Tauern Ramp at the northern margin if the Venediger Duplex; see Lammerer et al. 2008), a surprisingly consistent value varying between 31 and 32 km is obtained for post-duplex shortening in these western cross-sections (see Fig. 4 for profile traces). The deep structure of cross-sections 5 to 8 (Fig. 3c) is unconstrained, however. The amount of post-duplex N–S-shortening is certainly much less in the area of the central Tauern Window (cross-sections 5 and 6) and probably also less in cross-sections 7 and 8 in the eastern Tauern Window.

The lateral changes in style and geometry of post-duplex folding are very marked. Cross-section 2 (Fig. 3b) exhibits an overturned roof thrust at the southern margin of the duplex structure while the northern parts of the roof thrust exhibit a moderate dip of around 45°. In contrast, cross-sections 3 and 4 (Fig. 3b) show a rather symmetrical post-duplex dome. A drastic change in geometry occurs further

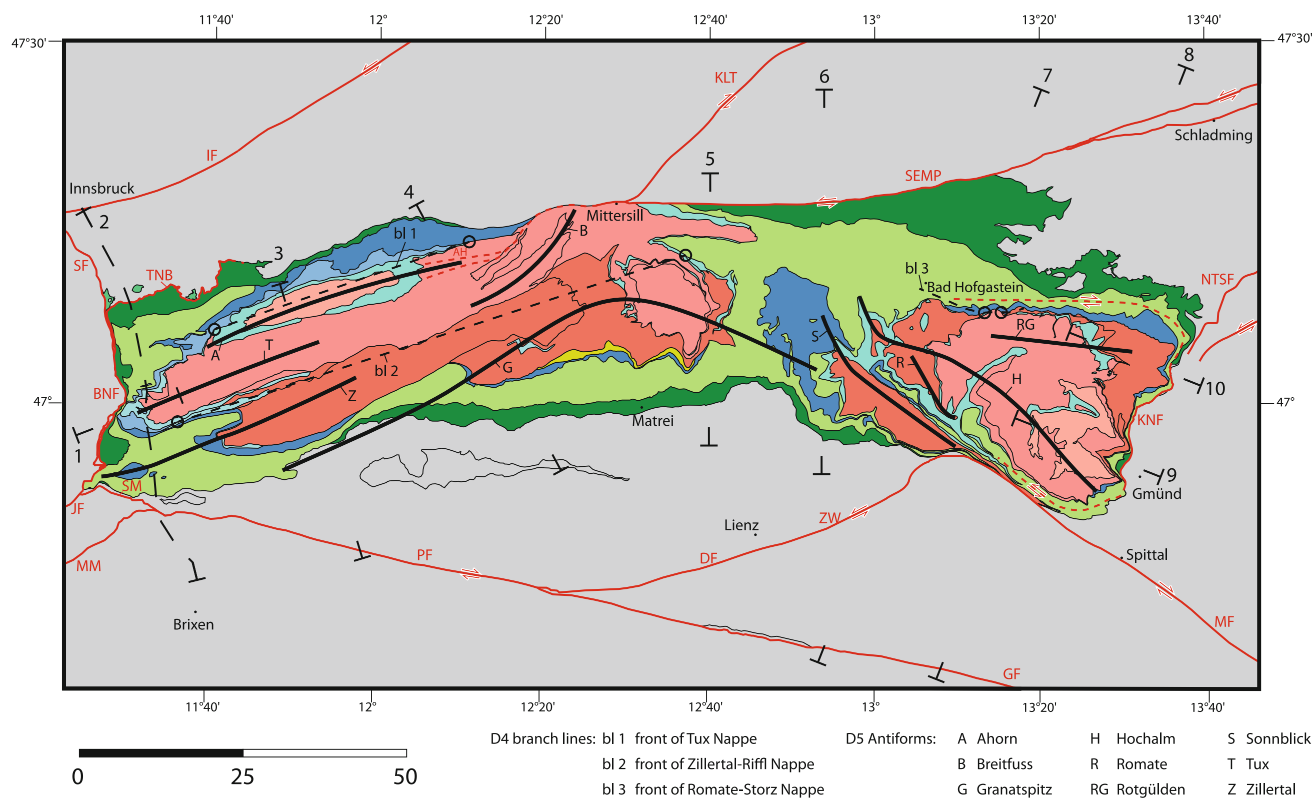


Fig. 4 Simplified tectonic map of the Tauern Window focussed on the internal structure of the Subpenninic and Penninic units. The *hinge lines* of the post-duplex (D5) antiforms are shown a *thick black lines* and *selected branch lines* related to duplex formation (D4) are shown as *dashed black lines*. Also shown are the traces of the cross-sections in Fig. 3. The Austroalpine and South Alpine frame around the Tauern Window is undifferentiated in *light grey*, except for the traces of major fault zones (*in red*). The abbreviations of the fault names are the same as on Fig. 1

east (Fig. 3c, cross-sections 5 to 8). In cross-sections 6 to 8, post-duplex doming is rather broad and the hinge of this dome is located much nearer to the southern margin of the Venediger Duplex compared to profiles 3 and 4 of Fig. 3b. This difference is even more salient from inspection of Fig. 4. In the western Tauern Window, the traces of the hinges of the post-duplex antiforms (labelled D5, see Chapter 5 for the discussion of the phases of deformation) run WSW-ENE and gradually approach the SEMP Fault at the northern margin of the Venediger Duplex. Those in the eastern Tauern Window, however, strike WNW-ESE and disappear westward. The Granatspitz Dome is confined to the central Tauern Window and disappears in both directions. We conclude that these post-duplex (D5) structures are significantly non-cylindrical.

Figure 4 additionally shows the three branch lines related to duplex formation that can be extracted from the tectonic map of Fig. 1. Two WSW-ENE-oriented ones are from the western Tauern Window and a WNW–ESE oriented one from the eastern Tauern Window. Originally, these branch lines probably were sub-parallel to each other, and became reoriented during D5 post-duplex folding. This again underlines important differences between western and eastern Tauern Window due to post-duplex overprint.

The late-stage antiforms cannot be traced across the Brenner- and Katschberg normal faults, which, amongst other arguments, leads to the conclusion that N–S shortening is coeval with the orogen-parallel extension achieved by these normal faults at the western and eastern margins of the Tauern Window (Fig. 3a). While all authors agree about the contemporaneity of late stage N–S shortening and orogen-parallel extension there is an on-going debate about the amount of orogen-parallel extension across the Brenner Normal Fault (see e.g., Fügenschuh et al. 1997; Rosenberg and Garcia 2011; Fügenschuh et al. 2012; Rosenberg and Garcia 2012). The construction of the parts of profiles 1 and 2 (Fig. 3a,b) that lie above the Earth's surface is made by projecting structures from the unfolded hangingwall west of the Brenner Fault on top of the folded area, east of the Brenner Fault. These constructions result in a dramatic attenuation of the thickness of the Glockner nappe and result in estimating a minimum amount of E-W stretching across the central part of the Brenner Normal Fault of around 44 km (Fügenschuh et al. 2012). Note, however, that, as clearly pointed out by Rosenberg and Garcia (2012), the amount of tectonic omission gradually decreases to the north and south; hence the estimate of a stretch of 44 km (Fügenschuh et al. 2012), and the geometry shown in profile 1 (Fig. 3a), can only be valid for the area around the Brennerbad locality (near the intersection point between profiles 1 and 2, see Fig. 4).

In contrast, the construction of cross-sections. 1bis and 2bis of Fig. 3a, b is made by projecting the folded structures east of the Brenner Fault above the surface. A control on the nappe thicknesses of Sects. 1bis and 2bis is obtained by projecting the top of the Glockner nappe upward, which dips with 40° westward underneath a half-klippe of Matrei Zone immediately north-northeast of Sterzing (Fig. 1). This results in a thickness of the Glockner nappe of less than 3 km in the profiles, corresponding to an attenuation of approximately 20 % with respect to its thickness in the footwall. This geometry reflects the idea of older mylonites having been folded in the core of the Tauern antiform and then cut by younger ones at lower structural levels, a process that causes tectonic omission in the absence of significant extension (see Rosenberg and Garcia 2012 for more details). These authors estimated the amount of E-W extension to be between 2 and 14 km only.

Orogen parallel extension estimated across the Katschberg Normal Fault is around 26 km (Scharf et al. 2013), valid at the locus of maximum tectonic omission, i.e. near the trace of cross-section 9 indicated in Fig. 4, constructed sub-parallel to the hinge line of the Hochalm Dome (Fig. 4). According to Lammerer and Weger (1998, their Fig. 10), there is, additionally, an unknown amount of post-duplex homogeneous stretching parallel to the D5 folds in the western Tauern Window. Adding some tens of kilometres of such homogeneous WSW–ENE-oriented stretch to the orogen-parallel extension achieved by offset across the Brenner and Katschberg normal faults, the total orogen-parallel stretch may amount to as much as 100 km across the entire Tauern Window when using the estimate of >44 km orogen-parallel extension across the Brenner Fault by Fügenschuh et al. (2012). Of course, it is considerably less when using the estimate of Rosenberg and Garcia (2011, 2012) for the amount of extension across the Brenner Fault. In any case, the estimate of 160 km orogen-parallel extension across the Tauern Window obtained by Frisch et al. (1998, 2000), seems unrealistically high since it entirely neglects denudation by erosion induced by contemporaneous N–S-shortening, as pointed out by Rosenberg et al. (2007).

On a lithospheric scale, the Tauern Window is located in a transition zone between the western part of the Alpine orogen, at present characterized by a SE-dipping European slab descending underneath the Alps, and the easternmost part of the Alps characterized by a NE-dipping Adriatic slab underneath the Alpine edifice (Lippitsch et al. 2003; Kissling et al. 2006). Figure 5 clearly shows that the western part of the Tauern Window, and the area around the northern part of the Giudicarie Fault, where it offsets the Periadriatic Fault (Stipp et al. 2004; Pomella et al. 2011), are located in an intermediate location where present-day slab polarity is undetermined, whereas the eastern part of the Tauern Window is located in the area characterized by an Adriatic slab presently descending NE-ward below the Alps. Given the unchanged architecture of the

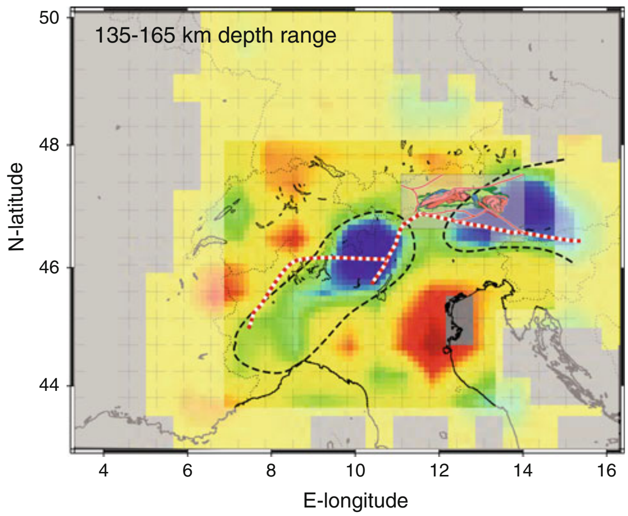


Fig. 5 Horizontal depth section at ca. 150 km depth (data from 135–165 km) through the 3-D Vp model of Lippitsch et al. (2003, their Fig. 13) superimposed with the outlines of the Tauern Window (see Fig. 1) and the trace of the Periadriatic Fault, offset by the Giudicarie Line (*red stippled line*). The depth section illustrates the variations in Vp within the upper mantle relative to the chosen 1D initial model. The positive velocity anomalies of >4 % Vp (*dark blue*) are interpreted as a SE-dipping European lithosphere in the Western Alps and a NE-dipping Adriatic lithosphere in the Eastern Alps (see Lippitsch et al. 2003 and Kissling et al. 2006 for further details). Note that the transition zone between the two high-velocity anomalies is located beneath the Giudicarie Line and the western part of the Tauern Window

nappes that characterize the crustal geometry of the Alpine edifice, this change in polarity primarily affected a decoupled mantle configuration and was induced at a late stage during Alpine orogeny, i.e. at around 20 Ma (Ustaszewski et al. 2008). Possibly, the non-cylindricity of the structures shown in Fig. 4, as well as the relative anticlockwise and clockwise rotations of the branch lines related to duplex formation in the western and eastern Tauern Window, respectively, from an unknown intermediate (E–W?) strike, is the result of this post-20 Ma reorganization of the geometry of the mantle slabs. Alternatively, this non-cylindricity may only concern the crust and simply result from the indentation of the South Alpine block east of the Giudicarie Fault as shown by analogue modelling (Rosenberg et al. 2004). According to this modelling, the different orientation of the D5 upright folds formed as a consequence of conjugate transpressional faults, with differences in fold amplification leading to a more localized deformation in the western Tauern Window.

8 Tectonic evolution of the Tauern Window

The map pattern (Fig. 1) and the cross-sections (Fig. 3), combined with palaeogeographical arguments based on a re-assessment of the Mesozoic cover of the Subpenninic nappes (Fig. 2), allow us to discuss the tectonic evolution of the Tauern Window. The exact timing of the five steps or phases shown in Fig. 6 is uncertain because of the notorious difficulties of interpreting radiometric ages in terms of tectono-metamorphic events, particularly in case of the high-pressure events (e.g., Berger and Bousquet 2008). Nevertheless, the sequence of events is clear, as described in the following.

8.1 Subduction of the Piemont-Liguria Ocean and accretion of oceanic relics in front of the Austroalpine nappe stack

There are only a few reliable age data from the Tauern Window and its immediate surroundings for the first deformational stage (D1), which is illustrated in Fig. 6a. The Matrei Zone and Reckner ophiolitic complex accreted to the Austroalpine nappe stack starting in the Turonian (about 90 Ma). This interpretation is based on a palaeogeographic position of Matrei Zone and Reckner ophiolitic complex in the Piemont-Liguria Ocean. It is also based on palaeontological and radiometric age data from the western margin of the Austroalpine nappe stack in Eastern Switzerland (e.g., Ring et al. 1988; Handy et al. 1993, 1996; Froitzheim et al. 1994; Schmid et al. 1996) that demonstrate the involvement of units of the Piemont-Liguria Ocean (Platta Nappe and Arosa Mélange) in W to WNW-directed nappe stacking during Late Cretaceous (post-Cenomanian) orogeny. The timing constraints are summarized in Handy et al. (2010; their Table 6).

It is very likely that the southernmost parts of the Valais Ocean, i.e. parts of the Glockner Nappe system, also reached the subduction zone at the active margin in front of the by now pre-structured Austroalpine nappe pile by the end of the Cretaceous (scenario depicted in Fig. 6a). Radiometric ages obtained for metamorphism in the Lower Austroalpine Radstädter Tauern between 80 and 50 Ma (Liu et al. 2001) indicate that the northern margin of the Austroalpine nappe pile was still part of an active margin until Eocene times. This is also supported by the age data of Dingeldey et al. (1997) indicating Eocene metamorphism in the Matrei Zone and thereby demonstrating re-working of the Matrei Zone and the Lower Austroalpine during the Cenozoic.

8.2 Subduction of the Valais Ocean and the most distal parts of the European margin

Figure 6b depicts Cenozoic subduction of the Glockner Nappe system and parts of the most distal parts of the European margin (Eclogite Zone and parts of the Modereck Nappe system) below an essentially rigid upper plate

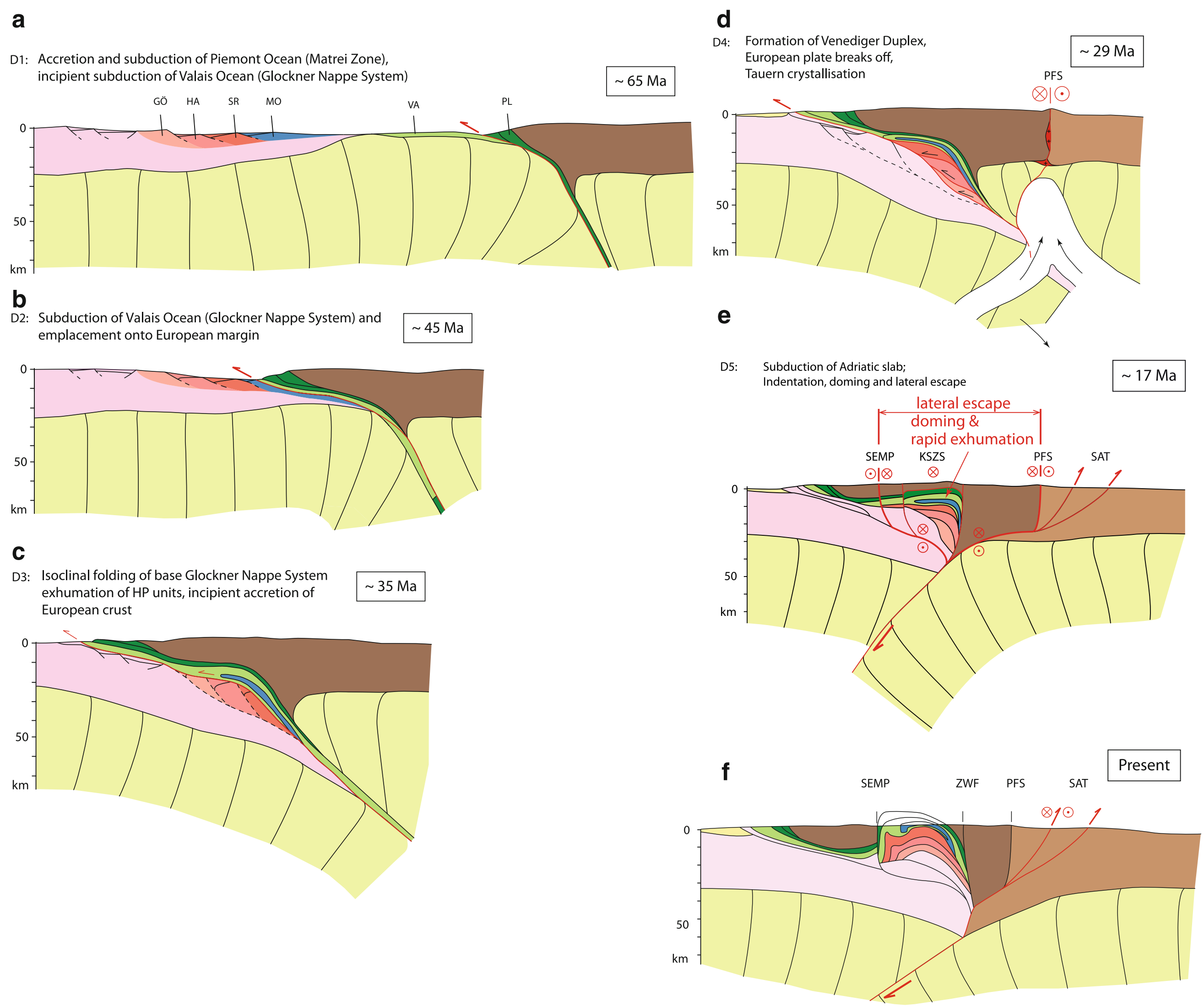


Fig. 6 Sketches illustrating the tectonic evolution of the Tauern Window. **a** D1 subduction of the Piemont-Liguria Ocean and accretion of oceanic relics in front of the Austroalpine nappe stack (≈65 Ma, i.e. Cretaceous-Palaeogene boundary), abbreviations as follows: GÖ Göss nappe, HA Hochalm nappe, SR Sonnblick-Romate nappe, VA Valaisan (Glockner Nappe system), PL Piemont-Liguria (Matrei Zone); **b** D2 subduction of the Valais Ocean and parts of the distal European margin (≈41 Ma; i.e. latest Lutetian); **c** D3 exhumation of the high-pressure units and incipient accretion of the European crust (≈35 Ma; i.e. Late Priabonian); **d** D4 formation of the Venediger Duplex and Tauern "Kristallisation" (≈29 Ma, i.e. Early Oligocene), *PFS* Periadriatic Fault system; **e** D5 indentation, doming and lateral extrusion (≈17 Ma, i.e. Burdigalian), *SEMP* Salzach-Ennstal-Mariazell-Puchberg Fault, *KSZS* Katschberg Shear Zone system, *SAT* Southern Alpine overthrusts; **f** schematic present-day lithosphere-scale cross-section across the eastern part of the Tauern Window, *ZWF* Zwischenbergen-Wöllatratten Fault

consisting of the Austroalpine nappe stack, including the previously accreted Matrei Zone, at about 41 Ma ago. After the closing of the Valais Ocean, the most distal parts of the European continental margin became part of the high-pressure belt.

We are well aware of the problems that arise when interpreting radiometric data in terms of the timing of eclogite-facies metamorphism in parts of the Glockner Nappe system and in the Eclogite Zone (Thöni 2006). Although no direct radiometric data are available for the age of eclogite-facies overprint of the Glockner Nappe system, this overprint is likely to have immediately predated the 36–32 Ma age range obtained by Zimmermann et al. (1994) for blueschist-facies metamorphism related to subsequent exhumation. Also, it is likely that high-pressure overprint in the Glockner Nappe system occurred more or less contemporaneously with that of the Bündnerschiefer of the Engadine Window, also attributed to the Valais Ocean and reported to have occurred some 42–40 Ma ago (Wiederkehr et al. 2008, 2009). The ages proposed for high-pressure metamorphism in the Eclogite Zone are between 45–40 Ma (Ratschbacher et al. 2004; Kurz et al. 2008) and around 39 Ma for parts of the Modereck Nappe system (Kurz et al. 2008). Herwartz et al. (2011) obtained an age of around 37–35 Ma for Alpine eclogite-facies overprint of the Adula Nappe that represents a lateral equivalent of the Eclogite Zone in Eastern Switzerland (Schmid et al. 2004). In conclusion, there is strong evidence that parts of the Glockner Nappe system and the Modereck Nappe system, as well as the Eclogite Zone, underwent eclogite-facies overprinting within the 45–35 Ma age range.

Glodny et al. (2005, 2008), on the other hand, propose an Oligocene age (31.5 ± 0.7 Ma) for eclogite-facies overprint of the Eclogite Zone, an age that is not only in conflict with all the above cited data but also with a multitude of geological constraints regarding the evolution of the greater Alpine area in the Oligocene (Handy et al. 2010). For example, there was substantial exhumation of high-pressure units before the intrusion of the Periadriatic plutons and the onset of movements along the Periadriatic Fault system (Rosenberg 2004). Rb–Sr multimineral isochrons of pristine eclogites and related eclogitic veins (Glodny et al. 2005, 2008) can only be interpreted as a pressure-peak age if one accepts post-pressure-peak closed system behavior with respect to Rb and Sr in a strict sense (Thöni 2006). This is a questionable assumption in view of the subsequent re-heating during a Barrow-type event (“Tauernkristallisation”) and after decompression (Kurz et al. 2008).

8.3 Exhumation of the high-pressure units and incipient accretion of the European crust

The spectacular large-scale isoclinal fold that folds the D2 thrust between Glockner and the Modereck Nappe systems (Fig. 6c), the Seidlwinkl fold nappe, is only preserved in the central part of the Tauern Window (cross-section 6 of Fig. 3c). The effect of D3 folding was to partially exhume the eclogitic rocks in the Eclogite Zone and in parts of the Modereck- and Glockner Nappe systems (see area of eclogite-facies overprint in Fig. 1). This juxtaposed eclogites with non-eclogitic parts of the Glockner Nappe system. The fact that this fold nappe is limited to the central Tauern Window, i.e. the part of the Tauern Window where eclogite-facies rocks were exhumed to the Earth’s surface, supports the view that D3 isoclinal folding represents a first stage of exhumation of the high-pressure units. We envisage incipient accretion of the mostly non-eclogitic part of the Subpenninic nappes to have occurred contemporaneously with this first stage of exhumation of high-pressure rocks in the same still-active subduction channel (e.g., Gerya et al. 2002). Decompression of the Eclogite Zone to some 1.0 GPa or less took place during the 38–32 Ma time interval (Kurz et al. 2008). Hence, we assign the D3 deformation depicted in Fig. 6c to this same time interval.

8.4 Formation of the Venediger Duplex and Tauern “Kristallisation”

The formation of the Venediger Duplex depicted in Fig. 6d (D4) predates final equilibration of all eclogitic and non-eclogitic units in all the Subpenninic nappes and the Glockner Nappe system under the P–T conditions that locally reached amphibolite-facies conditions during the Barrow-type event known as the “Tauernkristallisation”. Heat release from the radioactive decay of the accreted granitoid rocks of the Venediger Duplex probably plays an important role in contributing much to the heat production leading to the Tauernkristallisation (see discussion in Berger et al. 2011). This thermal overprint was prograde in the case of the newly accreted Venediger Duplex but probably associated with re-heating of the high-pressure units that cooled during D3 decompression, according to the P–T path compiled by Kurz et al. (2008; their Fig. 4), taking into account previously published literature data (Spear and Franz 1986; Inger and Cliff 1994; Zimmermann et al. 1994; Stöckhert et al. 1997; Kurz et al. 1998, 2001; Dachs and Proyer 2001).

The duration of the D4 duplex formation that immediately predated Barrow-type “Tauernkristallisation” is unknown. According to Christensen et al. (1994) final equilibration of garnet under peak conditions of 550 °C and 0.7 GPa in the western Tauern Window took place at 30 Ma. Rb–Sr whole-rock and white mica ages from the central Tauern Window cluster around 28–30 Ma and may approximately date the Tauern “Kristallisation”, since this same range of ages is found in the Eclogite Zone and in the adjacent Glockner Nappe system (Inger and Cliff 1994). This interpretation is supported by the Th–Pb allanite ages of Cliff et al. (1998) from the Mallnitz Synform north of the Sonnblick Dome, which cluster around 28 Ma. In summary, D4 deformation terminated around 28 Ma ago.

The scenario of D4 duplex formation scenario in Fig. 6d is contemporaneous with the intrusion of the Periadriatic plutons (in this case the Rieserferner, see Sect. 4 of Fig. 3b) that also took place at around 32 Ma (Rosenberg 2004), probably related to slab break-off due to decreasing rates of subduction (von Blanckenburg and Davies 1995).

8.5 Indentation, doming and lateral extrusion

The configuration of mantle slabs beneath the Eastern Alps changed fundamentally in the Early Miocene (Ustaszewski et al. 2008). After the European slab broke off (Fig. 6d), the Adriatic slab started to subduct NE-wards beneath the Alpine edifice, as depicted in Fig. 6e (mantle configuration only valid for the eastern half of the Tauern Window, see Fig. 5). At around 23–21 Ma ago (Scharf et al. 2013), the Southern Alpine crust east of the Giudicarie Belt started to indent the Eastern Alps, resulting in some 65 km of N–S shortening north of the Periadriatic line along a profile across the Tauern Window (Linzer et al. 2002), while their lithospheric underpinnings started to subduct beneath the Eastern Alps (Lippitsch et al. 2003, Horváth et al. 2006). This led to the doming in the Tauern Window and the lateral extrusion of the Eastern Alps (Ratschbacher et al. 1991; Rosenberg et al. 2007; Scharf et al.2013). Carpathian rollback and extension of the Pannonian Basin somewhat later at around 20 Ma (Horváth et al. 2006).

Determining exactly when the D5 doming and lateral extrusion began, including the initial activity of the Brenner- and Katschberg Normal Faults, is crucial for deciding if rapid exhumation and orogen-parallel extension were triggered by indentation of the Southern Alps east of the Giudicarie Line, as proposed by Scharf et al. (2013), or alternatively, by Pannonian extension, or by both. It is widely accepted that both processes had to interact in order to allow for the observed phenomena of coeval doming and lateral extrusion, as first proposed by Ratschbacher et al. (1991). However, different authors place different emphasis on the relative importance of these two processes and/or invoke alternative processes such as gravitational collapse of an over thickened crust (see Rosenberg et al. 2007 and Scharf 2013 for a discussion of this topic).

The timing constraints regarding the exhumation history of the Tauern Window may either be based on radiometric dating of syn-kinematic shearing that post-dated the "Tauernkristallisation" and is thought to be related to exhumation or, alternatively, on interpreting data on the cooling history. The age range for syn-kinematic sinistral shearing along several shear zones kinematically linked to the SEMP Fault obtained by $^{40}Ar/^{39}Ar$ in situ analyses of syn-kinematic phengite indicates that this sinistral deformation cannot be older than 32 Ma in the case of the northernmost (Ahorn) shear zone, and not older than 24–20 Ma in the case of all the other sinistral shear zones located further south (Schneider et al. 2013).

Dating the onset of exhumation based on cooling ages is problematic because the onset of rapid cooling lags behind the onset of rapid exhumation. Hence, we need additional information, including better temporal constraints on the P–T path of the exhumed rocks and, additionally, thermomechanical modelling of the exhumation history. So far such data are only available in the western Tauern Window, indicating that the onset of rapid exhumation in the footwall of the Brenner Normal Fault began at about 20 Ma (Fügenschuh et al. 1997).

The exhumation history of the Katschberg Normal Fault is more difficult to ascertain and discussed in more detail in Scharf (2013). Available thermochronological data indicate that rapid cooling of the eastern Tauern Window started earlier, i.e., before 20 Ma (see compilation of data by Luth and Willingshofer 2008; Scharf et al. 2013). If exhumation by normal faulting indeed started before 20 Ma ago in the east, it cannot have been triggered by extension in the Pannonian Basin and subduction rollback in the Carpathians, which started no earlier than 20 Ma (e.g., coincident with the onset of rifting in the Pannonian Basin, Horváth et al. 2006). Extension related to strike-slip and oblique-slip faulting in the Eastern Alps started even later: at 18 Ma in the Styrian Basin (e.g., Hohenegger et al. 2009), at about 17 Ma in various intramontane basins, such as the Fohnsdorf Basin (e.g., Strauss et al. 2001), and at 16 Ma in the Vienna Basin (e.g., Hölzel et al. 2008, 2010).

On the other hand, triggering of rapid exhumation by the indentation of the Southern Alps along the Giudicarie Belt, including the Giudicarie Line and an eastward adjacent sinistrally transpressive fault system (Massironi et al. 2006), is possible provided that doming and lateral extrusion in the Tauern Window did not start before some 21 Ma, the stratigraphically constrained onset of sinistral motion along the Giudicarie Belt. This constraint comes from the age of the youngest pelagic sediments affected by the activity of the frontal parts of the Giudicarie Belt, a belt extending from Meran (Fig. 1) southwards to the Lake Garda and linked to thrusting along the Milano Belt in front of the Lombardian Alps (Schönborn 1992). At Monte Brione, on the northern end of Lake Garda, the base of this pelagic sediment includes a part of the planktonic foraminiferal zone 5 (Luciani and Silvestrini 1996) that started at 21.5 Ma (Berggren et al. 1995). Hence, at least locally, activity along the Giudicarie Belt sets in after 21.5 Ma, which is consistent with the onset of rapid exhumation along the Brenner and Katschberg Normal Faults (20 Ma; Fügenschuh et al. 1997; Scharf 2013).

While these stratigraphic data constrain the maximum age for the onset of indentation and related D5 deformation within the Tauern Window, it should be noted that parts of the Tauern Window may well have undergone earlier (i.e., pre-D5) periods of exhumation, as suggested by some Rb–Sr white mica ages (e.g., Cliff et al. 1985) when interpreted as cooling ages. The period between 29 and 21 Ma ago is characterized by on going shortening across the Alpine chain west of the Tauern Window, concentrated in the northern foreland of the Alps and along the Southern steep belt of the Alps in the vicinity of the Periadriatic Line (Schmid et al. 1996). This was accompanied by conjugate sinistral and dextral shearing along the Engadine Line and the Tonale Line, respectively (Schmid and Froitzheim 1993; Ciancaleoni and Marquer 2008), leading to a pre-21 Ma period of lateral extrusion pre-dating our D5. Hence, a general uplift in the vicinity of the present Tauern Window could easily have led to an earlier, i.e. Late Oligocene to Early Miocene, period of exhumation by erosion.

Miocene (D5) and possibly older lateral extrusion is inadequately depicted in profile view (Fig. 6e) since it involves three-dimensional strain partitioning between N–S shortening and E-W extension, the latter again partitioned into strike-slip motion along sinistral (e.g., SEMP Fault) and dextral (e.g., Periadriatic Fault) shear zones, as well as normal faulting along the Brenner- and Katschberg Normal Faults. The interaction of the SEMP Fault with folding has been worked out in detail (Rosenberg and Schneider 2008), and also that between N–S compression and orogen-parallel extension in the area of the Katschberg Normal Fault (Scharf et al. 2013). However, determining the relative and absolute amounts of N–S shortening and E-W-extension in the area of the Brenner Normal Fault (Rosenberg and Garcia 2012; Fügenschuh et al. 2012) and on the scale of the entire Tauern Window requires further investigations. There are indications that a scenario of indentation, exhumation, doming and lateral extrusion very probably continues to the present day (e.g., Massironi et al. 2006), although the velocities at which these processes occur have probably decreased from their values at the onset of rapid exhumation some 23–21 Ma ago (Fügenschuh et al. 1997; Scharf et al. 2013).

9 Conclusions and unanswered questions

The Tauern Window exposes a Cenozoic nappe pile consisting of crustal slices derived from the distal continental margin of Europe (Subpenninic Units) and the Valais Ocean (Glockner Nappe system). These were accreted to an upper plate already formed during the Cretaceous and consisting of the Austroalpine Nappe pile and previously accreted ophiolites derived from the Piemont-Liguria Ocean. The present-day structure of the Tauern Window is characterized primarily by a crustal scale Late Alpine duplex, the Venediger Duplex, which formed during the Oligocene. This duplex was severely overprinted by doming and lateral extrusion, most probably triggered by the indentation of the Southalpine Units east of the Giudicarie Belt, which offset the Periadriatic Line by some 80 km, beginning at 23–21 Ma ago and linked to a lithosphere-scale reorganization of the geometry of the mantle slabs.

While this work hopefully contributes to a better understanding of the three-dimensional structure of the Tauern Window, two important problems remain. Firstly, what was the relative contribution of orogen-parallel extension by normal faulting, escape-type strike-slip faulting and orogen-normal compression, all of which acted contemporaneously during the Miocene? The answer to this question has a strong bearing on the relative importance of tectonic vs. erosional denudation. Secondly, there remains the unsolved problem of the quantification of kinematic and dynamic interactions between crustal (Adria-indentation, Carpathian roll-back and Pannonian extension) and mantle structures (reorganization of the mantle slabs underneath the Eastern Alps) that fundamentally and abruptly changed the lithosphere-scale geometry of the Alps-Carpathians-Dinarides system during a very severe Miocene overprint, initiating at around 20 Ma ago.

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