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Rift-related paleogeography of the European margin in the Eastern Alps (Central Tauern Window)

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Abstract

Continent-derived tectonic units in the Tauern Window of the Alps exhibit stratigraphic and structural traces of extension of continental margins eventually leading to the opening of the Alpine Tethys. In this study, we reassess lithostratigraphic data from the central part of the Tauern Window to reconstruct the post-Variscan evolution of this area, particularly the rift-related geometry of the European continental margin. The lithostratigraphy of the Alpine nappes reflects systematic variations of the structure of the European margin. The lowest tectonic units (Venediger nappe system, Eclogite Zone and Trögereck Nappe) are characterized by a thick succession of arkose-rich Bündnerschiefer-type sediments of probably Early Cretaceous age that we interpret as syn-rift sequence and which stratigraphically overlies thinned continental basement and thin pre-rift sediments. In contrast, the highest tectonic unit derived from Europe (Rote Wand Nappe) preserves a thick pre-rift sedimentary sequence overlying thinned continental basement, as well as a thick syn- to post-rift succession characterized by turbiditic Bündnerschiefer-type sediments of probable Cretaceous age. These observations point towards a highly segmented structure of the European rifted margin. We propose that this involved the formation of an outer margin high, partly preserved in the Rote Wand Nappe, that was separated from the main part of the European margin by a rift basin overlying strongly-thinned continental crust. The along-strike discontinuity of the Rote Wand Nappe is proposed to reflect the lateral variation in thickness of the outer margin high that resulted from margin-parallel segmentation of the European continental crust during highly oblique rifting antecedent to the opening of Alpine Tethys.

Keywords: Alpine Tethys, Continental margin, Rifting, Lithostratigraphy, Outer margin high

1 Introduction

Previous studies of a well-preserved Jurassic-Cretaceous rifting sequence in the Western and Central Alps have provided insights into the processes related to rifting and breakup of a stable continent in early Mesozoic time leading to the subsequent formation of the oceanic realm of Alpine Tethys (often also referred to as "Penninic Ocean") between the European margin in the North and Adriatic margin in the South (e.g., Froitzheim & Manatschal, 1996; Schaltegger et al., 2002). In the western Alps, tectonic units derived from Alpine Tethys (including continent-derived fragments such as the Briançonnais within them) are termed Penninic nappes. In analogy, the tectonic units derived from the European margin—usually located below the Penninic nappes—are termed the Subpenninic nappes (Schmid et al., 2004). In the following, we will adopt this nomenclature. The Penninic units presently exposed at the surface are largely continuous around the arc of the Western and Central Alps all the way towards the western boundary of the Eastern Alps near the Swiss-Austrian border (Fig. 1). However, several studies showed that nappes derived from both

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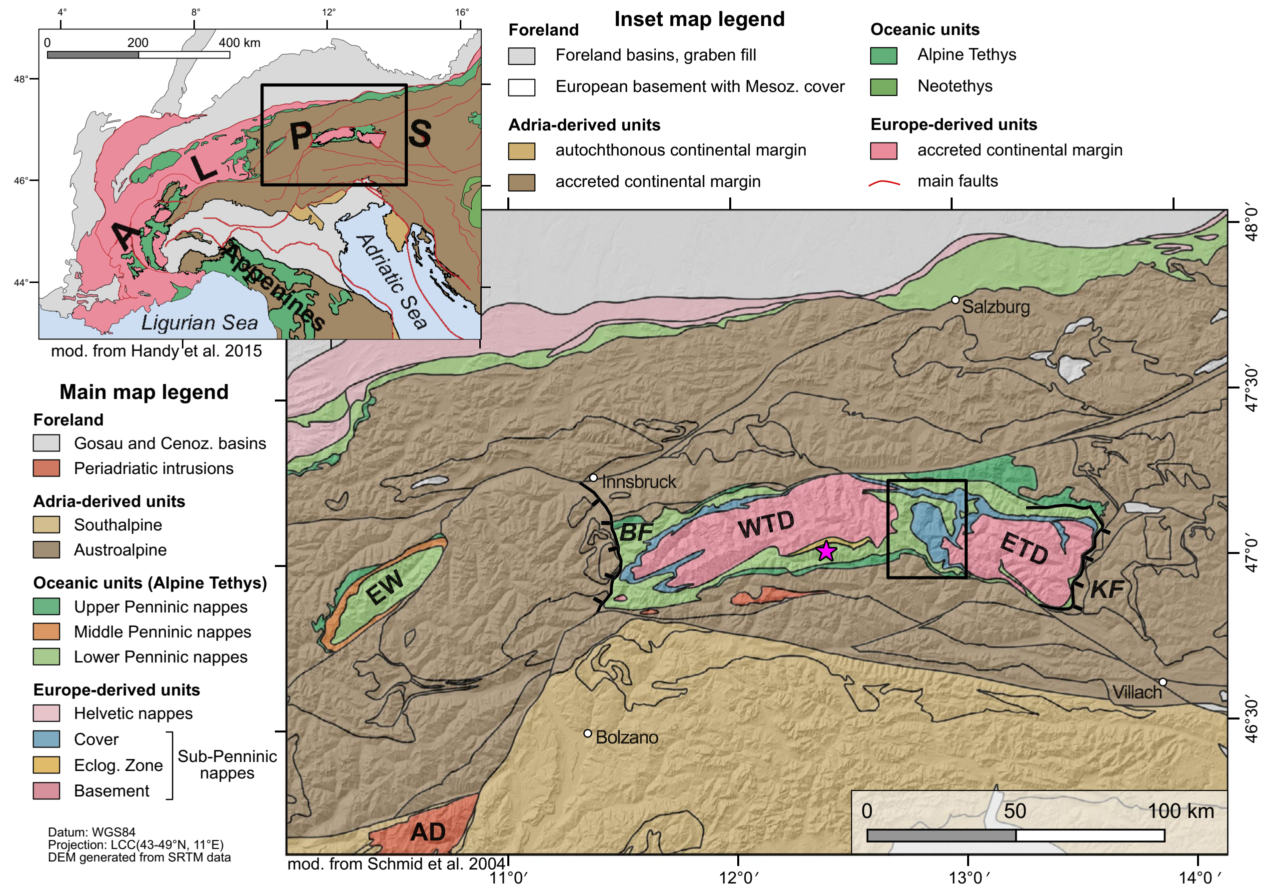

Fig. 1 Tectonic map of the Eastern Alps and Tauern Window with the Western Tauern Dome (WTD) and Eastern Tauern Dome (ETD). Map modified from Schmid et al., (2004, 2013); inset map of the Alps modified from Handy et al. (2015). Black rectangle outlines the study area and location of the tectonic map in Fig. 2. Pink star denotes the location of the metagabbro sample dated by Gleißner et al. (2021). *AD* Adamello Pluton, *EW* Engadine Window, *BF* Brenner Fault, *KF* Katschberg Fault

margins show features indicative of margin-parallel, rift-related segmentation of continental crust (e.g., Lemoine et al., 1986; Froitzheim et al., 1996; Ferrando et al., 2004; Manatschal and Müntener, 2009; Loprieno et al., 2011; Ribes et al., 2019). These inherited rift features may have been of critical importance in controlling the architecture of Alpine-type orogens during later convergence (e.g., Schmid et al., 1990; Handy et al., 1996; Mohn et al., 2014), especially by affecting the degree of cylindricity of such an orogen.

The rocks exposed in the Tauern Window of the Eastern Alps (Fig. 1) preserve relics of this major rifting phase, despite strong overprinting during later subduction, exhumation, collision and indentation (Groß et al., 2020). Attempts to reconstruct the geometry of this eastern part of the rifted European margin exposed in the Alps were made by, e.g., Frisch (1976), Ledoux (1984), Kurz et al. (1998), Schmid et al. (2013). Kurz (2006) proposed that Europe-derived units in the Tauern Window, e.g., the Rote Wand Nappe (Fig. 1), show signs of intense rift-related segmentation, and he interpreted this nappe as derived from an extensional allochthon or outer margin high that was separated from the proximal parts of the European margin by a narrow strip of possibly transitional, ocean-to-continent crust represented by a tectonic unit referred to as Eclogite Zone (see details below).

Based on new observations in the central part of the Tauern Window and a reinterpretation of published data, we propose refinements of the litho- and tectonostratigraphy that allow us to reconstruct the geometry of the rifted European margin in the Tauern Window area prior to the onset of Adria-Europe convergence and subduction of the Alpine Tethys. We will present a correlation of lithological associations and tectonic units based on the integration of a wealth of information provided by studies published over more than a century. Hence, we begin with a short review of the history of geological research in the region, which introduces the most important contributions relevant to this study.

2 Previous geological research

An account of the history of geological exploration in the region was recently presented by, e.g., Neubauer (2014) and Schuster (2015). In the following, we introduce those classical publications that are directly relevant to the study presented here.

Geological research in the Tauern Window and adjacent areas that can be considered as modern—in the sense of a mobilistic, nappe theory-based approach—that started with Termier (1904). One of the first, comprehensive nappe-based tectonic models of the Alps, including the Tauern Window region, was formulated by Eduard Suess (1909) in his seminal work "Das Antlitz der Erde". Following Termier (1904, 1906), Suess correctly described the Tauern Window as a tectonic window exposing Penninic nappes surrounded by the overlying Austroalpine nappe pile. This view is still valid today.

Argand (1909, 1911, 1916) developed a structural-kinematic-paleogeographic model often referred to as embryonic nappe tectonics for the Western and Central Alps. The most important characteristic of this model is the idea that formation of cylindrical fold nappes observed today initiated already in Mesozoic time with the closure of two marine basins and neighboring swells. Fold nappes were thought to have been directly engendered from these basins and swells with their characteristic Mesozoic sediments. Nappe theory was adopted by most geologists working in the Tauern Window, as indeed in mountain belts worldwide, leading to subsequent refinement and modernization of the tectonostratigraphy. For example, Staub (1924) described the eastern and western basement domes of the Tauern Window (his "Zentralgneise") as being overlain by a nappe made up of Bündnerschiefer and ophiolites (his "Glocknerdecke"). This is prominently exposed between these domes in a central depression (his "Glocknerdepression"), the main area of interest of our study. He proposed a correlation of the Glockner Nappe and Matrei Zone with the Margna-Dent Blanche Nappe and the Venediger crystalline basement with the Monte Rosa Nappe and stressed the continuity of these units along-strike of the whole orogen (Staub, 1924, p. 86). One of Staub's students, Hottinger (1935), mapping in the central Tauern Window proposed an early litho- and tectonostratigraphic division of the area and made very useful and detailed local observations. Staub (1924, p. 80) also interpreted the "Hochstegenkalk", a succession of marbles and dolomites, and its crystalline basement, the "Zentralgneis" of the Venediger nappe system, to represent the Briançonnais swell. This view was also expressed by Tollmann (1965). Later, it was realized that the Venediger nappe system is much more similar to the Helvetic (or Subpenninic) facies realm and therefore in fact represents the European margin rather than the Briançonnais (Thiele, 1970; Frisch, 1974; Lammerer, 1986).

A milestone in geological research of the central Tauern Window was the detailed geological map of the Großglockner region by Cornelius and Clar (1934), including its explanatory report (Cornelius and Clar, 1935) and, later, a more detailed description of the geology (Cornelius and Clar, 1939). In our estimation, this map is almost entirely correct and indeed it has formed the basis of subsequent geological research in the area. Most importantly for this study, Cornelius and Clar suspected that the Glockner Nappe is wrapped around the Rote Wand Nappe (their "Seidlwinkldecke"), a fold nappe that closes to the north. This was confirmed by Braumüller & Prey (1943) after they mapped to the northeast of the Cornelius and Clar (1934) map in the area of Wörth (Fig. 2), even though they proposed a rather strange and complicated geometry due to remaining flaws in the available lithostratigraphic concept. The publication of the geological map of the Sonnblickgruppe by Exner (1962) and its explanatory notes (Exner, 1964) extended the area with high-quality lithological and structural observations, mostly in the basement rocks, towards the east. Exner's publications include a wealth of structural and lithostratigraphic cross-sections and also provide a careful documentation of characteristic, thin basement nappes, that he termed "Gneislamellen". These turned out to be very helpful in our study for tracing the complex structure in the area.

The work of G. Frasl and W. Frank in the 1950s and 60s (e.g., Frank, 1965, 1969; Frasl, 1958; Frasl and Frank, 1964) provided further improvements to the lithostratigraphy of the central Tauern Window, thereby lending new insight into the local structure. For example, a recumbent, isoclinal fold nappe was defined by Frank (1965, 1969) and named "Seidlwinklfalte". The lithostratigraphy of the older part of the Rote Wand Nappe, as proposed by (Frasl and Frank, 1964), is in many respects still in use today.

(See figure on next page.)

Fig. 2 Tectonic map of the central Tauern Window compiled from sources listed in Table 1. Line A-A' marks the trace of the cross-section in Fig. 3 (northern part omitted). Black rectangle shows location of detailed geological map in Fig. 5. The blue star in the north shows the location of the Drei-Brüder Formation. Triangle symbols on thrusts denote the regional hanging wall for the respective thrusting event. Thrusts can locally be overturned by later deformation events, as e.g. the ocean-to-continent thrust in the footwall of the Seidlwinkl sheath fold nappe. The map also references geographic localities mentioned in the text

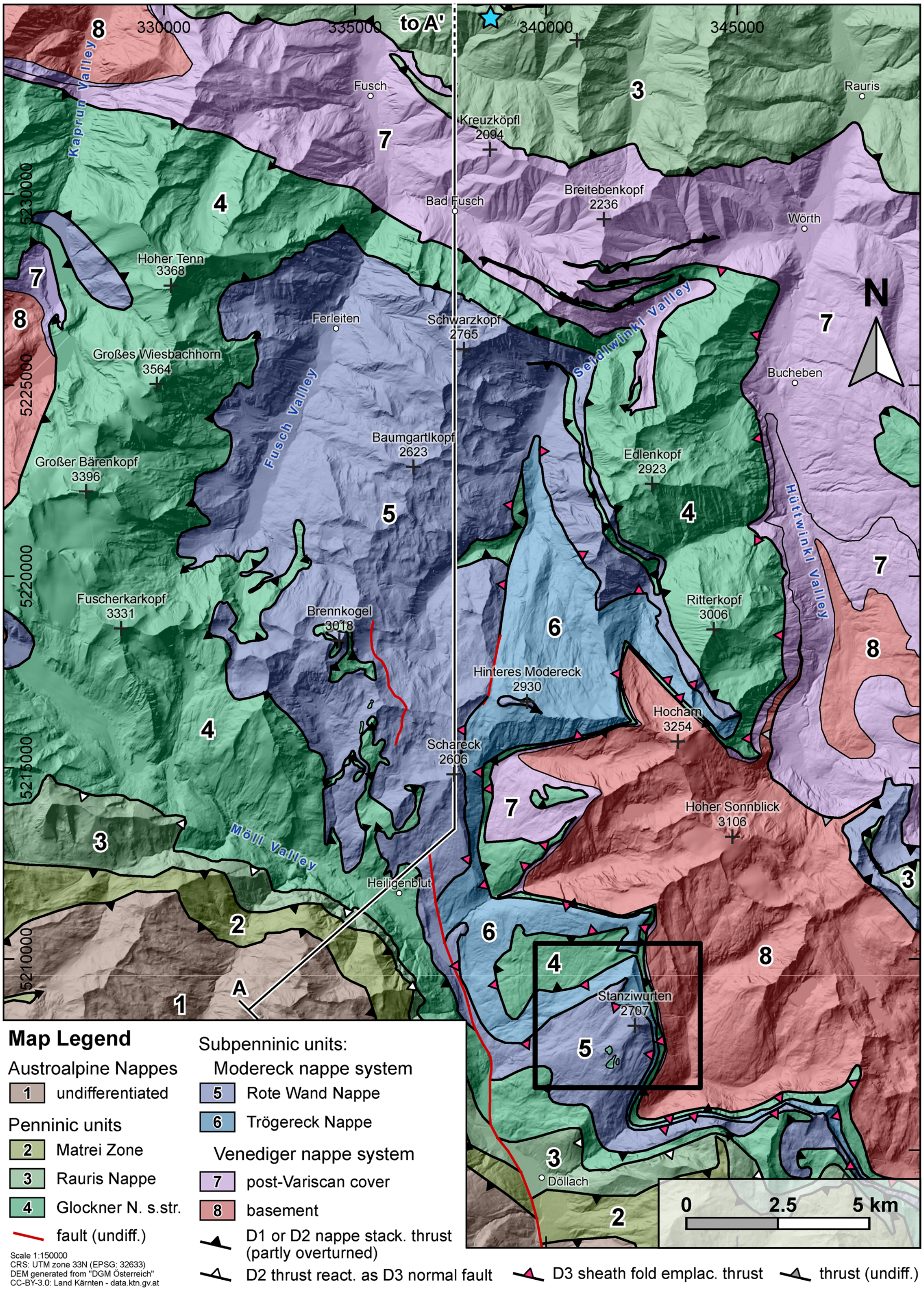

Fig. 2 (See legend on previous page.)

A turning point was the application of plate tectonic concepts to the Eastern Alps. Previously established paleogeographic reconstructions (e.g., Argand, 1911) could now be interpreted in the framework of plate motions that extended beyond the Alps (e.g., Laubscher, 1969, 1971; Trümpy, 1975; Frisch, 1979). Several studies constrained the degree and distribution of the Barrow-type regional metamorphism (e.g., Hoernes & Friedrichsen, 1974; Cliff et al., 1985; Frank et al., 1987; Dachs, 1990; Scharf et al., 2013), originally termed "Tauernkristallisation" by Sander (1911). The recognition of high-pressure mineral parageneses (e.g., Holland, 1979; Frank et al., 1987; Dachs and Proyer, 2001) proved the existence of formerly subducted rocks in the Tauern Window. Radiometric dating enabled the assignment of ages to the different orogenic stages (e.g., Oxburgh et al., 1966; Lambert, 1970; Zimmermann et al., 1994; Ratschbacher et al., 2004; Glodny et al., 2005; Kurz et al., 2008; Nagel et al., 2013). The discovery of fossils in the metamorphic rocks (e.g., Borowicka, 1966; Höfer & Tichy, 2005; Höck et al., 2006) further improved the litho- and chronostratigraphy (e.g., Pestal & Hellerschmidt-Alber, 2011). All these results have led to further refinement of the paleogeographic model of the central Tauern Window (e.g., Frank et al., 1987; Kurz et al., 1998; Schmid et al., 2013).

3 Geological overview and paleogeographic models

The Tauern Window is the largest tectonic window in the Alps. It provides a section through a large portion of the Alpine nappe stack (e.g., Schmid et al., 2004), from the highest units with remnants of the former Adriatic continental margin (Austroalpine nappes) down to the lowest units derived from the European continental margin (Venediger and Modereck nappe systems; Subpenninic nappes). The Austroalpine nappes form the perimeter of the Tauern Window, whereas the Venediger nappe system is exposed in two basement domes in the eastern and western parts of the window. The Austroalpine and Venediger nappe systems are separated from each other by the Penninic nappes, comprising an assemblage of several nappes mainly consisting of oceanic basement and marine sedimentary cover, referred to as Glockner nappe system, Matrei Zone and Nordrahmenzone (e.g., Pestal et al., 2009). These units are derived from the Jurassic-Cretaceous Alpine Tethys Ocean that separated the European continent in the north from the Adriatic continent in the south until the onset of collision (e.g.,. Kurz et al., 1996, 1998; Schmid et al., 2004). During Alpine late Cretaceous subduction and collision from Eocene time onwards, the Adriatic plate formed the upper plate to the subducting European lower plate (e.g., Frisch, 1979; Stampfli & Borel, 2004; Handy et al., 2010; with references therein). Apart from the Venediger nappe system, other thin nappes with European affinity are found in the Tauern Window, above the Venediger nappe system and usually at the base of the Penninic nappes. Only the central Tauern Window exhibits an exception of this simple tectonostratigraphy. There, some of the Subpenninic nappes (Modereck nappe system) are locally enveloped by Penninic nappes (Glockner nappe system), which is the result of a large composite fold nappe, the Seidlwinkl fold nappe (see Sect. 3.1). The Subpenninic nappes are characterized by continental basement that underlies Permo-Mesozoic cover rocks with a European affinity (e.g., Rote Wand Nappe, Trögereck Nappe, Wolfendorn Nappe; Kurz et al., 1998).

3.1 Regional deformation phases

The structural imprint in the Tauern Window is mainly the result of Cenozoic Alpine convergence of the European and Adriatic plates. Schmid et al. (2013) proposed the following succession of regional deformation phases that can be recognized in the region:

> D1—early Paleogene thrusting of the Austroalpine nappes onto the Matrei Zone and Nordrahmenzone.
>
> D2—late Paleogene thrusting of the Glockner nappe system onto the Modereck nappe system during Alpine subduction, forming a composite ocean-on-continent nappe at high-pressure conditions.
>
> D3—isoclinal folding of this composite nappe, which led to the formation of the km-scale Seidlwinkl fold nappe. Groß et al., (2020) reported that this folding occurred during extrusion-style exhumation of the composite high-pressure nappe to mid-crustal levels between a normal-sense shear zone above the fold and a basal thrust onto the Venediger nappe system. Ultimately, the folding resulted in a sheath-like geometry of the Seidlwinkl fold nappe. Its first order geometry is simple, with a part of the Glockner nappe system, the Glockner Nappe s.str., being wrapped around two units of the Modereck nappe system in the core of the fold, the Rote Wand Nappe above and the Trögereck Nappe below (Fig. 3). However, local complications of the structure exist: In the lower limb of the fold, the rocks are strongly thinned by intense deformation, so that especially the Glockner Nappe s.str. is locally missing. Small slices potentially derived from the Glockner Nappe s.str. are locally imbricated between the Rote Wand and Trögereck Nappes.
>
> D4—imbrication within the Venediger nappe system below the basal thrust of the Seidlwinkl fold

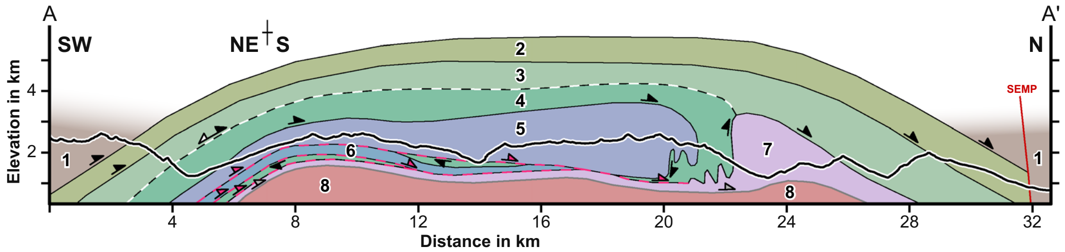

Fig. 3 Simplified tectonic cross-section of the central Tauern Window, with legend and location given in Fig. 2. Half-arrows denote nappe transport along thrusts for the main D1 and D2 nappe stacking thrusts (black symbols, locally overturned), reactivated by the D3 sheath fold emplacement thrusts in the lower limb of the Seidlwinkl sheath fold nappe (pink symbols), a thrust reactivated as a D3 normal fault in the hanging wall of the sheath fold (white symbols) and a D4 thrust within the Venediger nappe system (grey symbols; see Groß et al., 2020 and Groß et al., 2021 for details)

nappe and formation of the Wörth antiform in front (i.e. north) of the fold nappe (Groß et al., 2020). The Wörth antiform might be related to the last stage of upward extrusion of the fold nappe into shallow portions of the subduction channel. D4 is succeeded by a Barrovian metamorphic phase termed "Tauernkristallisation".

D5—late orogenic doming and orogen-parallel stretching in the area of the Tauern Window.

3.2 Paleogeographic models

Several different paleogeographic models have been proposed for the units derived from the Alpine Tethys in the Eastern Alps. In recent years, a consensus has emerged regarding some issues that were formerly strongly disputed, while other issues still remain unresolved. Based on clear stratigraphic evidence, the Venediger nappe system is now largely accepted to originate from the European continent (e.g. Thiele, 1970; Frisch, 1975a; Lammerer, 1986; Trümpy, 1988; Froitzheim & Manatschal, 1996; Kurz, 2006; Schmid et al., 2004, 2013), rather than being the eastward continuation of the Briançonnais microcontinent (e.g., Tollmann, 1965; Frisch, 1979). This Middle Penninic continental ribbon, the Briançonnais, is believed to wedge out from the Central Alps towards the northeast somewhere between the Engadine and Tauern windows (Trümpy, 1988; Froitzheim et al., 1996; Schmid et al., 2004, 2013), even though some authors discussed that it may find its continuation in some of the thin nappes composed of basement and its Mesozoic cover of the Tauern Window (Kurz, 2006). Whereas in the Western and Central Alps, the Briançonnais microcontinent separated the Jurassic (Piemont-Liguria) and Cretaceous (Valais) parts of Alpine Tethys, its disappearance in the Eastern Alps means that there, the Alpine Tethys has to be regarded as a single ocean basin that comprised both Jurassic and Cretaceous parts (e.g., Trümpy, 1988; Schmid et al., 2004; Pleuger et al., 2005; Kurz, 2006; Handy et al., 2010). The absence of units attributed to the Briançonnais complicates the interpretation of the attribution of oceanic units in the Eastern Alps to either the Piemont-Liguria of Valais branch, because these tectonic units cannot be assigned an age of formation merely based on their structural position in the nappe pile. Thus, one possible paleogeographic solution is that the Valais basin in the eastern part of Alpine Tethys opened within an already existing Jurassic Piemont-Ligurian Basin (Fig. 4b). Alternatively, the Valais Basin may have opened adjacent to the European margin (Handy et al., 2010) along the existing boundary between the European continent and the Piemont-Liguria ocean (Fig. 4c). We will evaluate these scenarios in Chap. 7.

Given the absence of Briançonnais-derived units, as in the Tauern Window, a distinction between the Valais and Piemont-Ligurian domain relies on the nature, age and distribution of pre-, syn- and post-rift sediments in the oceanic basin and its adjacent continental margins. The Matrei Zone and its equivalent, the Nordrahmenzone are clearly derived from the Jurassic part of Alpine Tethys. It contains numerous slivers from the overlying Austroalpine nappes, which is typical of the upper Penninic (Piemont-Liguria) units and indicates that it was accreted immediately at the base of the advancing Austroalpine nappes in Cretaceous times (Frisch et al., 1987). In contrast, the paleogeographic origin of the Glockner nappe system is controversial (e.g., Kurz, 2005, 2006; Schmid et al., 2004, 2005, 2013). Some authors argue in favor of an attribution of the Glockner nappe system to the Valais Ocean formed in Cretaceous times based mainly on lithostratigraphic correlation of this tectonic unit with Valais-derived calcareous micaschists ("Bündnerschiefer") in the Central and Western Alps (e.g., Schmid et al., 2013). Others argue that the transition of the Glockner nappe system to the overlying Matrei Zone and

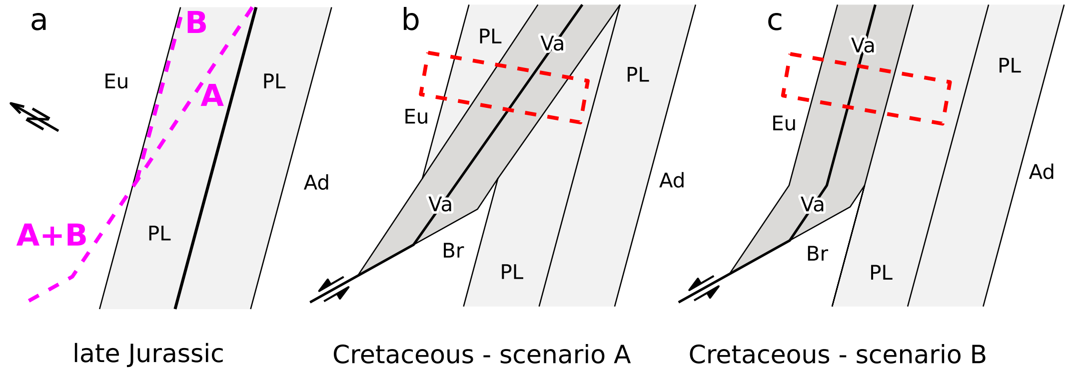

Fig. 4 End member scenarios of formation of the Alpine Tethys. **a** initial configuration after Late Jurassic opening of the Piemont-Liguria Basin followed by two scenarios (in pink) for the location of future spreading in Cretaceous times: **b** Scenario A (adapted from Pleuger et al., 2005), where Cretaceous opening of the Valais Basin separated the Briançonnais microcontinent from the European continent only in the SW and spreading continued within the Piemont-Liguria basin further to the NE, i.e., in the area of the Tauern Window. **c** Scenario B (e.g., Handy et al., 2010), where Cretaceous opening of the Valais Basin NE of the Briançonnais microcontinent localized along the existing ocean-continent transition between the European continent and Piemont-Liguria Ocean. The thick black line shows the locus of the Europe-Adria plate boundary. The red rectangle marks the approximate paleogeographic location of tectonic units in the central Tauern Window. *Eu* European continental margin, *Ad* Adriatic continental margin, *Br* Briançonnais microcontinent, *PL* Piemont-Liguria basin, *Va* Valais basin

Nordrahmenzone is often stratigraphic rather than tectonic (e.g., Frisch et al., 1987), which in turn would mean that at least the upper part of the Glockner nappe system could be of Piemont-Ligurian origin. Another criterion allowing to differentiate between Valais and Piemont-Liguria origins of the Penninic nappes in the Tauern Window is the magmatic age of oceanic crust. Recently, Gleißner et al. (2021) published the first U-Pb age of magmatic zircons from a metagabbro in the Glockner nappe system that yielded a Late Jurassic crystallization age (157 Ma, Kimmeridgian), which strongly suggests that this part of oceanic crust in the Tauern Window formed in the Piemont-Liguria basin, a point to which we will return below.

3.3 The different Bündnerschiefer-type metasediments

The Tauern Window comprises large volumes of, in first approximation, calcareous micaschists that are derived from marine marly sediments deposited in the Alpine Tethys and on its margins. We summarize these rocks under the general term Bündnerschiefer-type metasediments. However, several different characteristic types of these rocks can be recognized, and their appearance in certain tectonic units is not random but follows clear systematics, governed by the tectonic environment of deposition and the sediment provenance. In the following, we use this distinction as one important argument to reconstruct the paleogeography of the Alpine Tethys region. Here, we will first introduce the different types; more detailed descriptions are found in Chap. 4. Naturally, transitions between these types and combinations of them can also occur.

The first type can be regarded as the "classical" Bündnerschiefer or "Schistes lustrés", as prominently found in the central and western Alps. It is a calcareous micaschist and phyllite or micaceous marble that usually contains some organic matter and quartz. The protoliths are marls and impure limestones.

The second type is characteristic due to its high content of organic matter. It is a black phyllite that contains lots of graphite, white mica and variable amounts of carbonate minerals, quartz and sometimes feldspar.

The third type has a dominant arkosic character. It is a carbonate-bearing paragneiss or micaschist rich in feldspar clasts with some organic matter and quartz. Its protoliths are arkoses and breccias deposited in a marine environment.

The fourth type has a turbiditic character. It consists of quartzite beds (sometimes with carbonatic cement) rhythmically interlayered with dark brown calcareous micaschist that contains little or no feldspar and some organic matter. The carbonate phase is often ankeritic. The protoliths are quartz-arenite turbidites deposited in a basin with marly background sedimentation. This rock assemblage defines the largest portion of the Brennkogel Formation (see Sect. 4.2.3).

4 Tectono- and lithostratigraphic units

The sources from which a new tectonic map (Fig. 2) and cross-section (Fig. 3) and a geological bedrock map (representative key area in Fig. 5) of the central Tauern Window were compiled are listed in Table 1. A main requirement in compiling our tectonic map was to define and correlate lithological units across the individual

Table 1 List of maps used for map compilation and lithostratigraphic columns

Map	References
Geologische Karte des Grossglocknergebietes	Cornelius and Clar (1934)
Geologische Karte der Umgebung von Gastein	Exner (1956)
Geologische Karte der Sonnblickgruppe	Exner (1962)
Lithological map of the Sonnblick area	Favaro (2016)
GK50 Blatt 123 Zell am See	Heinisch et al. (1995)
GK50 Blatt 153 Grossglockner	Höck and Pestal (1994)
GK50 Blatt 124 Saalfelden am Steinernen Meer, prelim. Geofast map	Kreuss (2013)
GK50 Blatt 179 Lienz	Linner et al. (2013)
GK50 Blatt 154 Rauris, prelim. Geofast map	Griesmeier (2021)
Geologische Karte von Salzburg 1:200000	Pestal et al. (2005)

published maps. These units served as marker horizons for constraining the structure in the area. Most information provided here has already been published by other authors during the long history of geological exploration of the Tauern Window. Our purpose is therefore to give an up-to-date summary of the subject, explain the logic of the map compilation and integrate previous concepts with new observations and ideas. The description and nomenclature of the tectonic and lithological units and their geodynamic interpretation given here is largely based on Kurz et al. (1996, 1998), Pestal et al. (2009), Pestal and Hellerschmidt-Alber (2011) and Schmid et al. (2013). Lithostratigraphic columns of the individual tectonic units are shown in Fig. 7. The thicknesses of the lithostratigraphic units must be regarded as order-of-magnitude estimates relative to each other, derived from the map view or integrated field observations.

4.1 Venediger Nappe System

The lowest major tectonic unit of the Tauern Window is the Venediger Nappe system, prominently exposed in the centers of the eastern and western subdomes (ETD and WTD, respectively; Fig. 1). Following, e.g., Lammerer (1986), the Venediger Nappe system is interpreted to be derived from the proximal part of the former European margin ("Helvetic") adjacent to the Alpine Tethys. Such units derived from the European margin are often referred to as Subpenninic units (e.g., Milnes, 1974; Schmid et al., 2013). During Alpine subduction, the European margin was imbricated and formed a duplex of thrust sheets (Lammerer and Weger, 1998). In the tectonostratigraphic subdivision of Schmid et al. (2013), this crustal-scale Venediger duplex comprises at least three horses; from bottom to top: Göss, Hochalm and Sonnblick-Romate nappes in the Eastern Tauern Dome, and Ahorn, Tux-Granatspitz and Zillertal-Riffl nappes in the Western Tauern Dome. These duplex horses are usually characterized by basement-cover sequences. Of the above units, only the Sonnblick-Romate Nappe is relevant for our compilation. Therefore, we will only describe this tectonic unit below. Unless referenced otherwise, these descriptions incorporate most information from existing maps of Pestal (2008, 2009), Pestal and Hellerschmidt-Alber (2011), Favaro (2012), Favaro and Schuster (2012) as well as from own observations. The Sonnblick-Romate Nappe comprises late- to post-Variscan plutons that intruded an older basement and a post-Variscan metasedimentary cover sequence.

4.1.1 Basement of the Sonnblick-Romate Nappe

The Sonnblick-Romate Nappe occurs in two geographically distinct areas: The Sonnblick area in the south and in the Romate area in the north. The nappe is exposed in two large antiforms separated by a large synform (Mallnitz Synform) that obscures their direct contact (see Exner, 1964, Plate 2). Therefore, it is not clear whether they form a coherent tectonic unit or two sub-nappes. The reason for a differentiation into two sub-nappes is the striking contrast in their pre-Permian basement lithologies and the post-Variscan cover sediments: The Sonnblick part of the nappe consists mainly of late- to post-Variscan plutonic rocks ("Zentralgneis") and their country rocks ("Altes Dach" and "Altkristallin"), overlain by a very thin post-Variscan cover which is only locally preserved and strongly sheared. In the Romate part of the nappe, there is no Variscan or older basement. Instead, the late- to post-Variscan plutonic rocks are immediately overlain by a thick sequence of post-Variscan (Permo-Carboniferous? to Cretaceous?) sedimentary rocks. The main reason for grouping these occurrences together as a single Sonnblick-Romate Nappe is the similarity of their Mesozoic covers.

4.1.1.1 Altes Dach and Altkristallin of the Sonnblick-Romate Nappe (pre- to syn-Variscan) The oldest rocks of the Sonnblick-Romate Nappe are metamorphic rocks that often display primary intrusive contacts with late Variscan (Carboniferous-Permian; Eichhorn et al., 2000; Veselá et al., 2011) plutons. Therefore, the metamorphism is usually regarded as Variscan or older (Schmid et al., 2013). This metamorphic basement is traditionally referred to as "Altes Dach" (old roof) or "Altkristallin" (Pestal et al., 2009). Lithologically, this unit is quite diverse, containing porphyroblast-rich paragneiss, micaschist and amphibolite. The lithological map (Fig. 5) does not differentiate between these lithologies, instead it groups them together under the label "Altes Dach" and "Altkristallin".

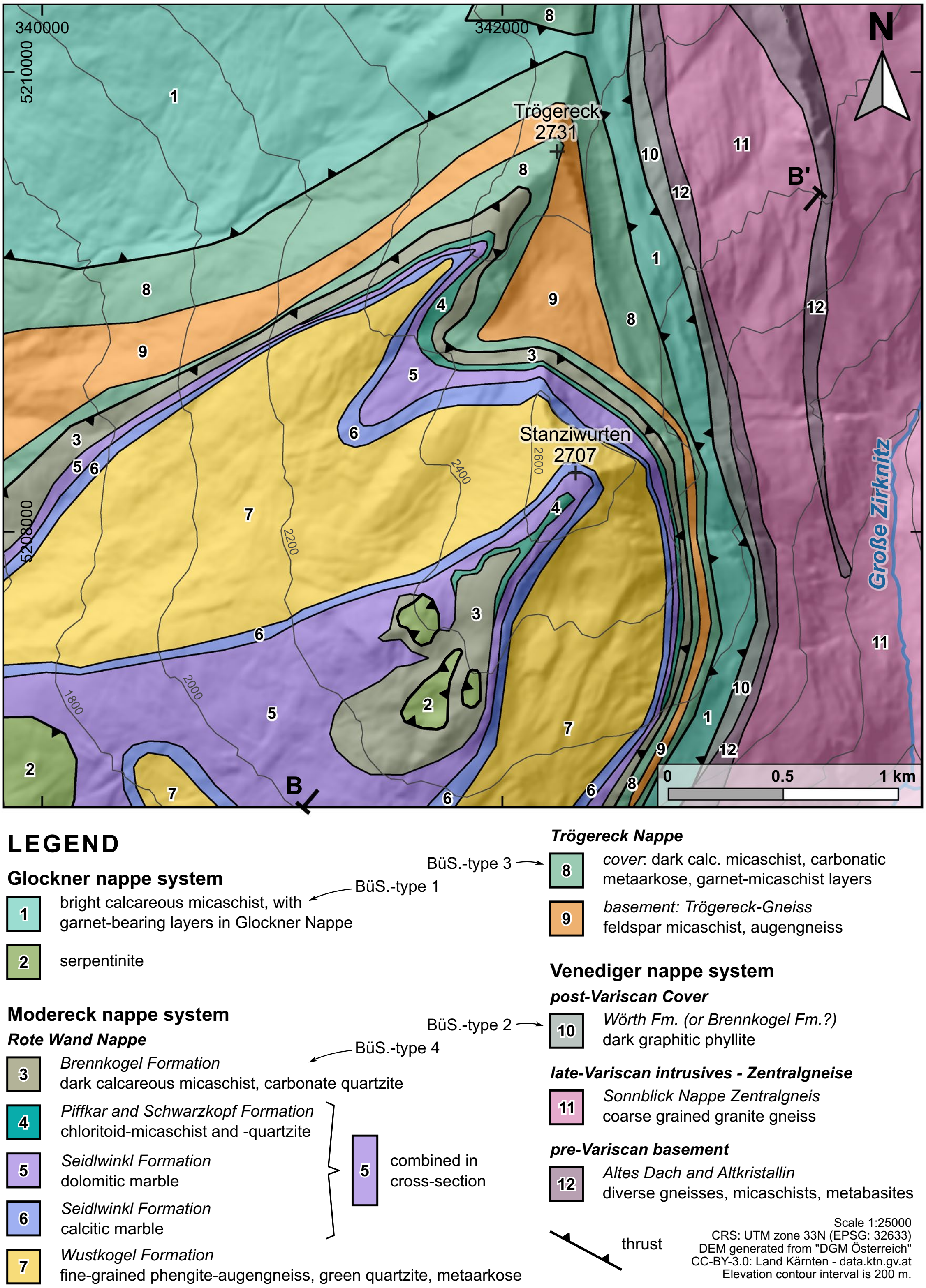

Fig. 5 Geological map of the Stanziwurten area (see Fig. 2 for the location) compiled from sources in Tables 1 and own observations. A "standard" inverted stratigraphic section of the Rote Wand Nappe is exposed along the crest north of the Stanziwurten summit. Triangle marks on thrusts denote the regional hanging wall. The location of the cross-section in Fig. 6 is marked by B-B'

4.1.1.2 Zentralgneis of the Romate part of the Sonnblick-Romate Nappe (late Variscan) The Zentralgneis of the Romate part of the Sonnblick-Romate Nappe comprises two varieties: (a) a mostly fine-grained, albite-rich granite gneiss with feldspar augen ("Siglitz gneiss"; Exner, 1949, 1957) and (b) a medium- to coarse-grained syenite gneiss, sometimes with flaser texture ("Romate gneiss"; Angel & Staber, 1952). These varieties are not differentiated in our compilation.

4.1.1.3 Zentralgneis of the Sonnblick part of the Sonnblick-Romate Nappe (late Variscan) The Zentralgneis of the Sonnblick part of the Sonnblick-Romate Nappe is made up primarily of leucocratic granitic augen gneiss and, to a lesser extent, of fine-grained grayish gneiss with large potassium feldspar-phenocrysts. Both are cut by aplitic dikes (Exner, 1964). All three varieties are regarded as one lithological unit in our compilation.

4.1.2 Post-Variscan cover of the Sonnblick-Romate Nappe

Following Schmid et al. (2013), strata deposited after the Variscan orogeny and the intrusions of late- to post-Variscan plutons are categorized as post-Variscan cover. These authors provided a comprehensive documentation of these lithologies in the whole Tauern Window and highlighted their importance as nappe separators. Favaro and Schuster (2012) give an overview of the post-Variscan cover lithologies, their suspected ages and their distribution in the vicinity of the Mallnitz Synform. Deposition of the post-Variscan cover of the Sonnblick-Romate Nappe probably started with Permo-Carboniferous clastics and continued, interrupted locally by some major hiatuses, at least until the Cretaceous.

4.1.2.1 Woisgenschiefer (Permo-Carboniferous?) The term "Woisgenschiefer" is used in the sense of Favaro and Schuster (2012) to refer to a variety of mainly metapelitic rocks of presumably Carboniferous to Permian age. The Woisgenschiefer in the strict sense is a silvery chlorite-muscovite schist rich in garnet- and chloritoid-porphyroblasts. However, biotite-porphyroblast and biotite-chlorite-epidote schists are also included in this mapped unit. These rocks occur only in the Romate part of the Sonnblick-Romate Nappe and are missing in the Sonnblick sub-nappe.

4.1.2.2 Wustkogel Formation (Permian to Lower Triassic) The Wustkogel Formation comprises mainly dark green and fine-grained, quartz- and phengite-rich augen gneiss (meta-arkose) and pale-green phengitic quartzite (see below for a more detailed description). In the Romate sub-nappe, the Wustkogel Formation is generally thin (few tens of meters) and unconformably overlies the Woisgenschiefer. It is exposed mainly on the western flank of the upper Hüttwinkl Valley (SW of Bucheben), but can also be found on the northern limb of the Falkenbach antiform ("Falkenbachlappen") in the Kaprun Valley (northwestern edge of map in Fig. 2). It is completely missing in the Sonnblick sub-nappe.

4.1.2.3 Silbereck Marble (Upper Jurassic) The term Silbereck Marble (locally called Angertal Marble) is a lateral equivalent of the famous Hochstegen Marble in the western Tauern Window. This unit is a succession of white to gray, thick-bedded marbles with variable amounts of white mica. This unit stratigraphically overlies the Wustkogel Formation, the Woisgenschiefer and the Romate Zentralgneis (Exner 1964; Höfer & Tichy, 2005) in the eastern Tauern Window. This suggests the existence of a major erosional unconformity at the base of the marble. At least locally, the marble contains large coral fragments (Höfer & Tichy, 2005). In the central Tauern Window, the Silbereck Marble is restricted to the eastern flanks of the upper Hüttwinkl Valley and the northeastern limb of the Mallnitz Synform, but is entirely missing in the Sonnblick sub-nappe. Sr-isotope dating (Favaro & Schuster, 2012), biostratigraphic dating with corals and ammonites (Höfer & Tichy, 2005) and regional correlation with the Hochstegen Marble in the western Tauern Window constrain the age of the Silbereck Marble to be of Late Jurassic age. This marble is stratigraphically overlain by a succession of Bündnerschiefer comprising mostly calcareous micaschist, black phyllite and a few greenschist layers (Exner, 1983).

4.1.2.4 Wörth Formation (Cretaceous?) The informal name "Wörth Formation" refers to a large mass of black phyllite extending in an E-W direction from the Rauris Valley to the Fusch Valley and even further to the west. These dark phyllites are fairly homogeneous but contain characteristic layers of metadiabase, metagabbro and metatuffite (see below).

The dark phyllites are fine-grained and comprise mainly white mica, graphitic organic matter, quartz and some carbonate. In areas with sufficient metamorphic overprint, the rock additionally contains abundant albite porphyroblasts (Fig. 8). The dark phyllites are intercalated with quartzite beds, layers of dark calcareous micaschist and fine-grained meta-arkosic layers, especially at the base of the Wörth Formation (Frasl, 1958, p. 399;). Frasl (1958, p. 399) explicitly pointed out the strong similarity of the meta-arkosic layers with gneisses in the Trögereck Nappe (see below).

According to Frasl and Frank (1966), the metadiabase, -gabbro and -tuffite layers mainly represent sills that intruded the black phyllites, but also formed as lava flows or tuff layers and must therefore be considered as broadly contemporaneous as the black phyllites. Although the layers are discontinuous, they are helpful as marker horizons to trace the large-scale structure. Similar metadiabase and -gabbro layers associated with arkosic Bündnerschiefer-type successions occur in the Kaserer Formation in the western Tauern Window (Höck & Miller, 1987; Rockenschaub et al., 2003), in the Eclogite Zone (Kurz et al., 1998), the Trögereck Nappe and also in the Nordrahmenzone (Höck & Miller, 1987).

The Wörth Formation is largely identical with what Exner (1957, p. 65) called "Mittlere Schwarzphyllitzone" and with the lower part of the "Weixelbachschuppe" of Frasl (1958, p. 398). Exner noted that this unit can be traced southward into the Rauris and Hüttwinkl valleys, always immediately underlying the Glockner Nappe s.str. Consequently, the unit overlies rocks of the Romate sub-nappe in the southern Hüttwinkl Valley. It is unclear whether or not the Wörth Formation continues south of the Romate sub-nappe, and overlies the Sonnblick sub-nappe basement, as shown in our compiled map (Fig. 2) and depicted in existing maps (GK50 Blatt 154 Rauris, Pestal, 2014). Our own observations in the Stanziwurten area (sample PG126, 47.02226°N 12.93057 °E, Fig. 5) confirm the existence of typical Wörth-type metasediments, e.g., feldspar-bearing dark phyllites, immediately overlying the Sonnblick Nappe basement as a thin lenticular layer. So far, there is no clear evidence that these phyllites actually correspond to the Wörth Formation. Rather, the dark phyllite overlying the Sonnblick Nappe basement may be part of the basement itself, which would mean that it represents a pre-Permian sediment.

Between the Rauris and Fusch valleys, the Wörth Formation is mainly exposed in a large E-W-striking antiform (Fig. 2), termed "Wörth Antiform"). Given its geometry and internal structures, this antiform is interpreted as the product of minor northward transport and shortening of Wörth Formation above a thrust delimiting its basal contact with the Sonnblick-Romate basement in the footwall. Therefore, a parautochthonous origin with respect to the Sonnblick- Romate Nappe is likely for these dark phyllites. This would render the Wörth Formation the stratigraphically highest part of the post-Variscan cover of the Romate sub-nappe. Since it consistently overlies the Upper Jurassic Silbereck Marble where the marble is present above the basement, a Cretaceous age would be expected for the dark phyllites.

The Wörth Antiform can be traced westward from the Fusch valley to the northeastern part of the Western Tauern Dome, where the antiform merges with the antiform formed by the basement of the Western Tauern Dome ("Falkenbachlappen"). This again strongly suggests that the Wörth Formation can be regarded as parautochthonous with regard to this basement. North of the Wörth Antiform, the Wörth Formation is tectonically overlain by the Rauris Nappe. The tectonic nature of this contact is implied by a marked increase in the intensity of deformation in the uppermost part of the antiform, and a sudden increase in the peak-metamorphic temperature that spatially corresponds to the suspected nappe boundary (Groß et al., 2021).

The Wörth Formation mainly comprises two of the Bündnerschiefer types (2 and 3) defined in Sect. 3.3; black calcareous phyllites with some arkosic intercalations. Therefore, it is interpreted here as distal syn-rift deposit that was deposited on the European margin in Cretaceous time (see also Sect. 6.4). It appears to be a deep and oxygen-starved and therefore more distal equivalent to the Cretaceous Kaserer Formation in the Western Tauern Window (Frisch, 1980; Lammerer, 1986), as well as to the syn-rift portion of the arkosic Bündnerschiefer deposits of the Modereck nappe system in the Central Tauern Window (see below).

4.2 Modereck nappe system

The Modereck nappe system is also part of the Subpenninic units in that it comprises several nappes that are also derived from the former distal European continental margin rimming Alpine Tethys to the north. Paleogeographically they were located more to the south than the Venediger nappe system and in a more distal position within this passive margin (e.g., Kurz et al., 1998; Schmid et al., 2013). In the study area, the Modereck Nappe system comprises two nappes: The Rote Wand Nappe and the underlying Trögereck Nappe.

4.2.1 Trögereck Nappe

The Trögereck Nappe, is named after the Trögereck summit (Fig. 5) in the Stanziwurten area (Exner, 1964), where this nappe is well-exposed. As is typical for the Subpenninic nappes, the Trögereck Nappe comprises a basement-cover sequence, although the sedimentary sequence is not as well-defined as that of the Rote Wand Nappe. Rather, it is largely obscured by tectonic and/or sedimentary mixing (mass wasting). The following compilation of its main lithologies is largely based on own observations and those of Frasl (1958), Exner (1964) and Alber (1974).

4.2.1.1 Trögereck Gneiss (post-Variscan metagranitoid or metaarkose) The Trögereck Gneiss ("Gneislamelle 3" in Exner, 1964) is the basement of the Trögereck Nappe. This gneiss is typically a medium-grained, phengite- and quartz-rich gneiss with microcline augen, up to 0.5 cm in diameter (Fig. 9). These augen are in fact porphyroclasts that partly preserve the original granitic microstructure, often including biotite relics (e.g., sample PG152, 47.10798°N 12.87691°E). The phengite-rich matrix is probably the product of strong metamorphic alteration of the protolith. Depending on the degree of alteration and deformation, the rock can be completely transformed to a phengite-schist, containing quartz and medium-sized (ca. 0.5 cm) albite-porphyroblasts. The Zentralgneis of the Venediger nappe system is often taken as the protolith of the Trögereck Gneiss (e.g., Exner, 1964). Based on petrographic criteria pointing towards diagenetic alteration (e.g., lack of plagioclase compared to the Zentralgneis), Frasl (1958) argued that large parts of these gneisses are in fact meta-arkoses that derive from eroded Zentralgneis. Our geochemical data support this notion (see below; Fig. 13a). In any case, this lithology is distinct from similar rocks of the Trögereck Nappe that belong to the Bündnerschiefer assemblage (details below).

4.2.1.2 Calcitic and dolomitic marble (Middle to Upper Triassic and Upper Jurassic?) The Trögereck Nappe contains lenticular calcitic and dolomitic marble layers with a maximum thickness of several meters. They stratigraphically overlie the Trögereck Gneiss and also occur as lenses in the arkosic-type Bündnerschiefer of the Trögereck Nappe cover (Pestal and Hellerschmidt-Alber, 2011; see below). They may be a lateral equivalent of the Triassic Seidlwinkl Formation of the Rote Wand Nappe (see below).In addition to these potentially Triassic carbonates, the Rauris map (Griesmeier, 2021) indicates lenses of presumed Late Jurassic marbles within the Bündnerschiefer of the Trögereck Nappe (see below). If correct, this would indicate a Cretaceous age of these Bündnerschiefer.

4.2.1.3 Arkosic Bündnerschiefer-type metasediments of the Trögereck Nappe (Cretaceous) The stratigraphically highest part of the Trögereck Nappe comprises a fairly diverse succession of Bündnerschiefer-type metasediments that partly resembles the Brennkogel Formation of the Rote Wand Nappe (see below), but shares more similarities with the Kaserer Formation in the western Tauern Window. These metasediments contain impure, carbonate-bearing arkosic gneiss (Fig. 9e-f), carbonate breccia, dark phyllite, calcareous micaschist and garnet-micaschist, all with gradual contacts. This succession sometimes also contains blocks or layers of garnet-bearing prasinites (see below). Metapelitic varieties are often relatively rich in organic matter. Thermobarometric investigation of the garnet-micaschists revealed a high-pressure metamorphic overprint of these rocks (Groß et al., 2020).

The gradual contacts of the meta-arkosic lithologies with calcareous micaschist is the main criterion for distinguishing metaarkoses from the Trögereck Gneiss (Frasl, 1958). Where this is not observed, they strongly resemble the Trögereck Gneiss, only that the meta-arkoses of the Bündnerschiefer assemblage of the Trögereck Nappe partly contain carbonate minerals, which is never the case in the Trögereck Gneiss. Additionally, some rounded clasts are often recognized that may be of detrital origin. We interpret these meta-arkosic rocks to represent the erosional product of the Trögereck Gneiss or Zentralgneis. Frasl (1958, pp. 369–372) carefully documents the meta-arkosic gneisses observed in the upper Seidlwinkl Valley (Fig. 2). This author also proposes that the degree of pleochroism in phengite helps to distinguish both types of gneisses; gneiss with weakly pleochroic, colorless to pale green phengite usually belongs to the arkosic Bündnerschiefer-type (carbonatic paragneisses), whereas strongly pleochroic phengite (colorless to intense green) is characteristic of the Trögereck Gneiss (Frasl, 1958, p. 372).

The Bündnerschiefer-type metasediments of the Trögereck Nappe essentially comprise all of the Bündnerschiefer types defined in Sect. 3.3, with a dominant arkosic component. Therefore, and in analogy to similar deposits in the Tauern Window and other parts of the Alps, this sequence can be interpreted as proximal synrift sedimentary mélange formed at the distal European margin that was intensely deformed during orogeny.

4.2.1.4 Garnet-bearing prasinite, eclogite relics The Bündnerschiefer-type assemblage of the Trögereck Nappe contains several layers or lenses of garnet-bearing prasinite. In analogy with similar rocks in the Glockner Nappe, these are interpreted as retrogressed eclogites that are derived from small mafic intrusions or volcanics. Alternatively, the magmatic protoliths of the metabasites could also be interpreted as olistoliths within the Bündnerschiefer succession, or as tectonically incorporated slices.

4.2.2 Eclogite Zone

The Eclogite Zone is a tectonic unit only found outside of our study area in the central Tauern Window (Fig. 1). Since it is subject of a later discussion, its main characteristics are described here. The following description is based on reports from the literature (mainly Miller et al., 1980; Kurz et al., 1998; Nagel et al., 2013) and existing maps (see Table 1). The Eclogite Zone forms a narrow strip of lithologies that runs along the southern margin of the eastern part of the Western Tauern Dome (near the pink star in Fig. 1). There, it immediately overlies the rocks of the Venediger nappe system and is in turn overlain by the Rote Wand Nappe. Unlike the Rote Wand Nappe in the central Tauern Window, the Eclogite Zone does not display a well-ordered stratigraphic succession. It comprises a tectonic and/or sedimentary mixture of metabasites and (Triassic?) carbonatic metasediments embedded in a diverse succession of Bündnerschiefer-type metasediments. These comprise essentially all Bündnerschiefer types introduced in Sect. 3.3., with a dominance of the organic-rich and arkosic types. In many of the rocks of the Eclogite Zone—most prominently in the metabasites—eclogite-facies mineral assemblages can be found, that indicate HP metamorphism during Alpine subduction (e.g., Zimmermann et al., 1994; Glodny et al., 2005; Nagel et al., 2013). The finding of a pre-Alpine garnet fraction in the eclogites indicates that at least some of the metabasites were already metamorphosed during earlier metamorphic cycles (Nagel et al., 2013). These can therefore be regarded as representing a mafic basement of the Eclogite Zone. The metasediments appear to be mostly of post-Variscan (Triassic to Cretaceous) age, given their striking similarities to the Seidlwinkl and Kaserer formations (Kurz et al., 1998). The close association of some of the metabasites (including pillow lavas, volcanic breccias and tuffites; Miller et al., 1980) with the Bündnerschiefer-type rocks of the Eclogite Zone might point towards a second, Mesozoic, generation of mafic magmatism. The rock sequence of the Eclogite Zone is usually regarded as representing a Mesozoic rifting environment on the European margin that involved terrigenous input of siliciclastic and carbonatic detritus, partly via mass wasting, and basaltic magmatic activity (Miller et al., 1980; Kurz et al., 1998). Given the striking similarities in terms of lithofacies, metamorphic grade and structural position in the nappe pile, we regard the Eclogite Zone and Trögereck Nappe as lateral equivalents (further discussed in Sects. 6 and 7).

4.2.3 Rote Wand Nappe

The Rote Wand Nappe, the structurally higher nappe of the Modereck nappe system in the central Tauern Window, where it is a part of a recumbent sheath fold nappe, often referred to as Seidlwinkl fold nappe (Frank, 1965, 1969). It roots in the south and closes in the north of the central Tauern Window (Groß et al., 2020). It comprises a sequence of post-Variscan metasediments that includes Permian to Lower Triassic siliciclastics (Wustkogel Formation), the "Seidlwinkl Triassic" which is a thick succession of Middle to Upper Triassic lagoonal or platform carbonates and evaporites, Upper Triassic to Lower Jurassic metapelites and -psammites and presumably Cretaceous Bündnerschiefer-type calc-schists (Brennkogel Formation). Our compilation is based on own observations and descriptions of the lithostratigraphic units by Exner (1964), Favaro and Schuster (2012), Frank (1969), Frasl and Frank (1964), Kurz et al. (1998), Pestal et al., (2009) and Pestal (2008, 2009). Figure 7 shows a "standard" stratigraphic section of the Rote Wand Nappe in the Stanziwurten area.

4.2.3.1 Wustkogel Formation (Permian to Lower Triassic) The Wustkogel Formation ("Wustkogelserie" of Frasl, 1958) is lithologically striking and serves as a valuable marker horizon for tracing large-scale fold structures and nappe geometries. It is named after the Wustkogel peak at the southern end of the Seidlwinkl Valley. The Wustkogel Formation is identical with what Exner (1964) called "Gneislamelle 4". The lithological content of the Wustkogel Formation is partly similar to that of the Trögereck Gneiss rock assemblage. The stratigraphically lowest part of the Wustkogel Formation is a fine-grained, dark green phengitic gneiss containing microcline- and/or albite-porphyroblasts and -clasts with a grain size usually less than 2 mm, which is smaller than what is usually observed in the Trögereck Gneiss (Fig. 9). The rock is probably a paragneiss derived from fine-grained arkosic debris of Zentralgneis-type material, but it seems likely that parts of these rocks are orthogneisses representing highly deformed and metamorphosed Zentralgneis (Exner, 1964). The characteristic green phengite is strongly pleochroitic in thin section (green-pale pink). Apatite is the dominating accessory mineral and occasionally, pyrite- and magnetite-rich varieties of the gneiss can also be found (e.g., Stanziwurten area, 47.00635°N 12.92761°E). The Wustkogel Formation also contains phengitic schist, arkosic gneiss and meta-conglomerate (e.g., Exner, 1964; Kurz et al., 1998). The stratigraphically highest part is a greenish-white phengitic quartzite. The depositional age of the metasediments ranges from Permian for the arkosic gneiss to Early Triassic for the greenish phengitic quartzite (Kurz et al., 1998; Pestal, 2009).

4.2.3.2 Seidlwinkl Formation (Middle to Upper Triassic) The Seidlwinkl Formation ("Seidlwinkeltrias" of Cornelius and Clar, 1939) is named after its type locality, the upper Seidlwinkl Valley. It follows conformably on top of the green phengite-quartzite of the Wustkogel Formation (Fig. 11a). Usually, this formation is subdivided into two distinct units: The stratigraphically lower part, consisting mainly of bright gray marble and an upper unit comprising yellow dolomite marble, cargneule (or Rauhwacke) and gypsum. The thickness of the Seidlwinkl Formation varies considerably in the study area, ranging from only a few meters to hundreds of meters. This is due to extreme thinning in the limbs of the recumbent folds and thickening in the fold hinges. The Middle to Late-Triassic depositional age of the Seidlwinkl Formation is based on various fossil evidences (Kristan-Tollmann, 1962; Borowicka, 1966; Pestal, 2009; as cited by Tollmann, 1977; Frisch, 1975a).

The lower part of the formation, the Seidlwinkl Marble s.str., comprises relatively coarse, sugary marble of white to light-gray color that is layered on the cm-dm-scale. These layers are typically weathered out and nicely rounded due to preferential erosion along the layer interstices. The rock contains considerable amounts of white mica, detrital (?) quartz and, occasionally, mm-sized tremolite crystals.

The upper part of the Seidlwinkl Formation consists of light yellow- to orange (or sometimes pinkish) dolomitic marble and cargneule (Fig. 10a), as well as fairly abundant massive gypsum. These lithologies are intercalated in a complex manner, presumably reflecting lateral facies changes in the former depositional environment. Usually, bedding cannot be recognized in outcrop. The dolomitic marble consists of large angular fragments of fine-grained dolomite bedded in an equally fine-grained dolomitic matrix. Additionally, it contains rounded, detrital (?) quartz and small flakes of white mica.

4.2.3.3 Piffkar and Schwarzkopf Formations (Upper Triassic to Lower Jurassic) The Piffkar (Pestal, 2008) and Schwarzkopf formations ("Schwarzkopffolge" of Cornelius and Clar, 1939) stratigraphically overlie the Seidlwinkl Formation. Even though they are distinct lithologies, we have grouped them into a single unit in Fig. 5 because they co-exist, and together make up only a small thickness (few tens of meters). Their thickness is somewhat greater at the northern end of the Rote Wand Nappe.

The Piffkar Formation is characterized by bright, chloritoid-bearing, phengite-poor quartzite on the one hand and bright-silvery chloritoid-bearing sericitic phyllite on the other hand (Fig. 10g, h). Both lithologies completely lack carbonate and feldspar, and are generally tightly interfolded so that they appear interlayered. Chlorite and kyanite are common as well, whereas epidote and clinozoisite occur only rarely. Very rarely, relics of garnet can be found in thin section. The main accessory mineral is allanite.

The Schwarzkopf Formation resembles the Piffkar Formation in basically all respects mentioned above, except for its very high content of carbonaceous matter, which lends the rock surfaces a dark sheen. The formation is mainly made up of dark-silvery, phengitic quartz-bearing phyllites rich in porphyroblastic kyanite that forms up to 1 cm long needles. This rock can also contain considerable amounts of chloritoid and clinozoisite. The carbonaceous matter is finely dispersed in the matrix and incorporated as tiny flakes inside the kyanite and chloritoid crystals, giving them black appearance in hand specimen. Additionally, dark gray (phengite-kyanite-chloritoid-) quartzite layers are intercalated with the phyllites, but usually these are less frequent than in the Piffkar Formation. The rocks of the Schwarzkopf Formation also completely lack carbonate minerals and feldspar.

Considering lithostratigraphic correlations with similar rocks in the Alpine realm (see Chap. 6), and given that the Piffkar Formation stratigraphically overlies the Middle to Upper Triassic Seidlwinkl Formation, the Piffkar and Schwarzkopf formations likely represent Late Triassic (Norian-Rhaetian) and Early Jurassic (Hettangian?) distal delta sediments, respectively, that were deposited on the southern margin of the European continent towards the Neotethys Ocean.

4.2.3.4 Brennkogel Formation (Cretaceous) The Brennkogel Formation (Frasl & Frank, 1966) occurs in the uppermost part of the Rote Wand Nappe. It is a few hundred meters thick and comprises mainly dark calcareous micaschist and bright carbonate quartzite as well as meta-conglomerates, -breccias, dark phyllite and dark garnet-chloritoid-micaschist. True meta-arkosic rocks are very rare in the Brennkogel Formation and occur noticeably only locally in the lower part of this unit. Usually, these lithologies are tightly interlayered or -folded (Fig. 10b), which is why they are grouped in a single unit. In the following, we will describe the main lithologies of the Brennkogel Formation. We use the term Brennkogel Formation in the original sense as described by Cornelius and Clar (1939) and Frasl and Frank (1966; their "Brennkogelfazies der Bündnerschieferserie") for successions as described above that are essentially devoid of arkosic layers. Such successions are typically found at the type locality, the flanks of the Brennkogel mountain in the southernmost Fusch Valley, where they are part of the Rote Wand Nappe. It is important to note that in contrast to the original description, the term Brennkogel Formation was expanded to similar-looking Bündnerschiefer-type successions in other parts of the Tauern Window that are largely dominated by arkosic layers (e.g., Pestal et al., 2009). In our view, this stance is problematic and should be avoided, since it implies a co-facial nature of successions with clearly distinct sedimentary facies and provenance. However, we acknowledge that gradual transitions between both types are certainly possible.

The basal contact of the Brennkogel Formation varies laterally. It can directly overlie the dark phyllites and quartzites of the Schwarzkopf Formation, or alternatively, older lithostratigraphic units of the Rote Wand Nappe (Fig. 11b). This indicates that the Brennkogel Formation was deposited after a period of widespread erosion of a marked paleotectonic relief on the European margin (Fig. 2 of Schmid et al., 2013). The stratigraphic lower parts of the Brennkogel Formation often contain a carbonate breccia, the so-called "Hochtor Breccia" (Pestal et al., 2009), which, where present, serves as a valuable marker horizon. The breccia clasts are usually several centimeters in diameter, but Frasl (1958) reports huge blocks of up to one meter in diameter. They are mainly derived from the carbonate rocks (especially dolomite) of the Seidlwinkl Formation, indicating locally deep erosion and rapid re-deposition of the detritus in small, isolated basins. The matrix of the breccia is phyllitic or quartzitic (Pestal et al., 2009). Usually, the breccia contains strongly deformed clastic components.

Most of the Brennkogel Formation is a dark carbonate-bearing micaschist (Fig. 10c, d). This lithology typically has rusty-brown spots on the weathered dark-gray cleavage surfaces. Phengite, quartz, carbonate (calcite, ankerite), carbonaceous matter and other opaque phases (hematite?) are ubiquitous. Chlorite, garnet, chloritoid, paragonite, albite, epidote, clinozoisite, rutile and titanite also occur, depending on bulk chemical composition. Zoned tourmaline is the main accessory mineral and locally very abundant.

The garnet-bearing varieties of the dark micaschist often contain pseudomorphs (clinozoisite, albite, chlorite, paragonite) after lawsonite as inclusions in garnet, indicating high-pressure metamorphism. These rocks tend to have a lower content of carbonate minerals than the usual dark Brennkogel schists. The chemical composition (details below; Fig. 13) of these garnet-micaschists is similar to the garnet-bearing metapelites of the Glockner Nappe s.str., but clearly distinct from the metapelites of the Piffkar and Schwarzkopf formations.

The quartzite is massive and occurs as dm-m thick layers intercalated with the micaschist (Fig. 10b). Usually, it is light-gray or light-brown, more or less carbonatic and poor in mica. Relict cross-bedding was found in one of these quartzite layers south of the Margarötzenkopf summit (3 km SSE of Brennkogel summit). Pestal (2008) describes these quartzite banks with several layers with graded bedding and interprets them to represent rhythmic flysch-like deposits.

In the upper part of the Brennkogel Formation, intercalations of calcareous micaschist in the main mass of dark Brennkogel micaschists (see above) are frequent. Hence, this part of the Brennkogel Formation resembles the metasediments of the Glockner Nappe. The stratigraphic top of the Brennkogel Formation is marked by a tectonic imbrication zone, where large blocks of serpentinite, prasinite and (Triassic) marble are embedded in a matrix of the Brennkogel metasediments.

The sedimentary age of the Brennkogel Formation is debated, either being seen as Liassic (e.g., Cornelius and Clar, 1935; Frasl and Frank, 1964) or Cretaceous (e.g., Thiele, 1980; Lemoine, 2003; Schmid et al., 2013). The striking differences in terms of lithological assemblage and metapelite chemistry (Chap. 5) between the probably Liassic Schwarzkopf Formation and the overlying Brennkogel Formation indicate profoundly different sediment routing systems and depositional environments. Moreover, the major erosional unconformity at the base of the Brennkogel Formation (Fig. 11b) suggests a (early) Cretaceous age for the Brennkogel Formation, as argued by Schmid et al. (2013). Below, we propose the following additions to the reasoning of Schmid et al. (2013):

As shown above, the Brennkogel Formation of the Rote Wand Nappe consists of two distinct lithological assemblages (dark micaschist with carbonate breccia and dark micaschist with quartzite banks), even though gradual transitions between both types clearly exist. The first type is well-developed, e.g., in the Hochtor and Spielmann peak areas (ca. 3 km SE and S of Brennkogel summit, respectively). Usually found at the stratigraphic base of the formation, this first type is characterized by the occurrence of relatively coarse-grained breccias with carbonatic components clearly derived from the Seidlwinkl Formation. This indicates erosion of the Triassic carbonate platform, a short transport distance and rapid deposition of the eroded material, making mass-wasting along escarpments related to fault activity in a syn- to post-rift environment very likely for the formation of this part of the Brennkogel Formation (e.g., Kurz et al., 1998).

The second type clearly corresponds to the turbiditic variety of Bündnerschiefer-type metasediments, as introduced in Sect. 3.3. It is especially well exposed at the northeastern flank of the name-giving mountain, the Brennkogel, and in the lower slopes of the Fusch Valley near Ferleiten. This type makes up the main (middle and upper) part of the formation and is characterized by relatively fine-grained, very mature quartz-rich turbidites that were rhythmically deposited in a basin dominated by organic-rich, fine-grained marly sediments. In addition, layers of calcareous micaschist (as in the Glockner Nappe) are intercalated in the upper parts of this succession, indicating proximity to the oceanic depositional environment as observed in the deposits of the Glockner Nappe s.str. This type of the Brennkogel Formation is more diagnostic of a post-rift environment, where eroding crystalline hinterland delivered mature siliciclastic sediments that were transported via turbidity currents to a slowly filling marine basin with a marly, organic-rich background sedimentation.

4.3 Penninic nappes

We use the term Penninic nappes to refer to all units sandwiched between the Austroalpine nappes above (derived from Adria) and the Venediger nappe system below (derived from Europe). Unlike the Penninic nappes in the Central and Western Alps, which contain

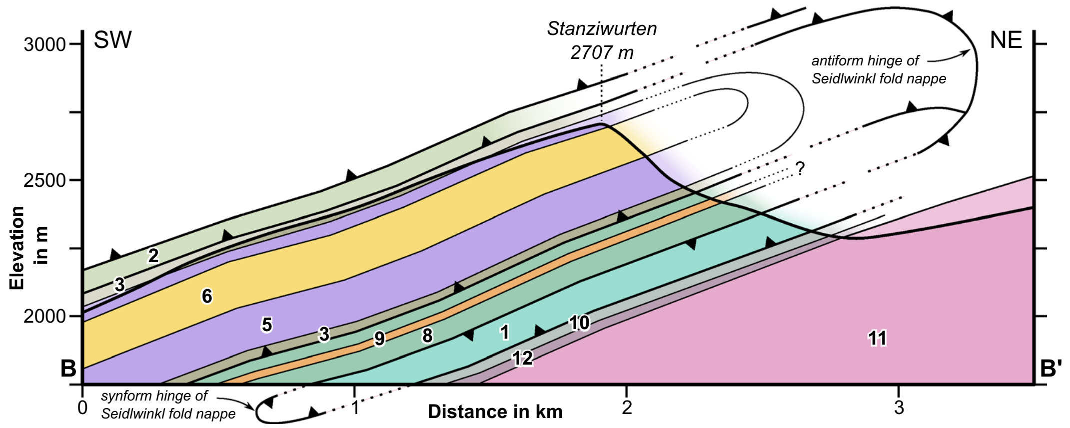

Fig. 6 Geological cross-section of the Stanziwurten area, with legend and location given on Fig. 5

Europe-derived basement (Briançonnais) wedging out eastward, these nappes in the Tauern Window comprise only basement and sediment derived from Alpine Tethys.

In the Tauern Window, two distinct Penninic nappe systems are usually distinguished: The upper system comprises Matrei Zone and Nordrahmenzone and the lower system is represented by the Glockner nappe system (e.g., Kurz et al., 1998; Schmid et al., 2004). Both systems consist of metamorphosed marine sediments with ophiolite fragments such as serpentinized peridotite and metabasites. During Alpine convergence, the Penninic nappes in the Tauern Window were subducted, exhumed and accreted in the orogenic nappe stack (e.g., Schmid et al., 2004; Handy et al., 2010).

4.3.1 Glockner nappe system

The Glockner nappe system comprises a strongly deformed succession of mainly Bündnerschiefer-type calcareous micaschist and dark phyllite, with subordinate prasinite layers and serpentinite lenses. Some parts of the Glockner nappe system experienced high-pressure eclogite-facies metamorphism, whereas other parts never exceeded lower blueschist facies conditions (Pestal and Hellerschmidt-Alber, 2011; Groß et al., 2020). These differences in peak pressure correspond to differences in the peak-T attained during subduction-related metamorphism (Groß et al., 2021). This allows for a subdivision of the Glockner nappe system into the structurally lower Glockner Nappe s.str. comprising local occurrences of eclogite-facies assemblages and the structurally higher Rauris Nappe lacking such metamorphism (e.g., Pestal and Hellerschmidt-Alber, 2011; Favaro and Schuster, 2012). Apart from this difference in metamorphic grade, both nappes essentially contain the same lithologies, but with varying proportions. Therefore, the following descriptions of the main rock types used in our compilation apply to both the Glockner s.str. and the Rauris nappes. These descriptions are largely based on Cornelius and Clar (1939), Frasl (1958), Frank (1969), Kurz et al. (1998), Pestal and Hellerschmidt-Alber (2011) and own observations.

In the southern part of the central Tauern Window, the top of the Glockner Nappe s.str. is marked by a tectonic contact to the overlying Rauris Nappe (Figs. 3 and 4). This contact originally was a thrust, but was later overprinted by a normal-sense shear zone during D3 (Groß et al., 2020), which also corresponds to a sudden upward decrease in peak-metamorphic conditions towards the Rauris Nappe (Groß et al., 2021). Here, the contact of the Rauris Nappe to the overlying Matrei Zone is gradual and not clearly visible in the field. In our tectonic map (Fig. 2), we used the first occurrence of exotic blocks of the Matrei Zone to trace the contact.

In the northern parts of the central Tauern Window, the base of the Rauris Nappe corresponds to a thrust contact with the upper part of the Wörth Formation in its footwall and no Glockner Nappe s.str. is found there anymore (Fig. 2). The tectonic nature of this contact is suggested by a local increase of the intensity of deformation and a slight upward increase in the metamorphic peak temperature (e.g., Sect. 5.4 and Fig. 6 in Groß et al., 2021). The contact of the Rauris Nappe to the overlying Nordrahmenzone is defined by a shear zone just above the Drei-Brüder Formation (Höck et al., 2006), located in the north of the map in Fig. 2.

4.3.1.1 Serpentinite Layers or lenses of serpentinite occur predominantly at the base of the Glockner Nappe s.str. near the contact with the underlying Modereck nappe system (Kurz et al., 1998). These lenses range in

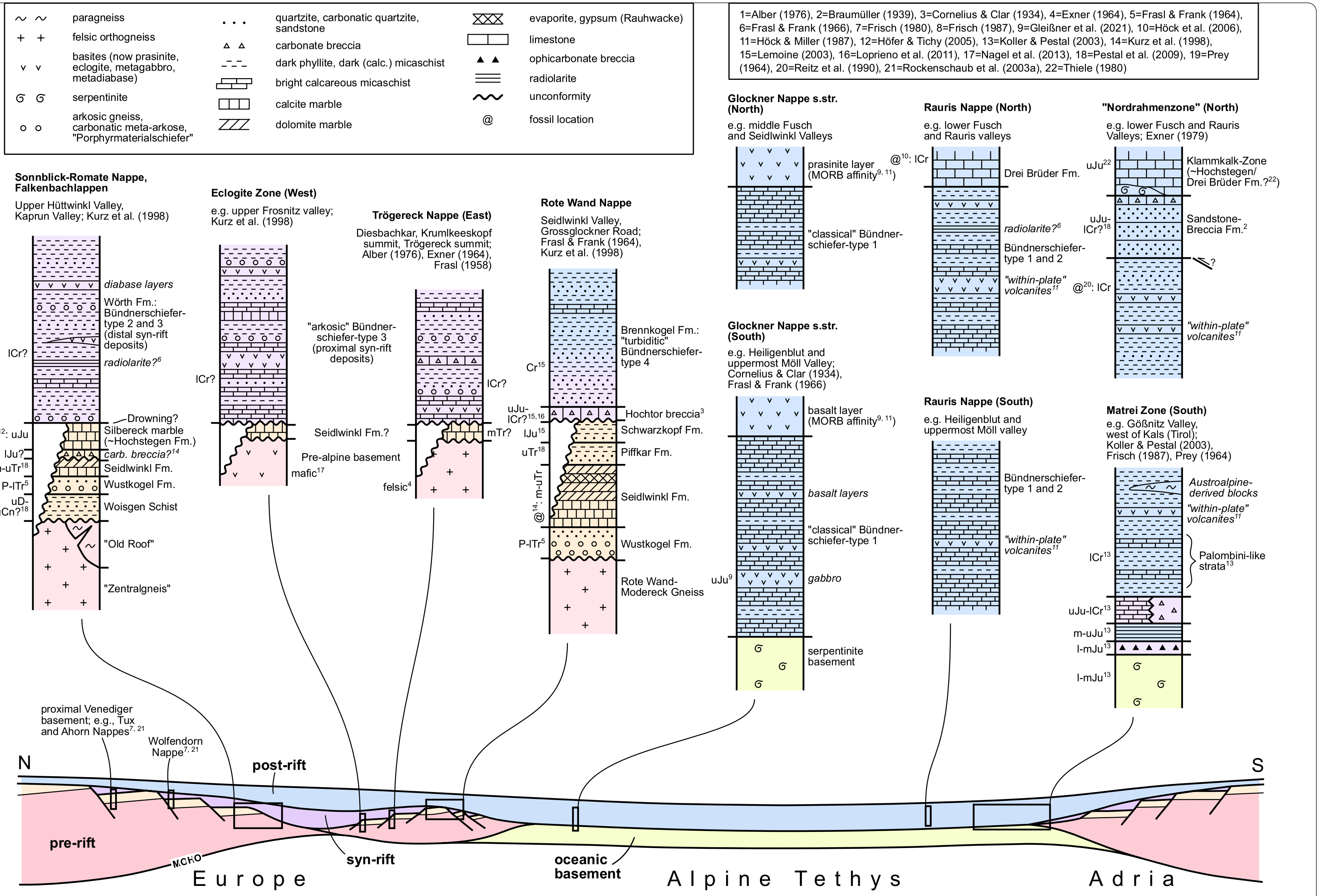

Fig. 7 Lithostratigraphic columns of tectonic units in the central Tauern Window. These sections are based on own observations, data from the geological maps in Table 1 and Alber (1974), Braumüller (1939), Cornelius and Clar (1934), Exner (1964), Frasl and Frank (1964), Frasl and Frank (1966), Frisch (1980), Frisch et al. (1987), Gleißner et al. (2021), Höck et al. (2006), Höck and Miller (1987), Höfer and Tichy (2005), Koller and Pestal (2003), Kurz et al. (1998), Lemoine (2003), Loprieno et al. (2011), Nagel et al. (2013), Pestal et al. (2009), Prey (1964), Reitz et al. (1990), Rockenschaub et al. (2003) and Thiele (1980). The order of the columns from north to south in the section reflects the present-day position of the tectonic units in the Alpine nappe stack as viewed from bottom to top. The colors indicate pre-rift (orange), syn-rift (purple) or post-rift (blue) sediments, irrespective of the individual age of rifting and existence of potential later re-rifting phases. See Chaps. 6 and 7 for explanation of the paleogeographic interpretation in the lower panel

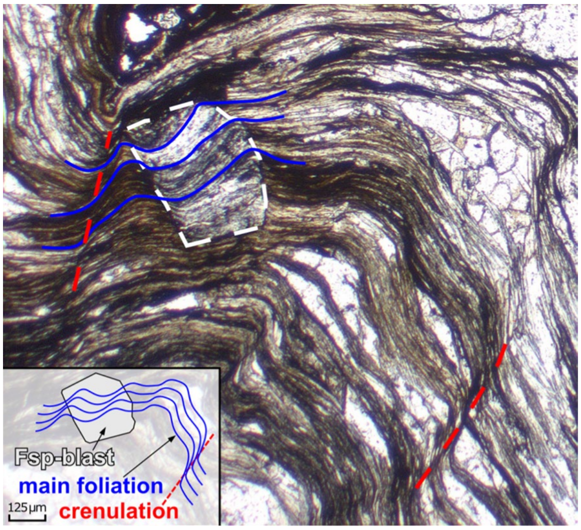

Fig. 8 Thin section image (parallel polarizers) of a crenulated dark phyllite from the Wörth Formation with a post-kinematic albite porphyroblast (sample PG247, 47.19540°N 12.85067°E)

size from several meters to a few hundreds of meters. The serpentinites are usually interpreted as the alteration product of peridotite derived from oceanic mantle lithosphere (Höck & Miller, 1987). Primary magmatic minerals are very rare. Often, the contact area of the serpentinite lenses with the surrounding calcareous micaschist matrix is characterized by metasomatic reaction halos.

4.3.1.2 Prasinite Both parts of the Glockner nappe system contain abundant prasinite that occurs as small to very large bodies and layers in the calcareous micaschist. The prasinite consists mainly of actinolite, Na-rich plagioclase (mostly albite), chlorite, epidote, clinozoisite, pyrite and carbonates in variable proportions. Locally, pseudomorphs after lawsonite (Fig. 12) document retrogression from lower blueschist- to greenschist-facies conditions. The prasinite has a geochemical signature diagnostic of tholeiitic mid-ocean ridge basalt (Höck & Miller, 1987), indicating that the protoliths of the prasinites were basalts extruded during spreading of Alpine Tethys. So far, the magmatic age of these basalts has not yet been determined directly. However, Gleißner et al. (2021) obtained a Late Jurassic (157 Ma, Kimmeridgian) crystallization age from a gabbro in the Glockner Nappe s.str. located west of our research area and near the contact with the Eclogite Zone and Venediger Nappe (locality shown in Fig. 1). This gabbro has a similar geochemical signature as the prasinites from the Glockner Nappe s.str. (Gleißner et al., 2021) and therefore, a similar age of at least parts of the prasinite protoliths appears likely. This finding implies that the Glockner Nappe s.str. originates from the eastward continuation of the Piemont-Liguria basin.

4.3.1.3 Eclogite, garnet-prasinite Retrogressed eclogite occurs as lenses or layers in the calcareous micaschist of the Glockner Nappe s.str. and in the imbricate zone between the Glockner Nappe s.str. and the Rote Wand Nappe. Due to the strong retrogression, omphacite is found only sporadically as relics (e.g., Dachs and Proyer, 2001). The matrix consists of greenschist-facies minerals (actinolite, albite, chlorite, epidote/clinozoisite, quartz, carbonate) and contains porphyroblastic garnet. Therefore, the rock is more appropriately termed a garnet-prasinite. Garnet often contains inclusions of glaucophane and pseudomorphs after lawsonite. They are usually surrounded by a corona of biotite and chlorite, presumably the product of partial garnet breakdown. Dachs and Proyer (2001) determined a peak pressure of ca. 1.7 GPa and 540–570°C for the eclogites from the Gamsgrube locality at the southern flank of the Fuscherkarkopf summit.

4.3.1.4 Calcareous micaschist Calcareous micaschist is the dominant lithology in most of the Glockner nappe system. The term calcareous micaschist refers to a succession of light gray to light brown, carbonate-rich micaschist and phyllite and mica-bearing marble that closely resemble what is known as "Bündnerschiefer" in the Engadine Window (Bousquet et al., 2002). Occasionally, layers of garnet-micaschist and dark, graphite-rich calcareous phyllite occur as well. In the Glockner Nappe s.str., layers of this dark phyllite occur only infrequently, and light-colored calcareous micaschist is the most common lithology. In contrast, graphitic phyllite is the dominating lithology in the Rauris Nappe. The calcareous micaschist essentially consists of calcite, white mica and quartz, with only rare chlorite and feldspar. In parts of the Rauris Nappe, the calcareous micaschist and calcareous phyllite are intercalated with particularly fine-grained, thinly bedded quartzite layers that are interpreted as meta-radiolarites (Frasl & Frank, 1966). A special lithology often found at the contact of calcareous micaschist to metabasite is a bright, quartz-rich garnet-white mica-schist that is carbonate-free and often very rich in epidote-group minerals. The calcareous micaschist of the Glockner nappe system corresponds to the first, "classical" variety of Bündnerschiefer-type metasediments, as introduced in Sect. 3.3, and the graphitic phyllite corresponds to the second type.

The sedimentary age of most of the calcareous micaschist is unconstrained in the central Tauern Window, but was inferred to be Early Cretaceous based on the lithological affinity with the Bündnerschiefer of Graubünden in eastern Switzerland (Schmid et al., 2013). So far, fossils have only been found in the Drei-Brüder

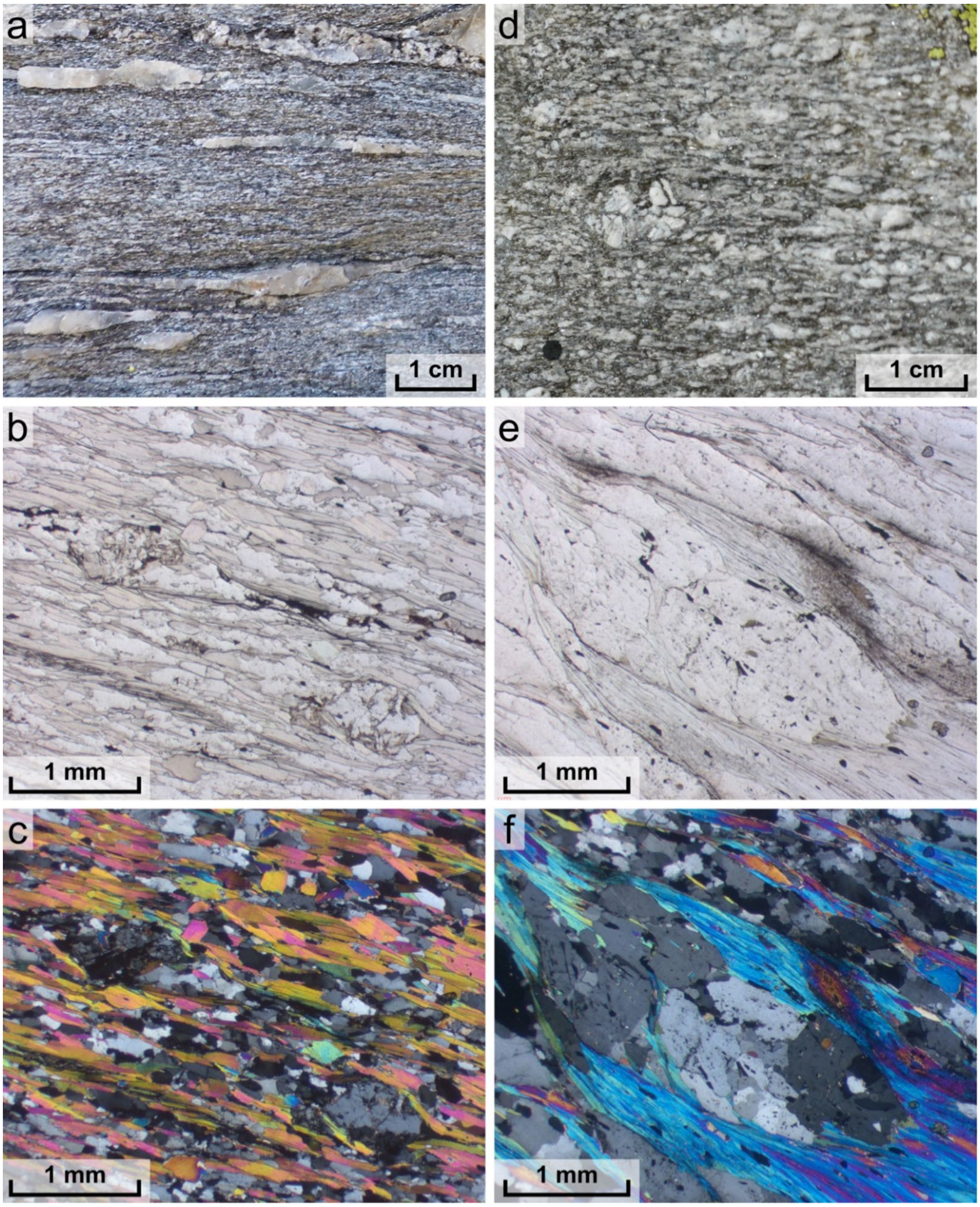

Fig. 9 Comparison of metamorphosed sandstones of different units of the Modereck nappe system: **a** fine-grained, phengite- and quartz-rich meta-arkose of the Wustkogel Formation. **b** and **c** thin section images with parallel and crossed polarizers, respectively, of a similar lithology to **a** from the Wustkogel Formation (sample PG75, 47.00636°N 12.92570°E). Note that this rock consists mainly of phengite and quartz, with only a few larger albite-clasts. **d** a relatively coarse-grained arkosic gneiss from the Trögereck Nappe. **e** and **f** thin section images with parallel and crossed polarizers, respectively, of a similar lithology to **d** from the Trögereck Nappe (sample PG78, 47.01618°N 12.92424°E). The rock mainly consists of phengite, quartz and relatively large albite clasts or blasts. Additionally, few biotite grains are present, e.g., at the tips of the elongated feldspar crystals. No carbonate minerals are present in this rock, which is why it is grouped with the Trögereck Gneiss (basement of the Trögereck Nappe)

Formation (Kleberger et al., 1981; Höck et al., 2006) that most likely forms the stratigraphically uppermost part of the Rauris Nappe. In our compilation, this formation was grouped with the calcareous micaschist unit, even though it shows some characteristics that are different from the "usual" calcareous micaschists. Using trace- and microfossils, Höck et al. (2006) obtained a sedimentary age for the Drei-Brüder Formation (location shown in Fig. 2 with a star) ranging from Tithonian to Berriasian for its stratigraphic lower (southern) part to latest Hauterivian or younger for its uppermost (northern) part. They give a minimum age for the base of the Drei-Brüder Formation of ca. 140 Ma and a maximum age for its top of ca. 110 Ma, which results in a life span of at least ca. 30 Ma for this unit. If the dating itself is correct, these ages indicate that the dark phyllite and calcareous micaschist in the Rauris Nappe, which is in the footwall of the Drei-Brüder Formation, was deposited before 140 Ma, i.e., during Late Jurassic to earliest Cretaceous time. This is younger than the aforementioned Late Jurassic (157 Ma) formation age of a gabbro sample in the Glockner Nappe s.str. that represents the part of oceanic crust on which the calcareous micaschist was presumably deposited.

4.3.2 Matrei Zone and Nordrahmenzone

The highest Penninic tectonic units in the Tauern Window are the Matrei Zone and the Nordrahmenzone. The term Matrei Zone originally referred to a unit near the town of Matrei at the southern margin of the Tauern Window, whereas Nordrahmenzone is used for the unit framing the window along its northern margin. The Matrei Zone is an imbricate or mélange zone comprising oceanic metasediments, metabasite and serpentinite from Alpine Tethys and slivers or olistoliths of the overlying Austroalpine nappes, including blocks of siliciclastics and metacarbonates (e.g., Peer and Zimmer, 1980; Frisch et al., 1987; Koller & Pestal, 2003).

This sequence is interpreted as a former accretionary prism that formed during early subduction of the Alpine Tethys below the active Austroalpine margin of the advancing Adriatic plate (Frisch et al., 1987). Therefore, and in analogy to the Western and Central Alps, the Matrei Zone/Nordrahmenzone was interpreted to represent the Piemont-Liguria part of Alpine Tethys in the Tauern Window (e.g.,Handy et al., 2010).

4.3.2.1 Bündnerschiefer-type sediments with exotic blocks (undifferentiated) This is a composite unit that comprises, on the one hand, the bulk of Bündnerschiefer-type metasediments of the Matrei Zone and Nordrahmenzone and, on the other hand, other lithologies that occur as blocks or lenses in the metasedimentary matrix. The Bündnerschiefer-type metasediments are made up mainly of dark phyllite and light calcareous phyllite and micaschist, often indistinguishable from those of the Glockner nappe system. These deposits correspond to the first and second varieties of Bündnerschiefer-type metasediments as introduced in Sect. 3.3.

The blocks range in size from meters to kilometers and comprise serpentinites, metaradiolarites, prasinites, Permian siliciclastics ("Alpine Verrucano") and Triassic metasandstone and -carbonate. There is one occurrence of datable fossils in the Bündnerschiefer of the Nordrahmenzone that yields Early Cretaceous ages for olistolith-bearing dark phyllites (Reitz et al., 1990). Metabasites included in these Early Cretaceous dark phyllites occur as lavas, tuffs and sills and have a "within-plate" geochemical signature (Höck & Miller, 1987), indicating that the Piemont-Liguria part of Alpine Tethys was affected by Early Cretaceous magmatic activity (Reitz et al., 1990), possibly related to rifting.

4.4 Austroalpine nappes (undifferentiated)

The perimeter of the Tauern Window comprises the Austroalpine nappes which are not differentiated tectonically or lithologically in our compilation. South of the Tauern Window, these units are mainly polymetamorphic para- and orthogneisses and amphibolites of the Schober Crystalline, whereas in the north of the window they are Paleozoic sand-, silt- and claystones of the Grauwackenzone (e.g., Pestal, 2009).

5 Geochemistry of metapelites and metapsammites

We obtained new bulk rock chemical data by X-ray fluorescence (XRF) analyses of metapelites and metapsammites, as well as other rock types, in order to compare lithological units from the central Tauern Window. The data allow us to deduce first-order information on the sedimentary protoliths of the analyzed samples, like the weathering state, the depositional system, or some rudimentary estimates on changes in sediment provenance. These aspects are discussed in more detail in Chap. 6. Sample preparation and analysis followed a standard procedure as described in Raschke et al. (2013). Major element compositions are reported in Table 2, trace element compositions in Table 3. In the following, we assume that the measured metapelite chemistry provides an estimate

(See figure on next page.)

Fig. 10 Lithologies of the Modereck nappe system. **a** cargneule (Rauhwacke) of the Middle to Upper Triassic Seidlwinkl Formation. **b** isoclinal fold in carbonate quartzite from the Brennkogel Formation. Figures **c** to **h** show thin section images of lithologies of the Modereck nappe system (parallel polarizers in **c**, **e** and **g** and crossed polarizers in **d**, **f** and **h**: The dark micaschist of the Brennkogel Formation (**c**, **d**; sample PG149, 47.17763°N 12.81997°E) consists primarily of phengite, quartz, carbonate minerals (calcite, ankerite?) and carbonaceous matter, feldspar is very rare. The arkosic layers within the Bündnerschiefer-type 3 metasediments of the Trögereck Nappe (**e**, **f**; sample PG62, 47.08515°N 12.87452°E) mainly consist of abundant albite blasts (or clasts), phengite, carbonate minerals, quartz, carbonaceous matter and some epidote. The chloritoid-bearing phyllite of the Piffkar Formation (**g**, **h**; sample PG141, 47.13907°N 12.84402°E) comprises phengite, quartz, chloritoid, chlorite and Ti-rich phases (ilmenite, rutile)

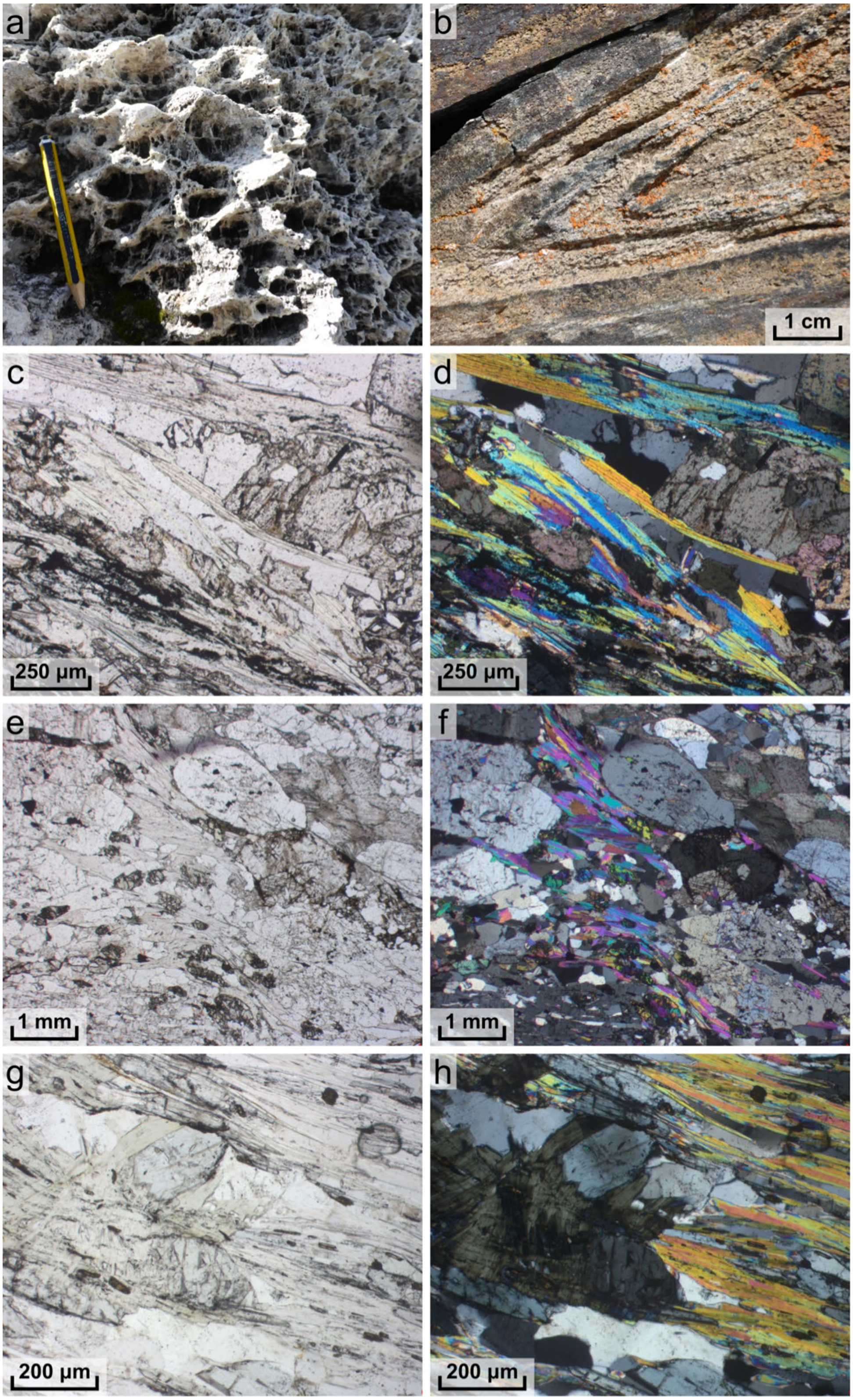

Fig. 10 (See legend on previous page.)

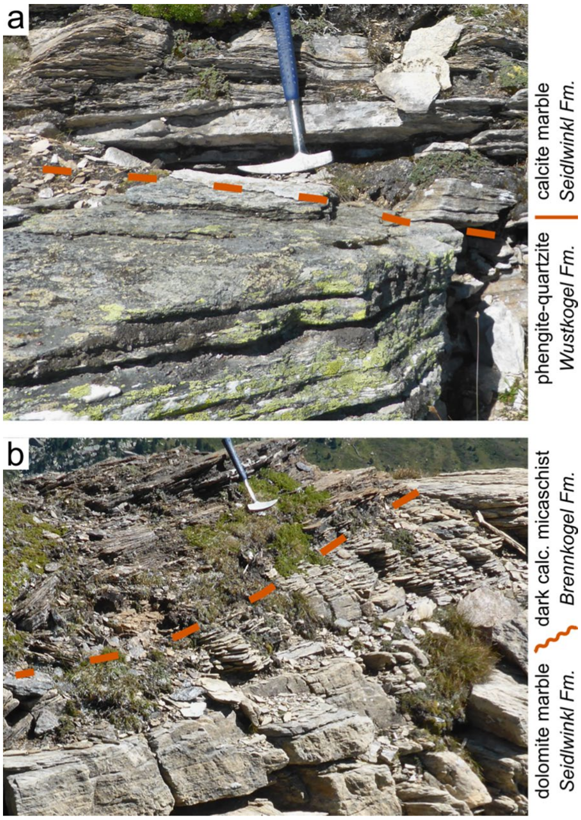

Fig. 11 **a** contact (47.00633°N, 12.92760°E) between the Wustkogel (greenish phengite-quartzite) and Seidlwinkl (bedded calcite marble) formations. **b** Unconformable, transgressive (?) contact (47.00830°N, 12.92625°E) between the Seidlwinkl Formation (dolomite and calcite marble) and the overlying Brennkogel Formation (dark calcareous micaschist). The Piffkar and Schwarzkopf formations are missing. Also note the slight angular unconformity

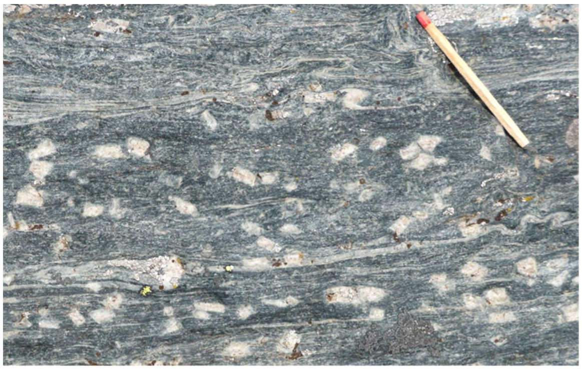

Fig. 12 Outcrop of prasinite (coordinates: 47.06482°N 12.75790°E) from the Glockner nappe s.str. The rock contains abundant light grey rectangular inclusions that are interpreted as pseudomorphs after lawsonite

of the geochemical composition of the sedimentary protoliths, i.e. that post-depositional (metasomatic) alteration is negligible.

In Fig. 13a, the relation Na_2O towards K_2O shows the degree of chemical alteration by weathering of the precursory sediments (Nesbitt and Young, 1982), whereas the content of CaO indicates the amount of carbonate minerals, apatite or plagioclase in the analyzed samples. The Zentralgneis lithologies show an intermediate composition with regard to these elements. Their potential erosion products, the (protoliths of the) Wustkogel paragneisses (and Trögereck metasediments), tend towards higher contents of K_2O. The metapelites of the Piffkar and Schwarzkopf formations are very poor in CaO and essentially barren of Na_2O. We interpret this observation to indicate increasing degrees of chemical weathering of siliceous rocks (Zentralgneis), which leads to sediments that become subsequently poorer in detrital plagioclase and alkali feldspar (Wustkogel paragneisses) and richer in newly-formed clay minerals (Piffkar and Schwarzkopf formations). In the metapelites of the Brennkogel Formation and the Glockner Nappe s.str., the content of CaO is generally higher than in the other lithologies. Here, the main CaO-bearing phases are carbonates, which might be interpreted to indicate a marine origin of these metapelites.

All analyzed lithological units display a positive correlation of Fe_2O_3 to MgO (Fig. 13b), even though the ratios are highly variable. The ratio of MgO to Fe_2O_3 in the Piffkar metapelites is on the order of 1:10, while it is generally above 1:5 in the other lithologies. A smaller ratio of MgO to Fe_2O_3 in the analyzed metasediments might reflect a higher relative abundance of Fe-oxides and -hydroxides vs. Fe-Mg-silicates (chlorite?) or Mg-carbonates in the sedimentary protoliths (Caracciolo, 2020).

The plot of $MgO + Fe_2O_3$ vs. TiO_2 in Fig. 13c (Bhatia, 1983) illustrates the high content of TiO_2 (1.6–0.7 wt%) of the Piffkar and Schwarzkopf metapelites compared to all other lithological units ($0.8 - 0.1$ wt%, excluding one outlier), which also show a positive correlation of $MgO + Fe_2O_3$ and TiO_2. This trend corresponds to the geotectonic environments (shown in Fig. 13c) described by Bhatia (1983). The low-$MgO + Fe_2O_3$ samples of the Piffkar and Schwarzkopf samples do not follow this correlation, which in their cases indicates anomalously high contents of TiO_2.

High-field-strength elements (HFSE) like Zr are mostly contained in refractory minerals like zircon or phosphates (Heinrichs et al., 2012). The transition trace elements (TTE) like Cr in (meta)sediments are usually interpreted to indicate provenance from ultramafic rocks (e.g., McLennan et al., 1993), even though high contents of TTE can also be caused by capture and enrichment

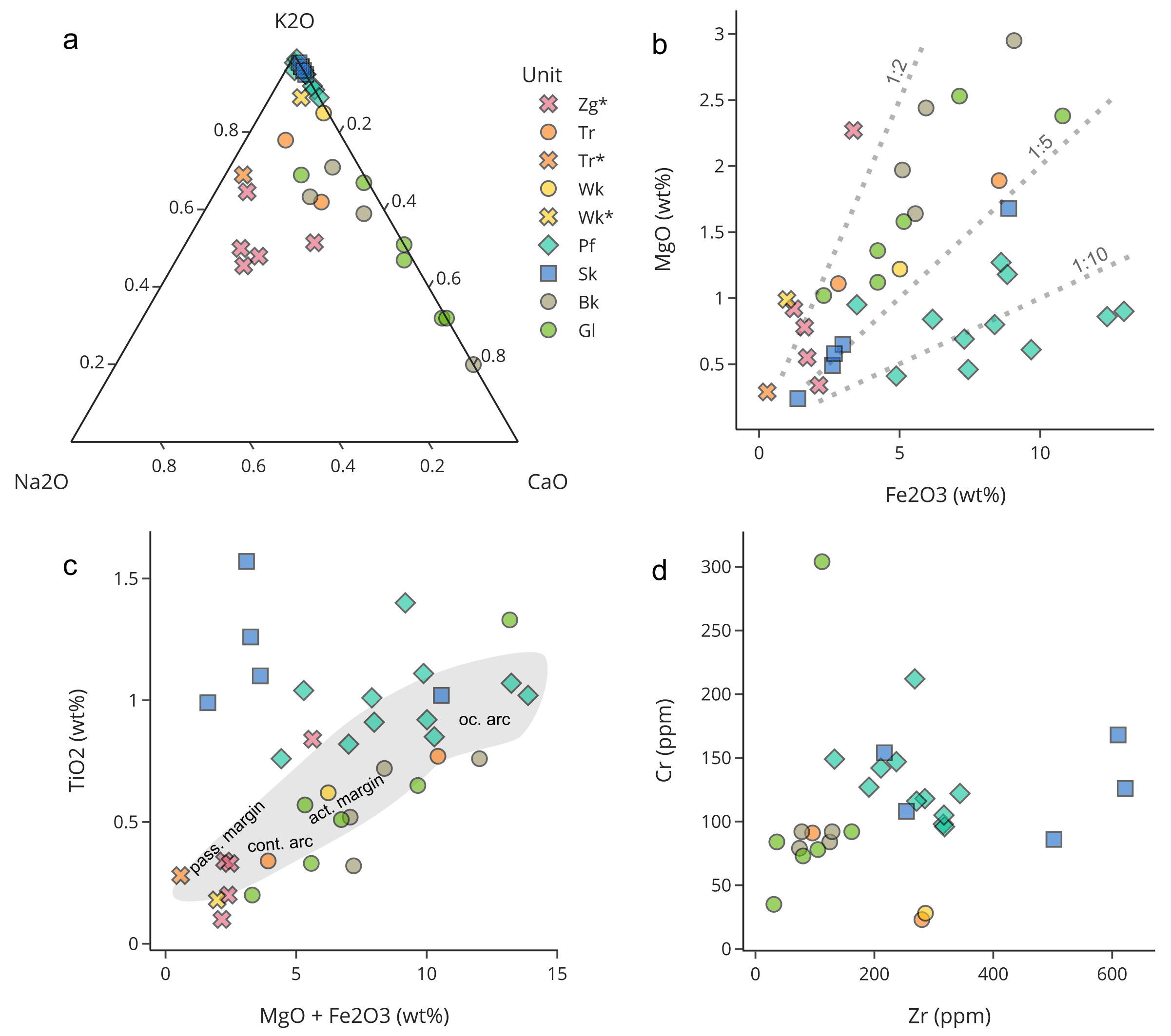

Fig. 13 Bulk-rock chemical characteristics (Tables 2 and 3) of silicatic metasediments (mainly pelites) from different lithological units in the central Tauern Window and potential source rocks (Zentralgneis). Variability in Na_2O-K_2O-CaO in **a**, content of Fe_2O_3 vs. MgO in **b**, MgO + Fe_2O_3 vs. TiO_2 (after Bhatia, 1983) in **c** and Zr vs. Cr in **d**. Zg* denotes rocks from the Zentralgneis of the Venediger nappe system taken from Exner (1957) (p. 78 samples 1 and 2; p. 119, samples 7, 8 and 9). Tr and Wk denote metasediments from the Trögereck Nappe and Wustkogel Formation, respectively. Analyses marked Tr* and Wk* were taken from Exner (1964) (p. 67, samples 1 and 2, respectively). Pf and Sk denote metapelite samples from the Piffkar and Schwarzkopf formations, Bk and Gl denote Grt-micaschist samples from the Brennkogel Formation and the Glockner Nappe s.str., respectively

of these elements in chlorite-type clay minerals during weathering (Heinrichs et al., 2012). Figure 13d shows the abundance of HFSE and TTE, best exemplified by Zr and Cr, respectively. In the Piffkar and Schwarzkopf metapelites, the contents of Zr (ca. 200–600 ppm) and Cr (ca. 100–200 ppm) are substantially higher than in almost all other analyzed samples, where Zr is below 200 ppm (two outliers) and Cr is below 100 ppm (one outlier). The high content of Zr in the Piffkar and Schwarzkopf metapelites agrees with our observation of abundant allanite, zircon and rutile in these lithologies. We interpret their high content of Cr to reflect the absorption of TTE in abundant clay minerals in their sedimentary protoliths, which is also in line with the high degrees of weathering-related chemical alteration in these sediments, as mentioned above.

6 Regional correlation of lithostratigraphic and tectonic units

Many characteristic lithological assemblages can be correlated across several tectonic units (see Fig. 7), giving insights in the paleotectonic evolution of the central

Table 2 Major element bulk-rock chemical composition (in wt%) of various lithologies from the central Tauern Window. In analyses where the volatile content was not determined by separate measurement of H2O and CO2, the cumulative volatile content is given as loss-on-ignition (LOI). All Fe was measured as Fe2O3. Abbreviations of lithostratigraphic units as in Fig. 13

Sample	Lat	Lon	Unit	Lithology	SiO_2	TiO_2	Al_2O_3	Fe_2O_3T	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2	LOI	Summe
F15/17	47.0916	12.9448	Pf	Cld-micaschist	63.00	1.40	20.10	8.38	0.02	0.80	0.12	<0.01	2.34	0.05			4.10	100.30
PG36	47.1152	12.8244	Pf	Cld-phyllite	67.40	1.04	18.00	4.88	<0.01	0.41	0.13	<0.01	4.76	0.06			3.00	99.70
PG60	47.0821	12.8345	Bk	Grt-micaschist	58.80	0.72	18.70	5.94	0.14	2.44	2.90	0.40	4.70	0.06			3.30	99.70
PG61	47.0815	12.8533	Pf	Grt-Cld-phyllite	67.40	0.85	16.10	9.68	0.03	0.61	0.13	<0.01	1.51	0.06			3.20	99.80
PG70	47.0131	12.9236	Sk	Ky-phyllite	76.60	0.99	14.20	1.38	0.02	0.24	0.04	<0.01	1.49	0.02			1.50	99.90
PG75	47.0064	12.9257	Wk	paragneiss	66.30	0.62	14.90	5.01	0.06	1.22	1.08	0.06	6.50	0.14			2.50	99.70
PG89	46.9997	12.9203	Bk	Grt-micaschist	80.50	0.32	7.60	5.56	0.24	1.64	0.41	0.10	1.27	0.10			1.90	99.90
PG109	47.0820	12.8344	Bk	Grt-micaschist	56.90	0.76	19.80	9.07	0.24	2.95	1.26	0.86	3.70	0.03			3.70	99.60
PG117	47.0860	12.8720	Sk	Cld-Ky-micaschist	66.80	1.57	23.10	2.61	0.02	0.49	0.09	<0.01	1.80	0.06			3.70	100.20
PG119	47.0131	12.9236	Sk	Cld-Ky-micaschist	57.20	1.10	29.60	2.98	0.04	0.65	0.18	<0.01	5.05	0.07			3.00	99.80
PG123	47.0226	12.9283	Tr	Grt-micaschist	43.90	0.77	18.60	8.54	0.41	1.89	1.37	0.71	3.39	0.09			20.20	99.80
PG130	47.1121	12.8253	Pf	Cld-micaschist	59.70	1.02	21.40	12.98	0.06	0.90	0.08	<0.01	0.80	0.03			3.30	100.30
PG131	47.1121	12.8253	Pf	Cld-Chl-schist	47.30	0.64	15.30	28.30	0.06	3.26	0.13	<0.01	<0.01	0.06			4.70	99.70
PG136	47.0865	12.7387	Gl	eclogite	43.10	0.92	16.50	9.67	0.25	7.85	9.98	3.60	0.17	0.08			7.50	99.60
PG137	47.0889	12.7343	Gl	Grt-micaschist	79.20	0.33	7.90	4.22	0.08	1.36	1.85	<0.01	1.94	0.05			3.70	100.70
PG139	47.1325	12.8412	Sk	Cld-Ky-micaschist	76.60	1.26	14.20	2.68	0.03	0.58	0.05	<0.01	2.59	<0.01			2.20	100.30
PG141	47.1391	12.8440	Pf	Cld-Ky-micaschist	57.40	1.11	24.10	8.61	0.04	1.27	0.13	<0.01	3.49	0.04			3.90	100.20
PG142	47.1415	12.8528	Pf	Cld-micaschist	67.50	0.82	16.40	6.17	0.04	0.84	0.60	<0.01	4.83	0.05			3.00	100.30
PG151	47.1079	12.8764	Pf	Cld-micaschist	58.90	0.92	22.50	8.83	0.03	1.18	0.18	<0.01	4.00	0.04			3.30	99.90
PG152	47.1080	12.8769	Tr	Bt-gneiss	73.90	0.34	13.70	2.82	0.05	1.11	0.51	0.71	4.40	0.09			2.10	99.70
PG161	47.1143	12.9265	Bk	Grt-micaschist	59.40	0.52	12.20	5.10	0.23	1.97	8.14	<0.01	2.00	0.09			10.20	99.90
PG226	47.1690	12.8513	Pf	Cld-phyllite	59.50	1.07	20.80	12.38	0.07	0.86	0.06	<0.01	1.20	0.07	3.91	<0.01		99.90
PG228	47.1680	12.8582	Sk	Cld-phyllite	57.60	1.02	23.40	8.88	0.07	1.68	0.11	0.01	2.78	0.09	4.12	<0.01		99.70
PG231	47.1456	12.8527	Pf	Cld-micaschist	64.90	1.01	17.90	7.44	<0.01	0.46	0.06	0.05	4.87	0.03	3.04	0.04		99.80
PG237	47.0969	12.8042	Pf	Cld-phyllite	73.30	0.76	14.40	3.48	0.01	0.95	0.08	0.07	3.72	0.04	2.78	0.20		99.80
PG265	47.0964	12.8489	Pf	Cld-micaschist	65.90	0.91	18.30	7.30	<0.01	0.69	0.05	<0.01	3.95	0.03	2.57	0.05		99.70
PG286	47.0633	12.7652	Gl	Grt-micaschist	48.60	1.33	18.70	10.80	0.36	2.38	7.89	0.09	3.72	0.18	2.79	2.60		99.40
PG288	47.0620	12.7690	Gl	Grt-micaschist	71.60	0.51	12.40	5.15	0.29	1.58	2.29	0.11	2.09	0.07	2.55	1.04		99.70

Table 2 (continued)

Sample	Lat	Lon	Unit	Lithology	SiO_2	TiO_2	Al_2O_3	Fe_2O_3T	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2	LOI	Summe
PG299	47.1317	12.7561	Gl	Grt-micaschist	88.70	0.20	4.60	2.30	0.26	1.02	0.98	<0.01	0.46	0.05	0.97	0.63		100.10
PG304	47.1064	12.7881	Gl	Grt-micaschist	72.10	0.57	12.20	4.22	0.07	1.12	0.55	0.47	2.26	0.09	2.70	3.38		99.70
PG306	47.0633	12.7652	Gl	Grt-micaschist	58.90	0.65	17.70	7.13	0.12	2.53	2.41	0.08	4.99	0.05	3.14	1.56		99.20

Table 3 Trace element bulk-rock chemical composition (in ppm) of various lithologies from the central Tauern Window obtained by XRF analysis. Abbreviations of lithostratigraphic units as in Fig. 13

Sample	Unit	Lithology	Ba	Cr	Ga	Nb	Ni	Rb	Sr	V	Y	Zn	Zr
F15/17	Pf	Cld-micaschist	561	212	24	35	52	191	56	126	33	22	268
PG36	Pf	Cld-phyllite	413	118	21	30	24	281	87	99	25	20	285
PG60	Bk	Grt-micaschist	488	84	23	15	62	199	96	138	27	93	125
PG61	Pf	Cld-phyllite	121	98	20	20	32	90	20	88	74	68	316
PG70	Sk	Ky-phyllite	238	86	17	21	< 10	106	54	80	30	< 10	502
PG75	Wk	paragneiss	268	28	21	17	13	316	106	37	42	80	286
PG89	Bk	Grt-micaschist	240	79	11	< 10	62	61	41	97	20	57	74
PG109	Bk	Grt-micaschist	392	92	24	19	79	155	85	157	17	139	129
PG117	Sk	Cld-Ky-micaschist	215	168	31	37	48	117	93	126	54	< 10	610
PG119	Sk	Cld-Ky-micaschist	783	154	42	37	45	324	144	161	61	< 10	217
PG123	Tr	Grt-micaschist	631	91	24	15	44	139	152	104	38	58	96
PG130	Pf	Cld-micaschist	109	147	28	28	88	67	41	115	32	98	237
PG131	Pf	Cld-Chl-schist	< 10	102	27	23	90	29	16	68	39	170	167
PG136	Gl	eclogite	60	236	15	15	106	23	265	128	25	57	50
PG137	Gl	Grt-micaschist	235	84	14	20	72	108	45	75	20	65	36
PG139	Sk	Cld-Ky-micaschist	367	126	22	38	32	172	97	58	32	16	622
PG141	Pf	Cld-Ky-micaschist	634	142	31	29	35	255	74	133	42	20	211
PG142	Pf	Cld-micaschist	1060	127	22	21	73	329	138	76	49	14	191
PG151	Pf	Cld-micaschist	1499	149	36	28	67	265	102	129	36	35	133
PG152	Tr	Bt-gneiss	561	23	25	20	< 10	158	77	14	44	22	280
PG161	Bk	Grt-micaschist	366	92	18	16	77	109	206	109	29	102	78
PG226	Sk	Grt-micaschist	140	122	22	25	31	72	38	111	56	55	344
PG228	Sk	Grt-micaschist	238	108	30	20	41	183	53	118	69	51	254
PG231	Pf	Grt-micaschist	439	116	23	25	51	271	71	102	30	23	271
PG237	Pf	Grt-micaschist	338	96	16	12	17	186	25	79	24	24	318
PG265	Pf	Grt-micaschist	669	105	22	21	55	245	44	93	35	42	317
PG286	Gl	Grt-micaschist	381	304	16	< 10	143	139	135	189	35	121	112
PG288	Gl	Grt-micaschist	244	73	13	10	76	100	108	117	24	93	80
PG299	Gl	Grt-micaschist	96	35	< 10	< 10	32	29	15	47	13	67	31
PG304	Gl	Grt-micaschist	445	92	15	11	25	112	166	103	18	87	162
PG306	Gl	Grt-micaschist	467	78	20	11	103	177	38	142	34	137	105

Tauern Window prior to Alpine nappe stacking and folding. In the following, a summary of the main stages of the post-Variscan tectonic evolution of this region is given based on the syntheses of Kurz et al. (1998), Kurz (2006) and Schmid et al. (2013) as well as findings described above.

6.1 Permo-Triassic sedimentation on the eroded Variscan Basement

The Variscan orogeny in the Alpine region was followed by almost complete denudation of this orogen (Veselá et al., 2011) and the sedimentation of a Germano-type Permo-Triassic sequence. The succession started in the Permian with the sedimentation of large amounts of rather coarse-grained siliciclastic material in isolated, graben-like intramontane basins that cut Variscan structures in the eroding basement. These are most prominently found in parts of the Western Tauern Window (e.g., "Porphyrmaterialschiefer Series"; Thiele, 1970, Veselá et al., 2008). During the lower Triassic, these separate basins connected to form a large, continuous basin (Franz et al., 2021) in which more mature and fine-grained siliciclastic material was deposited.

In the central Tauern Window, the Permian to Lower Triassic period of erosion is evidenced by siliciclastic metasediments of the Wustkogel Formation. These rocks are fairly abundant in the Rote Wand Nappe (Fig. 7), but also occur in the Sonnblick-Romate Nappe, for example in the lower Kruml valley (western flank of Hüttwinkl Valley). This phase of erosion of the Variscan basement is also witnessed by the systematic changes in chemical composition of the Variscan basement (exemplified by the Zentralgneis) to its weathering products (exemplified by the Wustkogel Formation): The Wustkogel paragneiss is enriched in K2O and depleted in Na2O and CaO relative to the Zentralgneis (see above, Fig. 13a), which is mainly caused by weathering-related decomposition of feldspars.

As in the rest of central Europe, Permian Rotliegend sediments are largely restricted to local intramontane grabens (e.g., Saar-Nahe basin; Henk, 1993), whereas lower Triassic Buntsandstein deposits also cover the basement exposed on the horsts. During the lower Triassic, the former Variscan orogen was largely denuded and a large peneplain had formed (Veselá et al., 2011) that reached from northern Germany to the Alpine region (Ziegler, 1988).

Denudation of the Variscan orogen was superseded by a northward marine transgression of the westernmost branch of the Neotethys ocean (locally called Meliata) in Middle to Late Triassic time that resulted in the formation of a shallow epicontinental sea ("Muschelkalkmeer"), as evidenced by the lagoonal carbonates and evaporites of the Seidlwinkl Formation. In the Tauern Window, these deposits are thickest in the Rote Wand Nappe. Thinner successions exist in the Trögereck and Romate nappes, as well as in other Subpenninic nappes of the eastern and western Tauern Window (e.g., Kurz et al., 1998; Schmid et al., 2013).

Regression of Neotethys during the Late Triassic gave way to the deposition of the siliciclastic rocks of the Piffkar and Schwarzkopf formations. This assemblage is typical of the Rote Wand Nappe in the central Tauern Window and is also found in other parts of the Modereck nappe system, e.g., in the Wolfendorn Nappe (Lammerer, 1986) and Neves areas in the southwestern Tauern Window, as well as in the Mallnitz Synform (Favaro & Schuster, 2012). These formations also occur in the other Subpenninic nappes of the Tauern Window, but are usually sparse. A strikingly similar high-pressure metamorphic succession exists in the Mesozoic cover of the Adula Nappe (Cavargna-Sani et al., 2014), which includes Lower and Middle Triassic deposits.

In terms of their bulk rock major and trace element composition (details in Chap. 5; Tables 2 and 3; Fig. 13), Piffkar and Schwarzkopf formation metapelites are quite similar. This indicates broadly continuous sedimentation of similar, clay-rich clastic material. At the same time, the Piffkar and Schwarzkopf metapelite geochemistry is clearly distinct from other clastic metasediments in the central Tauern Window and the potential source rocks (eroding European basement, e.g. Zentralgneis) of the sediments. The marked geochemical (and sedimentological) differences of the Piffkar and Schwarzkopf metapelites to their stratigraphic hanging wall, the Brennkogel Formation, indicates a pronounced reorganization of the sedimentary system in terms of depositional environment and/or provenance in the period between the deposition of the early Jurassic Schwarzkopf Formation and the younger Brennkogel Formation. Assuming an early Cretaceous age of the Brennkogel Formation (Schmid et al., 2013), this shift probably occurred during a phase of erosion or non-deposition in the Jurassic.

Potentially, the Piffkar and Schwarzkopf formations can be correlated with similar, but non- or low-grade metamorphic successions elsewhere in the Alps and central Europe, as attempted, e.g., by Cornelius and Clar (1939), Frasl & Frank (1964), Pestal (2008) and Schmid et al. (2013). The Piffkar Formation represents a local variety of the Quarten Formation ("Quartenschiefer") in the Helvetides of the Swiss Alps, which corresponds to the upper part of the Germanic Keuper in southern Germany ("Stubensandstein" or "Vindelician Keuper"; Frey 1968). These deposits were formed by prograding deltas that transported clastic sediment from northern Europe and the Bohemian Massif towards southern Germany and the central Alpine region (Wurster, 1968). Interestingly, equivalent deposits are found in some of the Lower Austroalpine nappes, for example in the Semmering Nappe ("Bunte Keuper", Bauer, 1967) and to a lesser extent in the Reckner (Tollmann, 1977) and Err-Bernina nappes. In these units, the Norian deposits contain predominantly evaporite layers, which indicates a transitional position between the terrestrial Germanic Keuper facies in the north and the marine Alpine facies in the south (e.g., Mandl, 2000) that is found in most of the Austroalpine nappes.

The Schwarzkopf Formation was interpreted as a Lower Jurassic deposit by Pestal et al., (2009). It might represent a deltaic, carbonate-free counterpart to the more distal, shallow-marine, organic- and clay-rich deposits of Lower Jurassic age that are frequent in the Helvetic Nappes of the central and eastern Alps. Examples are the upper part of the Prodkamm Formation of the eastern Helvetic Nappes in Switzerland (Trümpy, 1949) and similar deposits in the Mesozoic cover of the Gotthard Massif (basal part of Stgir Formation; Baumer et al., 1961) or the lowermost parts of the Gresten Formation at the northern front of the Eastern Alps (Frisch, 1975b).

In summary, the Piffkar and Schwarzkopf formations likely represent Late Triassic (Norian-Rhaetian) and possibly Early Jurassic (Hettangian?) distal delta sediments, respectively, that were deposited on the southern margin of the European continent towards the western branch of the Neotethys Ocean. Intense chemical weathering of the strata is indicated by our bulk-rock chemical data (details above). The large amount of organic matter in the Schwarzkopf formation potentially shows a shift to oxygen-poor conditions in the depositional environment during the earliest Jurassic.

6.2 Jurassic rifting and opening of the Alpine Tethys

The Subpenninic units of the central Tauern Window lack syn-rift sediments that would possibly be related to Early to Middle-Jurassic rifting and opening of the Alpine Tethys. Instead, their stratigraphic record is characterized by a major hiatus caused by erosion (and maybe non-deposition) that falls in this time frame (e.g., Schmid et al., 2013, their Fig. 2; our Fig. 7). This unconformity is interpreted to reflect the erosion of pre- and potentially syn-rift strata. Such unconformities are commonly explained by isostatically induced syn-rift uplift and erosion of parts of the rift shoulders due to asymmetric rifting (e.g., Wernicke, 1985). On the other hand, some authors argued that Lower Jurassic syn-rift deposits may possibly be present in the lower parts of the Brennkogel Formation (e.g., Cornelius & Clar, 1935; Frasl & Frank, 1964), a view that cannot be excluded on the basis of currently available data. However, as explained in more detail below, we infer an Early Cretaceous age for the Brennkogel Formation and the Wörth Formation (based on correlation with the Kaserer Formation). Therefore, the major unconformity at the base of the Brennkogel Formation is interpreted to be no younger than the presumably Early Cretaceous age of its basal part. The only sediments in the central Tauern Window that unequivocally record Early to Middle Jurassic rifting and opening of the Alpine Tethys are the deep-marine sediments deposited on the ophiolitic basement of the Matrei Zone, described by Koller and Pestal (2003). These authors correlate a succession of ophicarbonate breccia and radiolarite immediately overlying serpentinized lherzolite with an identical, clearly Jurassic assemblage in the Swiss Alps (e.g., Oberhalbstein and Engadine areas of Eastern Switzerland, e.g., Desmurs et al., 2001). The recent discovery of a Late Jurassic (Kimmeridgian) gabbro within the Bünderschiefer-type assemblage of a part of the Glockner Nappe s.str. (Gleißner et al., 2021) south of the Eclogite Zone indicates that ocean spreading in the eastern part of Alpine Tethys represented by the Glockner nappe system was already underway in Kimmeridgian time. This date therefore serves as a minimum age estimate for Jurassic rifting in the Eastern Alpine region. Furthermore, this age of magmatism in the Glockner Nappe s.str. is within the spread of ages found for mafic intrusions related to the opening of the Piemont-Liguria ocean in the central and western Alps (Gleißner et al., 2021).

In contrast to the Europe-derived Subpenninic units within the Tauern Window, sediments deposited on the southern, Adriatic margin of the Alpine Tethys contain abundant Jurassic rift breccias. For example, the lower Austroalpine nappes in the perimeter of the Tauern Window contain the Early to Middle Jurassic "Tarntal Breccia" of the Reckner and Hippold nappes (e.g., Tollmann, 1977; Häusler, 1988). These polymict breccias were deposited as submarine mass flows and contain diverse clasts of sedimentary and basement rocks derived from the Adriatic shelf and ophiolite detritus. They are covered by Middle to Late Jurassic radiolarites that represent the oldest post-rift sediments and record pronounced post-rift thermal subsidence (Häusler, 1988).

6.3 Late Jurassic carbonate shelf

Jurassic rifting antecedent to the opening of Alpine Tethys was followed by the formation of relatively deep-marine carbonate deposits on the outer shelf of the European continental margin in Late Jurassic times (Klebelsberg, 1940; Kießling, 1992; Höfer & Tichy, 2005). These are probably the result of post-rift thermal subsidence of the newly-formed margins. This phase is manifested by the laterally equivalent Silbereck, Angertal and Hochstegen marbles that are fairly widespread in several European-derived tectonic units of the western and eastern Tauern Window.

The Hochstegen Marble was dated upper Oxfordian to lower Tithonian based on radiolaria and an ammonite finding (Murtschlechner, 1956; Kießling & Zeiss, 1992). It is concordantly overlain by clastic sediments of the Kaserer Formation (Thiele, 1970; Lammerer, 1986). Based on the diversity of fauna (radiolarites and sponge spicules) in the Hochstegen Marble, Kießling and Zeiss (1992) inferred progressively deeper conditions (neritic to upper bathyal) during the deposition of the Hochstegen Marble on the deep, distal parts of the subsiding European shelf. A similar depositional environment is likely for the Silbereck Marble (Höfer & Tichy, 2005).

Given their age and lithology, the Hochstegen and Silbereck deposits are broadly analogous to Oxfordian to Lower Cretaceous cherty limestones of the Gresten Zone found as slices at the northern margin of the Eastern Alps (Frisch, 1975b) and originally deposited at the southern margin of the Bohemian Massif. Close similarities to the Late Jurassic Quinten Formation of the Swiss Helvetic Alps were noted byLammerer (1986).

Somewhat similar carbonate deposits are also known from the Penninic Units of the Tauern Window: The Klammkalk is a prominent part of the Nordrahmenzone in the northeastern Tauern Window. It was presumably deposited on the slope of the Adriatic margin (Frisch et al., 1987). Even though datable fossils have not been found so far in the Klammkalk, Thiele (1980) proposed a

Late Jurassic to Early Cretaceous sedimentation age similar to that of the Hochstegen Marble.

The Late Jurassic (upper Oxfordian to lower Tithonian) carbonate shelf successions of the Tauern Window (Hochstegen Marble) located on the European continental margin indicate deepening of the depositional environment that was contemporaneous with basaltic magmatism (Kimmeridgian) in the ocean basin of the Glockner nappe system. This likely reflects thermal subsidence affecting the European margin after initial breakup, while spreading within the oceanic basin of Alpine Tethys was ongoing.

Given that post-rift thermal subsidence usually affects large areas of continental margins (e.g., Wernicke, 1985), it is not surprising that these Late Jurassic post-rift carbonate deposits were widespread on both margins of the Alpine Tethys. Moreover, it is striking that the Modereck nappe system is basically void of such deposits. Late Jurassic marbles are clearly missing in the stratigraphy of the Rote Wand Nappe. In the Trögereck Nappe, the Bündnerschiefer succession contains few lenses of marble that may be temporal equivalents to the Late Jurassic Silbereck Marble (Griesmeier, 2021). Their lens-like appearance in map view and their stratigraphic context strongly suggest that they are olistoliths that were redeposited in post-Jurassic times. The absence of these Late Jurassic post-rift deposits in some of the European margin units can be explained in two ways: Either they were never deposited in parts of the margin to begin with, or they were selectively eroded. The latter is proposed by Schmid et al. (2013), who explain the erosion with rift shoulder uplift related to a Cretaceous rifting event during opening of the Valais Ocean. In any case, the lack of Late Jurassic carbonate deposits highlights the special tectonic and paleogeographic position of the Modereck nappe system in Cretaceous time.

6.4 Lower Cretaceous syn- to post-rift deposits

The Tauern Window comprises fairly large amounts of arkosic Bündnerschiefer-type sediments in several Europe-derived tectonic units. The protolith of these successions was a pelagic marl as background sediment that received input of feldspar-rich sandy detritus. Formation of such arkosic sediments, i.e., compositionally immature siliciclastic sands, requires the uplift and erosion of continental basement rocks and rapid redeposition of the detritus, otherwise the feldspars will largely weather to clay minerals (e.g., Dickinson, 1985). Therefore, these sediments document substantial basement uplift in the European margin during the time frame of their deposition. In our view, this phase of margin instability reflects an Early Cretaceous (see below for age estimate) rifting phase, during which parts of the margin were uplifted, so that continental basement was exposed on the surface, eroded and resedimented as arkosic sediment in neighboring submarine basins.

In the central Tauern Window, large masses of arkose-rich dark (i.e., organic-rich) Bündnerschiefer-type deposits are most prominently found in the Trögereck Nappe (Sect. 4.2.1) and the Eclogite Zone (Sect. 4.2.2). In our view, a more distal equivalent to these deposits is found in the Wörth Formation of the Sonnblick-Romate Nappe (Sect. 4.1.2) in the form of dark phyllites that contain fine-grained breccia-horizons. So far, all these successions were not directly dated by radiometric or paleontological methods. Therefore, our assignment of an Early Cretaceous age of these units relies on lithostratigraphic correlation with the almost identical Kaserer Formation of the Wolfendorn and Ahorn nappes in the western Tauern Window. There, the Hochstegen Marble is concordantly overlain by and grades up into (e.g., Höck, 1969; Thiele, 1970, 1974) a succession of partly calcareous dark phyllites, metaarkoses, quartzites and breccias that together form the Kaserer Formation (Thiele, 1970; Lammerer, 1986). It is usually assigned an Early Cretaceous age since it stratigraphically overlies the Upper Jurassic Hochstegen Formation (Thiele, 1970; Lammerer, 1986; for a differing view see Veselá and Lammerer, 2008). An analogous situation is reported in the eastern Tauern Window (Pestal et al., 2009 after Exner, 1983).

The arkosic dark Bündnerschiefer-type successions (types 2 and 3 of Sect. 3.3) are typically associated with mafic magmatism that appears to be largely contemporaneous with the deposition of the sediments. Höck and Miller (1987) found that these metabasites (their "Fusch metabasics", including metabasites from the Eclogite Zone and the Kaserer Formation)are enriched in incompatible elements, indicating a high degree of partial melting of an enriched mantle (clinopyroxene-bearing lherzolite). These authors envision a rift-related formation of these magmatites based on geochemical arguments (according to Pearce & Cann, 1973), potentially including those of the Wörth Formation.

A lithological association very similar to the Bündnerschiefer-type assemblage of the Wörth Formation (and to a lesser extent to the more proximal Trögereck Nappe, the Eclogite Zone and the Kaserer Formation) is the Complexe Antéflysch Formation in the Internal Valais Unit of the Western Alps (e.g., Loprieno et al., 2011). The Early Cretaceous Complexe Antéflysch Formation comprises black shales with variegated, clastic-rich and carbonate-bearing layers that were intruded by mafic sills and dikes. By analogy, the arkosic Bündnerschiefer-type sequences of the Tauern Window can be interpreted as syn-rift sedimentary successions formed at the European passive margin. The detritus derived from rapid erosion of both Mesozoic sediments and Variscan basement, followed by sedimentation of the immature erosion products (mainly carbonate breccias and arkoses) in a marine environment (carbonates) with rift-related mafic magmatism. In the Bündnerschiefer-type successions of the Trögereck Nappe, the Eclogite Zone and the Kaserer Formation, arkosic rocks are very abundant, which indicates proximity to areas of active basement uplift. In contrast, the Wörth Formation contains less frequent and more fine-grained arkosic layers and more dark phyllites, which therefore probably represents a more distal setting to the areas with basement exposure.

As noted above, testimony of an Early Cretaceous rifting stage is probably recorded in the Rote Wand Nappe (Sect. 4.2.3) in at least the lower part of the Brennkogel Formation. These deposits are characterized by coarse-grained carbonatic detritus (escarpment breccias?) that were shed into a marine basin with organic-rich, marly background sedimentation. This background sediment now forms the main mass of the metamorphic Brennkogel Formation in the form of dark-brown carbonatic micaschist. Since parts of these rocks are lithologically very similar to the metapelites of the Kaserer Formation in the western Tauern Window, both formations are usually taken as lateral equivalents (e.g., Pestal et al., 2009). On the basis of this lithostratigraphic correlation an Early Cretaceous age of the Brennkogel Formation appears plausible. However, it must be stressed that both formations show different sedimentological facies, especially concerning the coarse-grained clastic deposits: Arkosic layers are very common in the Kaserer Formation, but absent in the Brennkogel Formation, which in contrast typically appears as rhythmic intercalation of quartzite banks (turbidites) and carbonaceous micaschist (Bündnerschiefer-type 4 according our nomenclature in Sect. 3.3). Therefore, both formations have a clearly distinct sandstone provenance: No sandy detritus of freshly-eroded continental basement was able to reach the area where the Brennkogel Formation was deposited.

The Brennkogel Formation, as found in its type locality in the central Tauern Window, is remarkably similar to what is reported for the lithostratigraphy of the external Valais Units in the Western Alps, as reported, e.g., by Loprieno et al. (2011). Their Late Jurassic to Early Cretaceous syn-rift sequence (Pyramides Calcaires Formation of the Brèches du Grand Fond Group) consists of rhythmically-bedded brownish calcschist, black shales, calcareous quartz-sandstones and layers of fine conglomerates with Middle Triassic dolomite clasts that are clearly analogous to at least the lower part of the Brennkogel Formation. In contrast, the Liassic syn-rift sequence of the external Valais Units in the Western Alps (Dent d'Arpire Formation) described by Loprieno et al. (2011), entirely consists of polymict conglomerates and therefore differs from the typical rock assemblage of the lower part of the Brennkogel Formation.

The post-rift sequence of the external Valais Units contains, among others, the Marmontains Formation, which consists of alternating carbonate-free black shales and quartz arenites (Loprieno et al., 2011). This succession is clearly analogous to the Early Cretaceous "Gault-type" deposits in the Central Alps (e.g., Lemoine, 2003) and resembles the upper part of the Brennkogel Formation. An exception to this is the lack of carbonates, which, however, can be easily explained by deposition below and above the carbonate compensation depth. Therefore, in analogy to the Western and Central Alps, the Brennkogel Formation probably represents the transition from an Early Cretaceous syn-rift to post-rift setting.

In the Rote Wand Nappe, where the Hochstegen Marble as a clear age marker is missing, an alternative interpretation of the age of the Brennkogel Formation deposits is possible: There, the upper part of the Brennkogel deposits with post-rift characteristics and intercalations of calcareous micaschist may represent a distal, Early Cretaceous (Aptian to Albian; Lemoine, 2003) variety of the upper parts of the Kaserer Formation. In contrast, the lower part of the Brennkogel deposits with syn-rift characteristics can be interpreted as Early Jurassic rift deposits. This problem cannot be resolved with the data currently available, but in light of the discussion above, we favor a Cretaceous age of the entire Brennkogel-like deposits.

The aforementioned differences in sedimentary composition and grain size in the tectonic units point towards systematic differences in the depositional environments and tectonic settings: The sediment successions dominated by Bündnerschiefer-type 3 metasediments of the Trögereck Nappe and Eclogite Zone and similar deposits of the Kaserer Formation indicate deposition in the proximity of faults affecting basement rocks of the Venediger nappe system. The organic-rich metapelites of the Wörth Formation that contain less abundant and more fine-grained basement detritus can be interpreted as distal equivalent to the above, deposited in a deep-water, oxygen-starved part of the rift basin that was reached by only little clastic detritus.

In contrast, the coarse-grained carbonatic clastics of the Brennkogel Formation indicate proximity to faults in a carbonate-dominated hinterland, most likely the Seidlwinkl Formation of the Rote Wand Nappe.

6.5 Jurassic and Cretaceous post-rift sedimentation and spreading

Sediments deposited after either of the two Alpine Tethys rifting events in Middle Jurassic and Early Cretaceous times, i.e., post-rift sediments, are found in the

Penninic nappes of the central Tauern Window mainly in the form of the Bündnerschiefer-type 1 and 2 assemblages. They are represented by large volumes of calcareous micaschist that often contain intercalations of dark phyllite and metabasite with MORB signature. They are usually barren of fossils and therefore lack a precise depositional age. However, regional correlation with similar assemblages in the entire Alpine chain indicates largely Late Jurassic to Cretaceous ages of these rocks (Lemoine, 2003). This notion is consistent with sparse biostratigraphic data: Höck et al. (2006) determined an Early Cretaceous age (140–110 Ma) for the Drei-Brüder Formation (location in Fig. 2), a deep-sea fan carbonate sandstone deposit that stratigraphically overlies the Bündnerschiefer-type succession of the northern Rauris Nappe and therefore forms the uppermost part of the Rauris Nappe. This unit records long-lived (ca. 30 Ma), steady deposition of calcarenites, externally of the shelf slope in a fairly calm deep sea environment, which we interpret to indicate a post-rift setting, potentially in vicinity to the Adriatic continental margin. Reitz et al. (1990) also obtained Early Cretaceous ages for an olistostrome-rich flysch assemblage in the Nordrahmenzone. The upper part of the Brennkogel Formation, which is characterized by deposition of rhythmic, mature quartz turbidites and pelitic marly background sedimentation, may also be interpreted as an Early Cretaceous post-rift sequence. In contrast, the recent discovery of a Late Jurassic gabbro within calcareous micaschists of the Glockner Nappe s.str. (Gleißner et al., 2021) makes it very likely that at least parts of these Bündnerschiefer-type sediments were deposited already in the Late Jurassic.

It is important to note that the age of these highly deformed oceanic metasediments only gives minimum estimates for the formation of the oceanic lithosphere on which they were deposited. The precise age of oceanic lithosphere formation is ideally obtained from isotopic crystallization ages of magmatic minerals in oceanic basement rocks (i.e., basalt and gabbro), or from biostratigraphic ages of deposits in direct stratigraphic contact with oceanic basement. The only isotopic age so far is the Late Jurassic intrusion age of a metagabbro from the southern Glockner Nappe s.str. published by Gleißner et al. (2021). The paucity of such data is problematic when trying to correlate the Penninic units in the Tauern Window with those in the Central and Western Alps, a topic of great controversy, as discussed above (e.g., Frisch, 1980; Trümpy, 1992; Kurz, 2006; Schmid et al., 2013).

7 The paleogeography of the rifted European margin

7.1 Reconstruction of the margin geometry

In the following, we will try to reconstruct the geometry of the rifted European margin by comparing our findings regarding the tectono-sedimentary evolution recorded within the individual tectonic units with regularities observed in studies on modern examples of rifted margins (Fig. 14a; e.g., Tugend et al., 2014; Osmundsen and Péron-Pinvidic, 2018; Nirrengarten et al., 2020; Zastrozhnov et al., 2020). These regularities define characteristic paleogeographic domains in a rifted margin setting. As summarized by Manatschal et al. (2022), these domains can also be recognized on well-exposed fossil examples of rifted margins. We used their criteria for distinguishing different margin domains in our reconstruction. Structures (e.g., faults, basin geometries, etc.) of the rifting stage could not be clearly recognized so far in the central Tauern Window, given that they were potentially obscured by the intense overprint during subduction- and collision-related processes. Therefore, we focus our argumentation on (1) the nature of the basement, (2) the composition and depositional environment of the syn-rift deposits, (3) observed changes in sedimentary facies between successions of comparable age, (4) relations of basement and pre-rift strata to its cover and (5) the nature of magmatic rocks potentially present in a rock succession. Applying these criteria to the tectonic units of the central Tauern Window, four distinct paleogeographic margin domains ("building blocks" (BB) in the scheme of Manatschal et al., 2022) of the rifted margin can be identified. These are (Figs. 7 and 14): (1) inner (or proximal/stretching) domain (BB1), (2) hyperextended domain (BB4 or BB5), (3) outer margin high ("residual keystone" domain) (BB3) and (4) oceanic domain (BB7). This structuring of the European margin is mainly the result of the Early Cretaceous rifting phase.

The inner (or proximal/stretching) domain (BB1) is characterized by largely preserved pre-rift cover on upper crustal basement, which is overlain by variable amounts of syn-rift sediments bound to steep normal faults. The sequence is overlain by only little post-rift sediment. In the Tauern Window, this domain is potentially represented by some parts of the Venediger nappe system that contain abundant deposits of the Kaserer Formation (e.g., Tux and Ahorn nappes of the western Tauern Window) and the Wolfendorn Nappe.

The hyperextended domain (BB4/5) is characterized by a substantial rift basin filled with a thick syn-rift sequence deposited directly on upper or lower crustal basement; pre-rift sediments are tectonically removed by a low-angle normal fault ("necking fault"). This fault also facilitates uplift and erosion of the basement (and

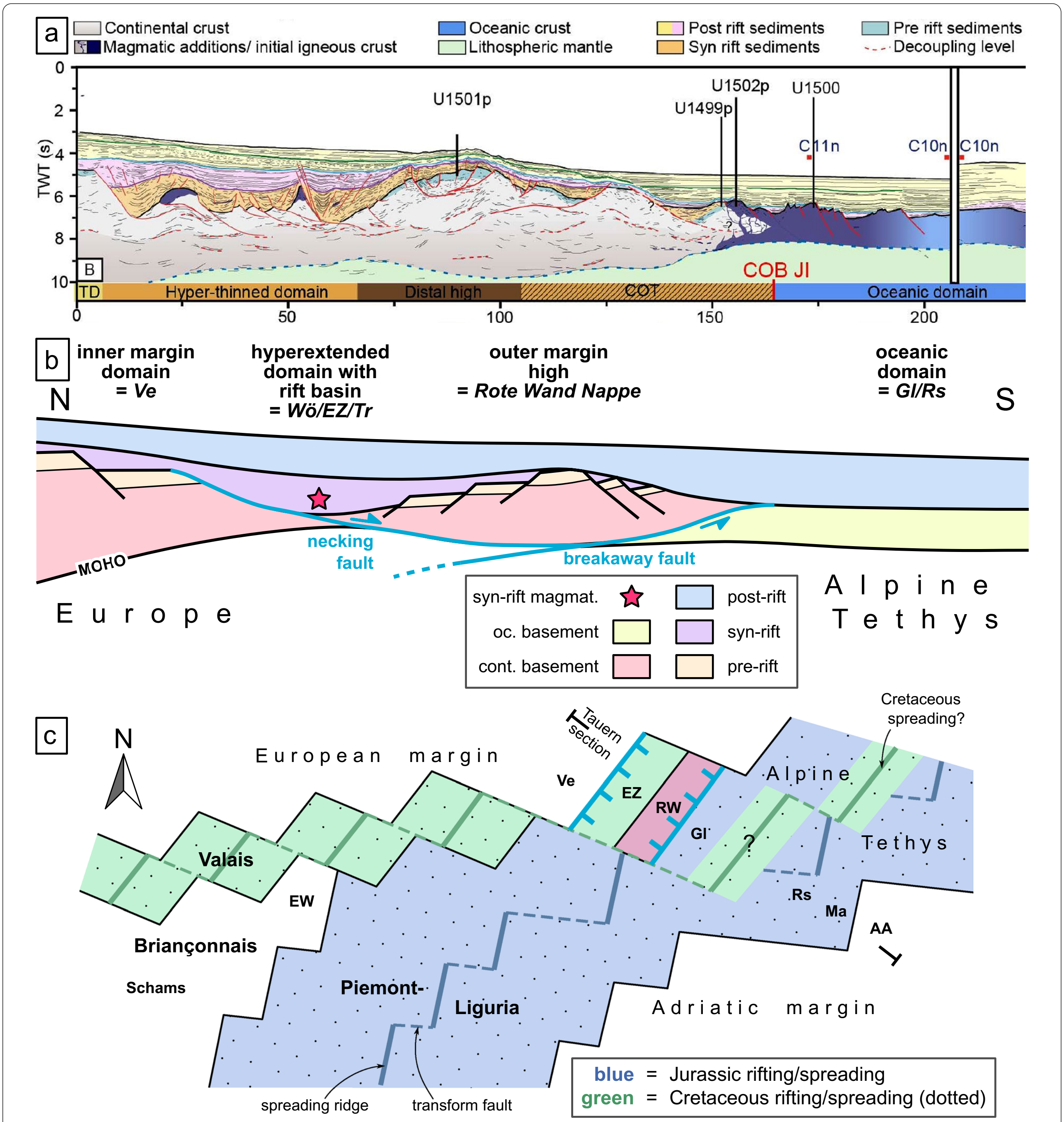

Fig. 14 Comparison of a present-day hyper-extended margin with outer margin high (**a**; Nirrengarten et al., 2020) and our reconstruction of the European margin of Alpine Tethys (**b**) based on lithostratigraphic observations in the central Tauern Window. Note similarities between thickness of the continental basement and distribution and nature of sediments and magmatic rocks. **c** shows a speculative map-view reconstruction of the region for Late Cretaceous time, including the potential paleogeographic origins of tectonic units of the central Tauern Window (inspired by Weissert & Bernoulli, 1985). Areas with new oceanic crust are dotted. *AA* = Austroalpine nappes, *EW* Engadin Window, *EZ* Eclogite Zone + Trögereck Nappe + Wörth Formation, *Gl* Glockner Nappe s.str, *Ma* Matrei Zone, *Rs* Rauris Nappe, *RW* Rote Wand Nappe, *Ve* Venediger nappe system

potentially relics of pre-rift strata) and rapid redeposition of the detritus in the newly-formed basin, which results in relatively coarse-grained immature siliciclastic sediments. The intense crustal thinning favors quick subsidence and generally deep-water conditions. In the central Tauern Window, this hyperextended domain in the form of a large rift basin is represented by the Eclogite Zone and the Trögereck Nappe, and in addition their more distal equivalent, the Wörth Formation of the Sonnblick-Romate Nappe (Fig. 7).

The domain of the outer margin high (or "residual keystone" domain; BB3) is characterized by largely-preserved pre-rift strata overlain by post-rift sediments that resemble those in the adjacent ocean basin. Syn-rift sediments are largely sparse and restricted to small rift basins at minor steep normal faults with modest throw. Therefore, the syn-rift sediments mainly consist of detritus derived from eroded pre-rift strata and little or no basement detritus. In the central Tauern Window, this domain is represented by the Rote Wand Nappe : It comprises (see Fig. 7 and Sect. 4.2.3) a well-preserved pre-rift sedimentary succession, locally overlain by little syn-rift deposits of Early Cretaceous age that are characterized by carbonate breccias and totally lacking arkosic rocks (i.e., detritus from pre-rift strata but not from continental basement), which grades upwards into a rhythmic flysch-like succession with layers of calcareous micaschist (identical to those from the oceanic Glockner nappe system) that we interpret as post-rift deposit (details in Sect. 6.5). The generalized features of outer margin highs, as derived from the fossil rifted Adriatic margin in the central Alps (Manatschal et al., 2022), compare well with modern-day examples that are documented from several passive margins all around the globe, e.g., in western Norway (Osmundsen and Péron-Pinvidic, 2018), the Bay of Biscay (Tugend et al., 2014) and the South China Sea (Lei et al., 2020). In the ocean-continent transition in the South China Sea investigated by Nirrengarten et al. (2020), a large outer margin high was repeatedly drilled and seismically imaged, revealing a margin-parallel ridge in the bathymetry that comprises continental basement with a preserved pre-rift cover sequence. Syn-rift sediments on the ridge are relatively thin and locally missing. Marine post-rift deposits are similar to sediments draped on the oceanic basement. In the hyperextended domain that separates the outer margin high from the proximal part of the margin, a thick syn-rift sequence directly overlies strongly thinned continental basement, whereas pre-rift sediments are entirely missing due to normal faulting and erosion. Instead, and in contrast to the outer margin high, this rift basin contains several rift-related intrusions.

The oceanic domain (BB7) is characterized by deep-sea sediments (fine-grained marl, clay or radiolarian ooze) deposited on exhumed mantle rocks (serpentinite) or mafic magmatites (mainly MORB). In the Tauern Window, this domain is represented by the Glockner nappe system and the Matrei Zone: Both comprise (Fig. 7 and Sect. 4.3) a clearly oceanic basement with serpentinite and MORB-type metabasite which are overlain by metamarls (calcareous micaschist). In addition, the Matrei Zone also contains some meta-radiolarite.

The simplest kinematic model of accretion in a subduction setting is in-sequence foreland-propagation of thrusting. This means that material is progressively accreted to the base of the upper plate—or the already-present accretionary complex—as it is transported to the subduction zone with the incoming lower plate. No tectonic unit is inserted out-of-sequence into the nappe stack. If we apply this kinematic model of southward subduction and accretion to the tectonic units of the central Tauern Window, then the stacking order of tectonic units (from top to bottom) corresponds to the map-view succession of paleogeographic domains in the Alpine Tethys and its margins (from south to north). This simple logic tells us how to localize the margin domains identified in the tectonic units (as shown above) relative to each other, which essentially results in a qualitative reconstruction of the geometry of the rifted European margin. The succession of margin domains from south to north as implied by the stacking order of the tectonic units is the following:

- Austroalpine nappes—inner margin domain (BB1) of the Adriatic continental margin.
- Matrei Zone and Nordrahmenzone—oceanic domain (BB7; Alpine Tethys).
- Rauris Nappe—oceanic domain (BB7; Alpine Tethys).
- Glockner Nappe s.str.—oceanic domain (BB7; Alpine Tethys).
- Rote Wand Nappe—outer margin high (BB3) of the European continental margin.
- Eclogite Zone, Trögereck Nappe and Sonnblick-Romate Nappe (with Wörth Formation)—rift basin in the hyperextended domain (BB4/5) of the European continental margin.
- Lower parts of Venediger nappe system—inner margin domain (BB1) of the European continental margin.

Consequentially, we propose that the Rote Wand Nappe originates from a distal margin high that was located at the northern edge of Alpine Tethys (Fig. 14b). This crustal ridge was separated from the proximal part of the European margin by an extensive rift basin, which had formed on a hyperextended portion of the European crust, presumably during Early Cretaceous rifting. This process resulted in intense margin-parallel segmentation of the European continental crust within a wide zone between the main margin and the newly-formed oceanic crust.

This interpretation is similar to the paleogeographic models of the rifted European margin proposed by Kurz (2006). It resembles the model by Ledoux (1984) which is based on observations in the northwestern Tauern Window. In contrast to the models by Kurz et al. (1998) and Schmid et al. (2013), no out-of-sequence thrust is required to explain the emplacement of the Eclogite Zone in its present position in the nappe stack. The main difference with their models is the paleogeographic position of the Eclogite Zone (at the ocean-continent transition) and the interpretation of the Rote Wand Nappe as an outer margin high.

7.2 The lateral continuation of the margin domains

The view of the Rote Wand Nappe as originating as a crustal ridge separated from the proximal part of the European margin raises the question of whether this outer margin high is the eastward continuation of the Briançonnais (Middle Penninic) microcontinent. As already noted by Kurz (2006), the structural setting of the Rote Wand Nappe, which essentially forms a thin basement lamella with sedimentary cover, is similar to several Briançonnais-derived units in the central Alps, e.g., the Tasna Nappe. This would be the case if the main rifting in Early Cretaceous time had occurred in the hyperextended domain between the proximal part of the European margin represented by the Venediger nappe system and the Rote Wand outer margin high, thus making the intervening rift basin (Eclogite Zone, Trögereck Nappe) in this hyperextended domain the eastward continuation of the Valais part of the Alpine Tethys. If the locus of Cretaceous rifting was south of the Rote Wand outer margin high, i.e., within the already existing Jurassic part of Alpine Tethys, the outer margin high cannot be regarded as an equivalent of the Briançonnais microcontinent. It must be noted that the Mesozoic lithostratigraphy in the Rote Wand Nappe has a clear affinity to the European margin, rather than to the Briançonnais. Furthermore, the Wörth Formation, the Eclogite Zone and the Trögereck Nappe, which in our view represent the hyperextended portion of the European margin, are floored by continental basement and not by oceanic lithosphere.

Rifting and opening of the Alpine Tethys was likely occurring in a transform regime (e.g., Weissert & Bernoulli, 1985), which probably resulted in highly-oblique spreading axes relative to the general margin orientation. Recent examples of rifted margins show that transform faults can cause intense margin-parallel segmentation of the rift domains. For example, outer margin highs are typically discontinuous along strike of the margin, because they are abruptly cut by transform faults (or fracture zones; e.g., Tugend et al., 2014; Nirrengarten et al., 2020). Figure 14c shows such a hypothetical scenario of a transform-dominated rifting of the Alpine Tethys. The Rote Wand outer margin high is laterally terminated by transform faults and separated from the main European margin by a large rift basin, which we regard as a non-oceanic branch of the Valais basin. However, crustal extension in the rift basin was less intense than in the Valais ocean basin further west, since break-up was most likely not reached in the rift basin. This might indicate that most of crustal extension due to Cretaceous plate divergence might have been transferred from a position close to the European margin in the west to a position within the existing Jurassic ocean basin in the east, potentially along a set of transform faults. In this scenario, the Rote Wand outer margin high would be the easternmost (known) margin segment that separated from the main European margin by Cretaceous re-rifting. This solution to the question where Cretaceous plate divergence was accommodated east of the Briançonnais microcontinent incorporates elements of both scenarios A and B as presented above in Fig. 4: As in A, Cretaceous spreading within the existing Piemont-Ligurian ocean led to a thin strip of this oceanic crust stranded between Valais and Europe. As in B, a Cretaceous rift basin separated the Rote Wand high from Europe. This suggests that a large portion of Cretaceous extension was accommodated along the European margin. Admittedly, this scenario is difficult to test, given that most parts of the European margin and Alpine Tethyan lithosphere were subducted during later convergence, or are covered by the Austroalpine nappe pile in the Eastern Alps.

The question of the localization of Cretaceous divergence east of the Briançonnais is closely related to the question of whether the Glockner nappe system originates from an oceanic basin that was formed during Jurassic or Cretaceous rifting and spreading, a topic already discussed above and by others (e.g., Kurz, 2005, 2006; Schmid et al., 2004, 2005, 2013). From a lithostratigraphic point of view, the sedimentary succession of the Glockner nappe system is more similar to Valais than to Piemont-Liguria assemblages in the Central and Western Alps, which implies that the Glockner nappe system could also be of Valais origin and therefore of Cretaceous age. However, as pointed out above and by others (Frisch et al., 1987; Kurz, 2005), the sedimentary record is ambiguous in this respect. Moreover, the recently reported Late Jurassic magmatic age of a metagabbro from the Glockner Nappe s.str. (Gleißner et al., 2021) is a strong argument for a Piemont-Liguria origin of at least parts of the

Glockner nappe system. Especially the Rauris Nappe of the Glockner nappe system has similarities to the lower parts of the Matrei Zone (e.g., also contains radiolarites; Frasl & Frank, 1966). The existing biostratigraphic data (Höck et al., 2006) strongly imply that the sediments of the Rauris Nappe below the Drei-Brüder Formation (ca. 110–140 Ma) are entirely older than ca. 140 Ma, which is substantially older than magmatic ages of Valais ophiolites (ca. 93 Ma) in the central Alps (Liati et al., 2003; Liati & Froitzheim, 2006) and also falls outside of the regionally constrained ages for opening of the Valais basin (131−84 Ma; Handy et al., 2010). Therefore, the Rauris Nappe might represent a paleogeographic position in the Jurassic part of Alpine Tethys, potentially located not far from the clearly Piemont-Liguria Matrei Zone.

Late Jurassic to Early Cretaceous rifting is not only documented along the northern margin of Alpine Tethys, but potentially also in the south: Koller and Pestal (2003) proposed that corresponding syn-rift deposits can be found in parts of the Matrei Zone and Lower Austroalpine (Geier Formation of the Reckner Ophiolite) in the Tauern Window. It must be stressed that the existence of such syn-rift deposits would pose a complete anomaly, since nothing similar is known from the Austroalpine or Piemont-Liguria-derived units in the rest of the Alps. If this proposal turns out correct, it would mean that in the section of the Alpine Tethys and its margins, which are now represented by the rock record in the Tauern Window area, extension during Early Cretaceous times may have indeed affected both continental margins. However, the amount of such syn-rift sediments is substantially larger in the Europe- than in the Adria-derived units, which in any case indicates that the main Cretaceous rifting activity was located on the northwestern side of the existing basin. On the other hand, an Early Cretaceous rifting episode on the southern side of the Alpine Tethys would further support our notion that plate divergence in this time was partitioned to several distant rift centers, which might have been linked kinematically by transform faults (Fig. 14c). This would also still leave the possibility that some of the Cretaceous divergence was accommodated within the pre-existing Alpine Tethys basin. The part of the Glockner nappe system with evidence of Jurassic magmatism would then represent a segment of Piemont-Ligurian ocean floor stranded between the European margin in the north and a potential Cretaceous (Valais) part of Alpine Tethys further southeast within the existing Jurassic ocean (Fig. 14c).

7.3 Alternative scenarios, open questions and outlook

In the previous chapters, we tried to summarize all previous and recent findings from the central Tauern Window, which are relevant in our attempt to reconstruct the rift-related geological evolution of the area. The resulting model is certainly not perfect, but rather represents our best-fit solution given the currently available data. The rock record in the central Tauern Window is often ambiguous and alternative interpretations are possible. In other cases, reliable or unequivocal data is simply missing so far, and we had to rely on educated guessing. Therefore, additional or totally new findings could make significant changes of our reconstruction of the rifting history necessary. In the following, we will shortly discuss the most problematic aspects of our attempt and discuss alternative solutions by anticipating possible future findings contradictory to previous interpretations. We will also sketch lines of future research that could help clarify these issues.

In our view, the most pressing block of problems comes from the fact that many critical rock successions are effectively undated so far. This is especially the case for the Brennkogel Formation, the arkosic Bündnerschiefer of the Trögereck Nappe and Eclogite Zone, and the Wörth Formation. Given the lack of biostratigraphic and radiometric data, we relied on lithostratigraphic correlation with the Kaserer Formation and other boundary conditions in assigning a broadly lower Cretaceous age to these successions.

Since the discovery of an ammonite in the Hochstegen marble, an Early Cretaceous age of the Kaserer Formation in the western Tauern Window is the most plausible estimate for its age, because the Kaserer Formation is regarded the stratigraphic hanging wall of the Hochstegen Formation. Recently, on the basis of several different lines of observation, Veselá and Lammerer (2008) and Veselá et al. (2022) argued that the Kaserer Formation represents a Permo-Triassic succession. From our perspective from the central Tauern Window, we regard their arguments as inconclusive; however, the question of the age of the Kaserer Formation appears to be not completely resolved so far.

For the Wörth Formation, it has not been proven that it stratigraphically follows on the Angertal (Silbereck) or Hochstegen marble, which opens the possibility of an allochthonous origin relative to the Sonnblick-Romate Nappe and essentially the entire age spectrum from pre-Variscan to Eocene (?) ages would become possible. If there are no fossils in the succession, its age could potentially be determined by the age of the magmatic protoliths of the metabasite layers present in the succession of the Wörth Formation.

For the Brennkogel Formation and the arkosic Bündnerschiefer successions of the Trögereck Nappe and Eclogite Zone, a post-Triassic sedimentation age is certain, since all these units contain blocks of Triassic carbonates. However, if the correlation of these units to the Kaserer Formation is incorrect, or if the Cretaceous age of the Kaserer Formation itself is incorrect, a (Early) Jurassic age of these deposits would be the next plausible interpretation. Given the clastic nature of these successions, future fossil findings are unlikely, and the most promising direct dating method for these successions is again via the metabasites incorporated in the metasediments. First attempts in obtaining magmatic protolith ages of the metabasites from the Eclogite Zone were unsuccessful (Gleißner et al., 2021) or ambiguous (Nagel et al., 2013). Dating detrital zircons might at least give minimum sedimentation ages of the succession, if suitable grains can be found that did not suffer from later Alpine metamorphic overprint.

If the alternative scenario turns out to be correct, that all or most of the sediment successions with syn-rift characteristics are early to middle Jurassic (or older) in age, the notion of a single-stage rifting process of the Alpine Tethys would be strongly supported.

8 Conclusion

Based on a reassessment of lithostratigraphic data from nappes in the central Tauern Window (Fig. 7), we reconstructed the post-Variscan geodynamic evolution of the European continent now exposed in the central Tauern Window. This study largely confirms earlier reconstructions (e.g., Kurz et al., 1998) but also proposes some refinements on the existing models. This refinement builds on observations of lithostratigraphic characteristics and the rift architecture in examples of recent and fossil rifted margins. The deposition of Permian to Upper Triassic pre-rift strata was followed by Jurassic rifting and the opening of the Piemont-Liguria ocean basin. Jurassic syn-rift sediments are effectively missing in the Europe-derived units; instead, this period is marked by an erosional unconformity or hiatus of approximately Middle Jurassic age. Post-rift thermal subsidence of the European margin enabled the formation of a Late Jurassic carbonate shelf. We propose that this period of relative quiescence was superseded by intense rifting activity during the Early Cretaceous, which led to some magmatic activity and the deposition of large masses of clastic sediments derived from eroded basement rocks. Following Kurz (2006), we propose that during this period, a deep rift basin formed in the distal European margin to the Alpine Tethys, which led to the separation of a crustal ridge, expressed as an outer margin high, from the main continent (Fig. 14). During later convergence and subduction of the margin, parts of the margin were sheared off from the down-going European plate. The crustal ridge formed the Rote Wand Nappe, while the relics of the rift basin can now be found in the Eclogite Zone, the Trögereck Nappe and the Wörth Formation.

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Author contributions
PG: Fieldwork, sampling, sample analysis, manuscript conceptualization, writing and editing. JP: Assistance during fieldwork, manuscript writing and editing. MRH: Assistance during fieldwork, manuscript writing and editing. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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