1

Geological and Tectonic Setting of Austria

Ralf Schuster and Kurt Stüwe

Abstract

The landforms of Austria are the direct consequence of a continuous interplay between tectonic and climatic forces that have built, destroyed and reshaped the surface of the most iconic mountain belt on Earth for almost 40 Million years. As such, landforms can only be understood with a thorough geological background. This paper gives an overview of the tectonic evolution, the geological build up and the landscape evolution in the Austrian territory. The tectonic evolution of the rocks forming the major tectonic units of Austria can be traced back to some 500 Million years when they were located at different ancient continents including Gondwana, Avalonia and Laurasia. In the late Palaeozoic, the basement rocks were affected by the Variscan tectonometamorphic event during amalgamation of the supercontinent Pangaea and by a Permian extensional event. The latter is responsible for and was followed by a long-lived phase of thermal subsidence triggering the deposition of the Mesozoic sedimentary pile of the Northern Calcareous Alps. The formation and later subduction of the Neotethys and Penninic oceans began in Triassic and Jurassic times, respectively. The Alpine orogen as we know it today is largely the consequence of the head-on collision between the Adriatic and European plates once subduction had terminated around 40 Ma. The geological build up of Austria includes the Alps and its northern foreland. The foreland is composed of Variscan gneisses in the Bohemian Massif, their Mesozoic cover and Cenozoic sediments in the Molasse Basin. The Alps are made up of tectonic units derived from the European and Adriatic continents and the Neotethys and Penninic oceans that are covered by some intramontane and marginal basins that are filled with Neogene sediments. The landscape evolution evolved since the Oligocene and is highly influenced by processes in the mantle. It involved the interplay of many kilometres of rock uplift and simultaneous erosion so that few rocks at the surface today can be traced back to this time. Nevertheless, low-temperature geochronology, a series of fossil relict surfaces and enigmatic deposits like the Augenstein Formation on the plateaus of the Northern Calcareous Alps testify of a stepwise formation of the landscape over the last 25 Million years. Current research shows that up to 500 m of surface uplift may have occurred in the last 5 Million years alone.

Keywords

Austria • Geology • Geodynamics • Palaeogeography • Mantle structure • Landscape evolution

1.1 Introduction

The morphology of the Earth's surface is not only a reflection of atmospheric and hydrospheric processes, but—in fact—mostly the result of geological processes in the lithosphere and in the asthenospheric mantle. The plate tectonic environment causes compressional or extensional regimes that are responsible for the thickness of the crust and lithospheric mantle, which, in turn, are the basic controlling parameters for surface elevation on large length scales. On a smaller scale, lithologies and their sedimentary or deformation features are important parameters for the geomorphology as their physical and mechanical characteristics control the nature of weathering and ultimately erosion. Therefore, geographical and geological subdivisions of an area often go hand in hand. However, in many regions, they do not correspond (Fig. 1.1).

R. Schuster (✉)
Geological Survey of Austria, Neulinggasse 38,
1030 Vienna, Austria
e-mail: ralf.schuster@geologie.ac.at

K. Stüwe
Department of Earth Sciences, University of Graz,
Universitätsplatz 2/11, 8010 Graz, Austria

C. Embleton-Hamann (ed.), *Landscapes and Landforms of Austria*, World Geomorphological Landscapes,
https://doi.org/10.1007/978-3-030-92815-5_1

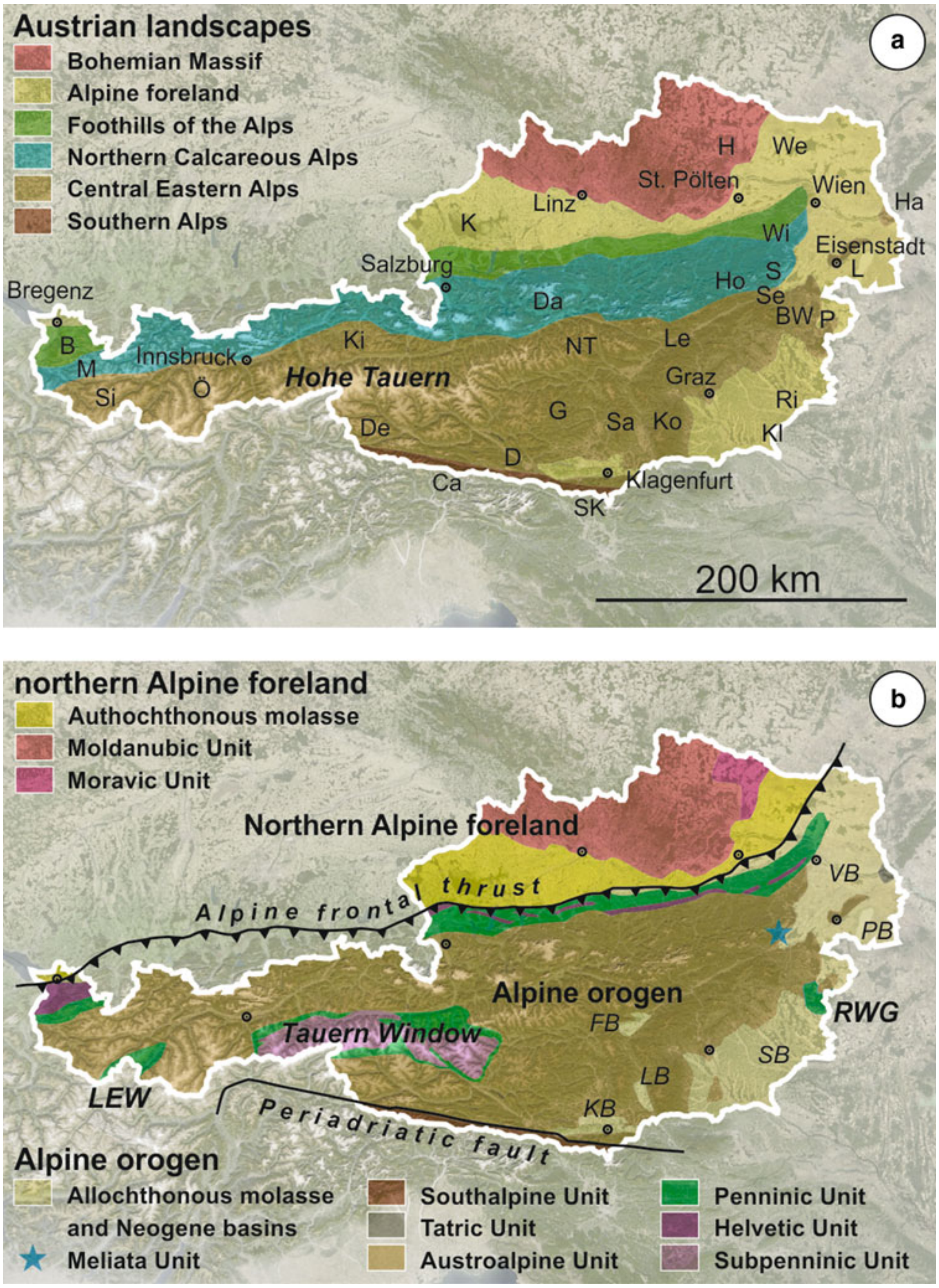


Fig. 1.1 Comparison of the distribution of landscape **a** and major tectonic **b** units in the territory of Austria. Obvious similarities of the geographical and geologic subdivisions indicate a strong influence of the geology on geomorphology. Geographic places: B = Bregenzer Wald, BW = Bucklige Welt, Ca = Carnic Alps, D = Dobratsch, Da = Dachstein, De = Deferegger Alps, G = Gurktaler Alps, H = Horn, Ha = Hainburg Mountains, Ho = Hochschwab, K = Kobernausser Wald, Ki = Kitzbühel, Kl = Klöch, Ko = Koralpe, L = Leithagebirge, Le = Leoben, M = Montafon, NT = Niedere Tauern, Ö = Ötztal, P = Pauliberg, Ri = Riegersburg, S = Schneeberg, Sa = Saualpe, Se = Semmering, Si = Silvretta, SK = South Karawanken, Wi = Wienerwald, We = Weinviertel. Geological features: LEW = Lower Engadine Window, RWG = Rechnitz Window Group, FB = Fohnsdorf Basin, KB = Klagenfurt Basin, LB = Lavanttal Basin, PB = Pannonian Basin, SB = Styrian Basin, VB = Vienna Basin

From a plate tectonic view, the territory of Austria is located at the compressional plate boundary between the Eurasian and the Adriatic plates. It covers the eastern portion of the Alpine orogenic belt and its northern foreland. This setting is the result of convergence of the African and Eurasian plates, which was more or less continuous since the Early Cretaceous. The geology of the Alpine-Mediterranean realm is complex, however, because several microplates formed and vanished between the two major plates, and the interplay between shortening processes and lateral movements makes it difficult to determine the plate tectonic arrangement through time (Froitzheim et al. 2008; Handy et al. 2010).

This complicated geology of the Austrian Alps was explained differently during three distinct periods in the geological exploration history. The first period is that of the "*Old Geology*" (as referred to by Kober 1938). It started with the first "geognostic" excursions in the late eighteenth century and was followed by the "Erste Geologische Landesaufnahme" (first geological mapping campaign), resulting in a map by Hauer (1867) on the scale of 1: 576.000. At that time, the rock series were thought to be more or less autochthonous, meaning that they were formed at the place where they still are. This implies that older rocks are overlain by younger ones. Mountain ranges were interpreted to be anticlines formed by contraction of Earth, or by the inversion of “geosynclines”. Geological maps of this period show typically several zones with old “primary” rocks in the centre and younger “secondary” and “tertiary” sediments towards the sides (Sedgwick and Murchinson 1832). Terms like “Sandsteinzone”, “Grauwackenzone” or “Nördliche Kalkalpen”, which are still in use in a geographic sense, are remnants from this period, but they are often obsolete or problematic in the geologic nomenclature of today.

Towards the start of the twentieth century, the period of *nappe tectonics* was born when it was realized that older rocks might be thrust over younger ones, forming distinct nappe-shaped packages of rock that can travel up to hundreds of kilometres. Names like the Austrian geologists Eduard Suess or Otto Ampferer are closely connected to this development that was paralleled by equivalent discoveries by Swiss geologists. With this knowledge of nappe motion, it was possible to explain the distribution of the rocks at the surface, but the driving mechanisms were still not understood. Nevertheless, this knowledge allowed a process-driven subdivision of the Alps (e.g. Suess 1909). With little change, this general tectonic subdivision of the Alps into Helvetic, Penninic, Austroalpine and Dinaric (Southalpine) units is still in use today. However, for the internal subdivision of these units, many different suggestions exist (e.g. Kober 1938; Tollmann 1977; Neubauer et al. 2000; Schmid et al. 2004; Janák et al. 2004). For the Variscan rocks in the northern part of Austria, the major tectonic units were also established at approximately this time (Kossmat 1927). In the territory of Austria, these are the Moravian and Moldanubian units (Suess 1912), which have since been subdivided further (e.g. Fuchs 1976; Neubauer and Handler 2000; Linner 2013; Finger and Schubert 2015).

The third period is that of *modern plate tectonics*. The first interpretation of the Eastern Alps in terms of this concept was given by Frisch (1979). Today, there is a broad consensus that the Alpine orogen in central Europe developed from four major palaeogeographic realms existing in Jurassic and Cretaceous times (Fig. 1.2). These are the African and the European continental realms, and the Neotethys and the Penninic (Alpine Tethys) oceans (e.g. Froitzheim et al. 1996; Neubauer et al. 2000). While this subdivision of the Alpine orogenic cycle appears well established, the plate tectonic framework for the Variscan orogenic cycle is less clear (e.g. Matte 1986; Franke 2000; Kroner and Romer 2013).

Today, geophysical methods allow us to look at the deep structure of the Alps giving the chance to confirm some of the plate tectonic interpretations. Based on the depth of the Mohorovičić discontinuity (MOHO) and the distribution of shear wave velocities, it can be shown that the Eurasian Plate dips southward underneath the Alps, whereas the Adriatic Plate—representing a former promontory of Africa—is dipping northward below the active Alpine orogen. However, the mantle structure and its evolution in the last Million years, which is highly important for morphological changes in the past, is still a matter of debate (Lippitsch et al. 2003; Mitterbauer et al. 2011). Detailed geological maps on the scale 1:50.000 and 1:75.000 are available for the major part of the territory of Austria (http://www.geologie.ac.at/services/), and a catalogue of geological aerial photography is present (http://www.alpengeologie.org). From these, it is impressive to see how closely the morphology is related to the lithology or to lithogenetic units when field observations are compared to high-resolution digital elevation models and geological maps (Stüwe and Homberger 2012).

The following sections give an overview on the geodynamic and plate tectonic evolution as well as the lithologic content of the geologic units within the territory of Austria. Finally, the evolution of the landscape from the Eocene onward is described.

1.2 Palaeogeographic and Plate Tectonic Evolution

The following description of the geodynamic evolution of the Alpine area since the late Neoproterozoic summarizes the major tectonometamorphic events recorded in the rock series and the oceanic and continental areas from which the major tectonic units developed. It is based on Stampfli and Borel (2004), Handy et al. (2010), Faccenna et al. (2014) and others and is summarized by Schuster and Stüwe (2010) and well illustrated by Stüwe and Homberger (2012) or Schuster et al. (2014).

Following the Cadomian orogeny in the late Neoproterozoic (c. 600 Ma), all continental units present in the territory of Austria were located at the northern margin of the Gondwana continent in close proximity to the South Pole. In the late Cambrian and Ordovician (510–460 Ma; Fig. 1.3a), an abundance of magmatic rocks formed in an extensional environment (Neubauer 2002). The continental fragment of Avalonia, including the rocks of the Moravian and Brunovistulian units of the Bohemian Massif broke off from Gondwana and drifted northward. It was welded to the Laurussian continent in the frame of the Caledonian collisional event at the Ordovician/Silurian boundary (c. 420 Ma; Fig. 1.3b).

From the Late Devonian to the early Permian (380–260 Ma; Fig. 1.3c, d), the Pangaea supercontinent formed by amalgamation of all major pieces of continental crust on Earth. One important continental collision event that unified

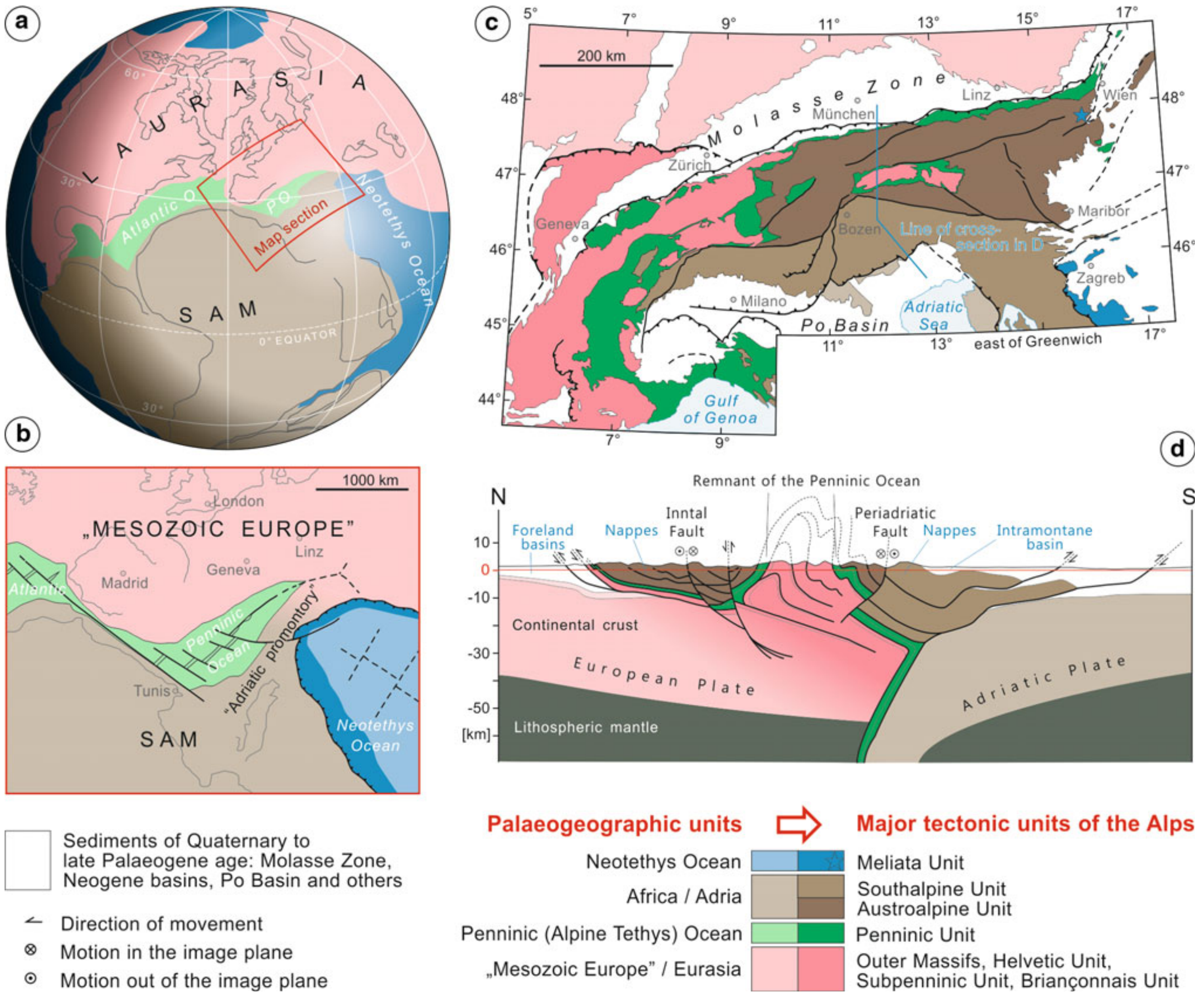


Fig. 1.2 Global **a** and regional **b** reconstructions showing the major palaeogeographic units of the Alpine realm and their transformation into the major tectonic units of the Alps, shown in map view **c** and section **d**. After Schmid et al. (2004) and Schuster et al. (2014) and references therein. SAM = southern continent assemblage that has split since that time into several continents (e.g., Africa, Adria, Australia), PO = Penninic (Alpine Tethys) Ocean

the continental masses of Laurussia and Gondwana at this time is referred to as the Variscan event. It lasted roughly from the Late Devonian to the end of the Carboniferous (380–300 Ma). In Austria, the Moldanubian and Moravian units of the Bohemian Massif represent tectonic units that were thrust during this Variscan event onto the foreland, then represented by the Brunovistulian Unit. The latter had already been consolidated during the earlier Cadomian event (Kroner and Romer 2013). Variscan metamorphism and deformation is also evident in many of the Austroalpine and Southalpine basement units.

Following the Variscan orogeny, Pangaea had a C-shape (Fig. 1.3d, e) with the Tethys Ocean forming an embayment coming in from the east (Stampfli and Borel 2004). Rock units from the Austrian territory were located at this time close to the western end of the Neotethys embayment (also called the Meliata-Hallstatt Ocean). In Permian and Triassic times (285–220 Ma), this area was affected by an extensional event. Thinning of the lithosphere caused basaltic underplating of the crust, resulting in magmatic activity and widespread high-temperature metamorphism (Schuster and Stüwe 2008). At the surface, grabens formed that accommodated new sediments and volcanoes erupted. Since the Early Triassic (c. 245 Ma) the Neotethys Ocean propagated westward. Parts of the Moldanubian and Moravian units formed an island, whereas the other units of Austria were located at a broad shelf and partly also on the slopes of the southern continental margin towards the Neotethys Ocean.

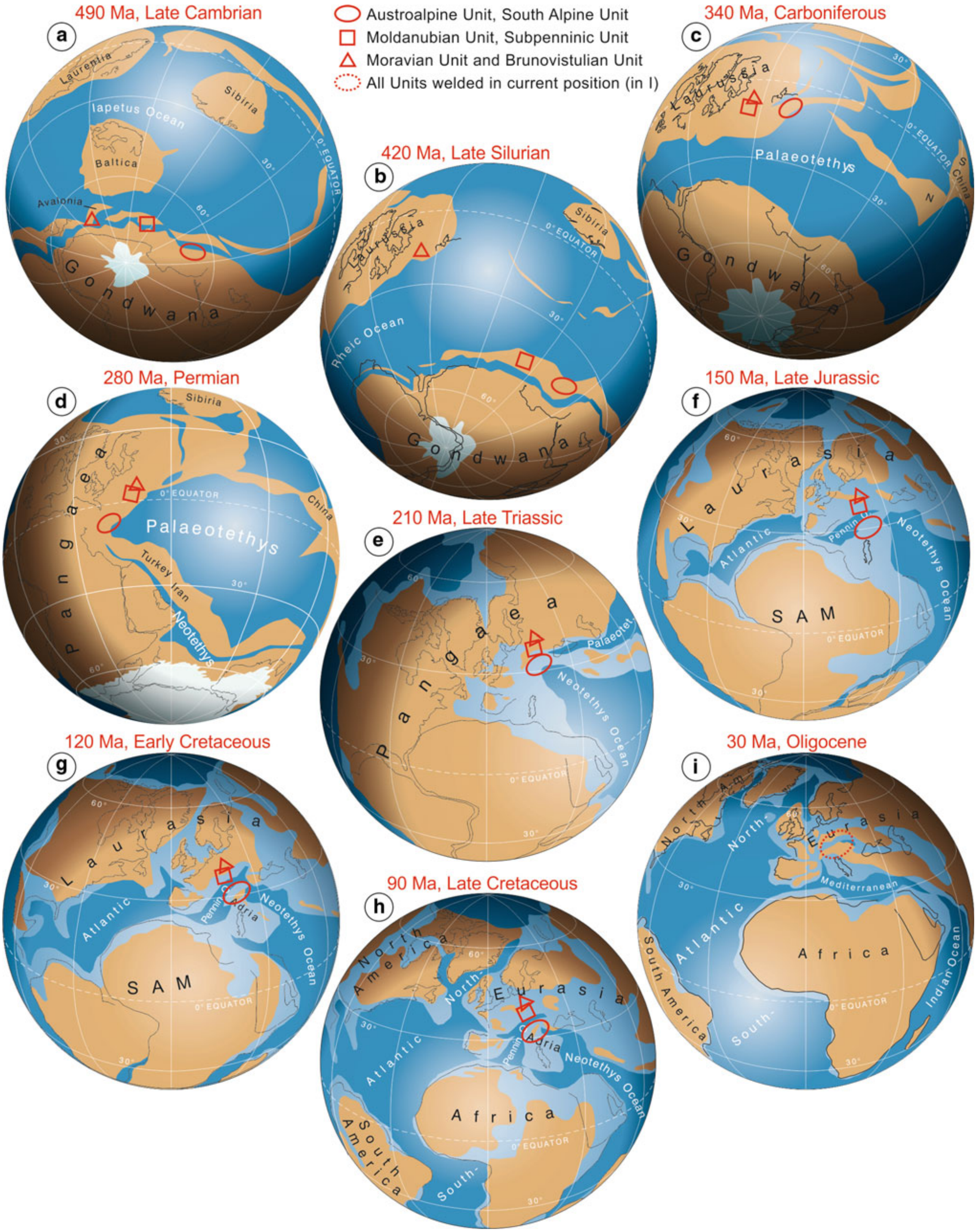


Fig. 1.3 Reconstructions of the global palaeogeography through Phanerozoic time based on Schuster et al. (2014). The positions of major continental tectonic units in the territory of Austria are shown through time. Explanation see text. SAM = southern continent assemblage that has split up since that time. Continental land masses are in brown, continental shelfs in light blue and oceanic basins in dark blue

A prolonged phase of thermal subsidence followed the termination of the Permian extensional event. During this time, the up to 3000-m-thick carbonate platforms of the Northern Calcareous Alps formed on the subsiding shelf. In the Middle Jurassic (c. 150 Ma; Fig. 1.3f), opening of the Atlantic Ocean initiated the breakup of Pangaea. The continent Laurasia was split from a southern continent assemblage including Africa, which started drifting eastwards. While the Atlantic was opening in north–south direction, a wrench corridor with sinistral offset propagated eastward into the region that forms the Alpine realm today (Frisch 1979). This early arm of the Atlantic is referred to as the Penninic Ocean, which is also known by the name "Alpine Tethys". At the same time, the closure of the Neotethys Ocean further east and south started at an intra-oceanic subduction zone. In the Late Jurassic, ophiolite nappes from this subduction zone were obducted onto the shelf margin (Missoni and Gawlick 2010). These nappes are widespread in the Dinarides. In the Eastern Alps and Western Carpathians, only tiny remnants of these obducted nappes are preserved and referred to as the Meliata Unit. In Austria, they are located in a Cretaceous out-of-sequence thrust within Permo-Mesozoic sediments of the Austroalpine Unit in the Schneeberg area in Lower Austria (Mandl and Ondrejickova 1993). In addition, eroded material from related nappes is present within Cretaceous sediments (Faupl and Wagreich 1992). Following these obduction processes (in the latest Jurassic or earliest Cretaceous around 145 Ma), a major sinistral strike-slip fault system cut the continental bridge between the Neotethys and Penninic oceans that was formed by the Adriatic promontory (Fig. 1.2b). In the Early Cretaceous (c. 130 Ma; Fig. 1.3g), this fault was activated as a south dipping intra-continental subduction zone, which ultimately became responsible for the formation of the Alps (Stüwe and Schuster 2010). Since that time, about 900 km of north–south convergence and 30° of anticlockwise rotation of the Adriatic Plate towards the Eurasian Plate was accommodated at this subduction zone (Handy et al. 2010).

In the frame of the so-called Eoalpine event in the Early to Late Cretaceous (130–80 Ma), the Austroalpine nappes and the nappes of the Central Western Carpathians formed from continental crust dragged into this subduction zone in a pro-wedge setting. Some nappes reached eclogite facies metamorphic conditions at depths of more than 80 km (Tenczer and Stüwe 2003; Janák et al. 2015) in early Late Cretaceous time (c. 95 Ma; Fig. 1.3h; Thöni 2006). As subduction proceeded, oceanic lithosphere of the Penninic Ocean was subducted into the same zone in the middle Late Cretaceous (starting at about 85 Ma). Finally, in the early Eocene (c. 45 Ma), the southern margin of the European continental lithosphere was also drawn into the same suture zone. During this process, the Penninic, the Helvetic and the Subpenninic nappes formed. Subduction related, pressure-dominated metamorphism in the Eocene and early Oligocene (at about 45–30 Ma) reached blueschist and eclogite facies conditions in parts of the Penninic and Subpenninic nappes. The final closure of the Penninic Ocean occurred in the middle to late Eocene (c. 40 Ma; Schmid et al. 2004) and a head-on collision between the Adriatic and European plates terminated the subduction process. The northern Alpine foreland basin developed on top of the down bending European continental lithosphere. In the middle Eocene to early Oligocene (40–28 Ma; Fig. 1.3i), the subducted slab, from which all the nappes were detached, broke off from the Eurasian plate at depth (von Blankenburg and Davies 1995). Around 30 Ma, this caused intense magmatism (Periadriatic magmatism) and dextral slip on the Periadriatic fault (Mancktelow et al. 2001), which since forms the boundary between the Austroalpine and Southalpine units. Surface uplift related to isostatic rebound produced the first topographic development in the range.

In the earliest Miocene (c. 21 Ma; Schmid et al. 2013), the Southalpine indenter pushed northward and caused further north–south shortening along the northern margin and in the western part of the Eastern Alps. Along the northern margin, parts of the foreland basin were sheared-off and incorporated into the orogenic wedge as the so-called Allochthonous Molasse (until the Ottnangian; c. 18 Ma). In the east (in the area of the Pannonian Basin), the last remnants of the Penninic Ocean were subducted (Faccena et al. 2014) and the retreat of the oceanic lithosphere lead to stretching in east–west direction, especially in the eastern part of the Eastern Alps (lateral escape of Ratschbacher et al. 1989, Robl et al. 2008a, Bartosch et al. 2017). East–west extension was accommodated by thinning of the lithosphere. Around 15–17 Ma, the extension in connection with the retreating subduction zone was associated with calc-alkaline volcanism (Pannonian magmatism; e.g. in the Styrian Basin; Fodor et al. 2008). In the upper part of the crust, a system of strike-slip (e.g. Mölltal, Inntal, Salzach-Enntal-Mariazell-Puchberg faults; Peresson and Decker 1996; Linzer et al. 2002; Pischinger et al. 2008) and normal faults (e.g. Brenner, Katschberg normal faults) developed (e.g. Genser and Neubauer 1989; Fügenschuh et al. 1997; Scharf et al. 2013), along which the Alps were extruded to the east. In the centre of the range tectonic windows formed (Lower Engadine, Tauern and Rechnitz windows), where Subpenninic and Penninic nappes were exhumed from below the Austroalpine. Blocks in between the faults were tilted, uplifted or subsided. A series of basins formed along the strike-slip faults and these accommodated sediments (e.g. Fohnsdorf, Tamsweg, Klagenfurt, Lavanttal, Vienna, Styrian and Pannonian basins). Since the middle Miocene, the eastern part of the Alps and surrounding areas were uplifted, most probably due to processes in the upper mantle (Wagner et al. 2010; Baran et al. 2014; Legrain et al. 2014). During further uplift, the basins in eastern Austria rose up to about 150–200 m above sea level, while the Bohemian Massif established as a new, low mountain range. Generally, these Miocene tectonic processes, in combination with the erosive overprint during the glaciation periods in the Quaternary (since 2.6 Ma), are responsible for many topographic features we can observe today.

1.3 Description of the Major Geologic Units

In this section, the major geologic units appearing within the territory of Austria are described. We begin with the units from the northern Alpine foreland. After that, those of the Alps follow. Each part is described in an order from bottom to top and from north to south (numbers in parentheses refer to Figs. 1.4 and 1.5).

1.3.1 Units in the Foreland of the Alps

The northern Alpine foreland comprises the pre-Variscan and Variscan metamorphosed basement of the Brunovistulian, Moravian and Moldanubian units. These are transgressively overlain by late Carboniferous to Cretaceous sediments and by Oligocene to Pannonian sediments of the Autochthonous Molasse.

1.3.1.1 Pre-Variscan and Variscan Metamorphosed Basement

Within the Austrian territory, the **Brunovistulian Unit** occurs in the subsurface below the Neogene sediments of the northwestern Weinviertel (Lower Austria). It received its present structural and metamorphic imprint during the Cadomian orogeny in the late Neoproterozoic (c. 600 Ma) and is the oldest unit in Austria. It consists of paragneisses, micaschists, marbles and minor quartzites as well as amphibolites that are intruded by large amounts of Cadomian granites and granodiorites. During the Variscan and Alpine orogenies, it always remained in the foreland (Finger et al. 2000).

During the Variscan event in the Late Devonian to Carboniferous (380–300 Ma), parts of the Cadomian basement were sheared-off and incorporated into the Variscan orogen at a late stage and in a marginal setting. These parts are referred to as the **Moravian Unit** (26). The Variscan metamorphic and structural overprint increases towards the tectonic higher units in the west. Within the Moravian Unit, the lower Thaya and Svratka nappes are characterized by a lower greenschist facies overprint and minor deformation. The textures of the Cadomian granites are still well-preserved (e.g. Maissau granite, Eggenburg granite) (Fritz et al. 1996). In contrast, the higher Pleißling nappe reached amphibolite facies conditions and shows a penetrative, often mylonitic schistosity (e.g. Bittesch and Weitersfeld orthogneisses).

The **Moldanubian Unit** (25) represents a deep level of the internal part of the Variscan orogen. Its eastern part is formed by the Moldanubian nappes, which are characterized by a granulite facies metamorphic imprint with metamorphic peak conditions at up to 1000 °C and 1.6 GPa at c. 340 Ma (Petrakakis 1997). The lowermost Ostrong Nappe System is formed by monotonous paragneisses (“Monotonous series”), whereas the paragneisses of the overlying Drosendorf Nappe System contain many intercalations of amphibolites, marbles and graphitic schists (“Variegated series”; Fuchs and Matura 1976). At the base of the next higher Gföhl Nappe System, an amphibolite-rich sequence (Rehberg amphibolite) is present, which is interpreted as an ophiolite remnant. Above this, there are Ordovician orthogneisses (Gföhl orthogneiss) with slices of ultramafic mantle rocks at their base. In the uppermost nappe of the Gföhl Nappe System, the orthogneisses show a mylonitic texture and are referred to as “granulites”. The Moldanubian nappes were intruded by the South Bohemian Batholith at 335 to 300 Ma. The Rastenberg granodiorite, Weinsberg granite, Eisgarn granite and Mauthausen granite are the most important intrusions (Gerdes et al. 2000). In the west, the whole sequence experienced an additional high-temperature overprint at c. 330 Ma causing widespread migmatisation. This part is referred to as Bavaric Subunit.

Geographically, the Variscan basement units build up the Bohemian Massif with its elevated, but rather flat and smooth topography cut by deep river gorges like Strudengau, Wachau, Kamp Valley or Thaya Valley, indicating a young and immature landscape. The valley sides are characterized by steep cliffs of massive rocks with a widely spaced cleavage.

1.3.1.2 Carboniferous to Cretaceous Sediments and Autochthonous Molasse

The **late Carboniferous to Cretaceous sediments** (24) that overlie the Variscan basement are only visible in a few places (e.g. near to Zöbing). They were deposited during several transgressional phases in the Permian, Jurassic and Cretaceous. However, below the Autochtonous Molasse, they occur more frequently and are well-studied because of their importance for the hydrocarbon industry (Wessely 2006).

The late Oligocene to Miocene (35–18 Ma) sediments of the **Autochthonous Molasse** (23) were deposited in the foreland basin of the Alpine orogen (Rupp et al. 2006; Wessely 2006). It formed as a southward dipping basin on the Eurasian plate due to topographic loading by the northward moving Alpine nappe pile. The main part of the basin is filled by marine sediments. At the northern margin gravel,

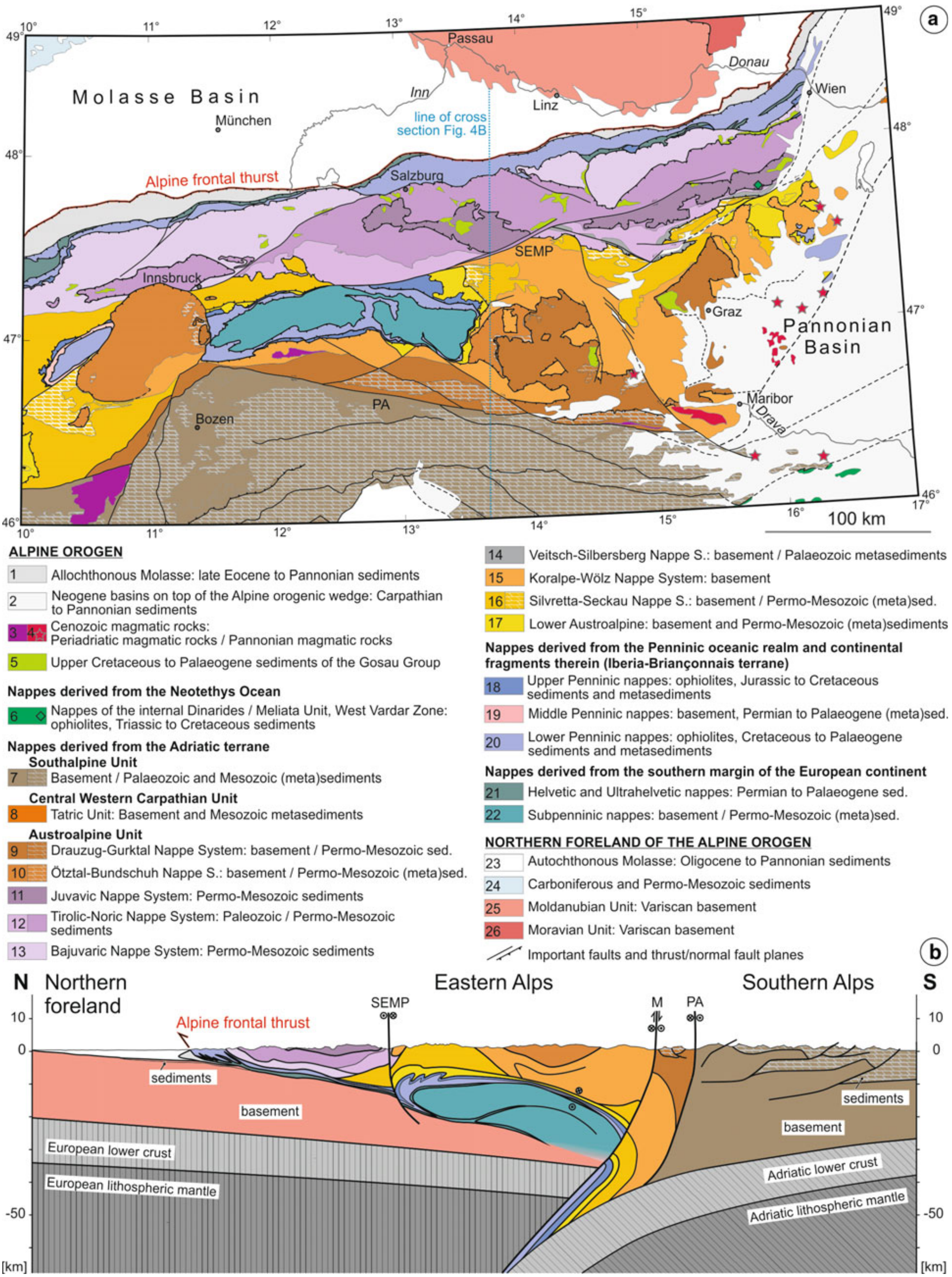


Fig. 1.4 Tectonic map **a** of the Eastern Alps and its northern foreland according to the nomenclature in Schmid et al. (2004). The numbers of the units refer to the text. Section **b** through the Eastern Alps according to Schmid et al. (2004). SEMP = Salzach-Ennstal-Mariazell-Puchberg fault, M = Mölltal fault, PA = Periadriatic fault

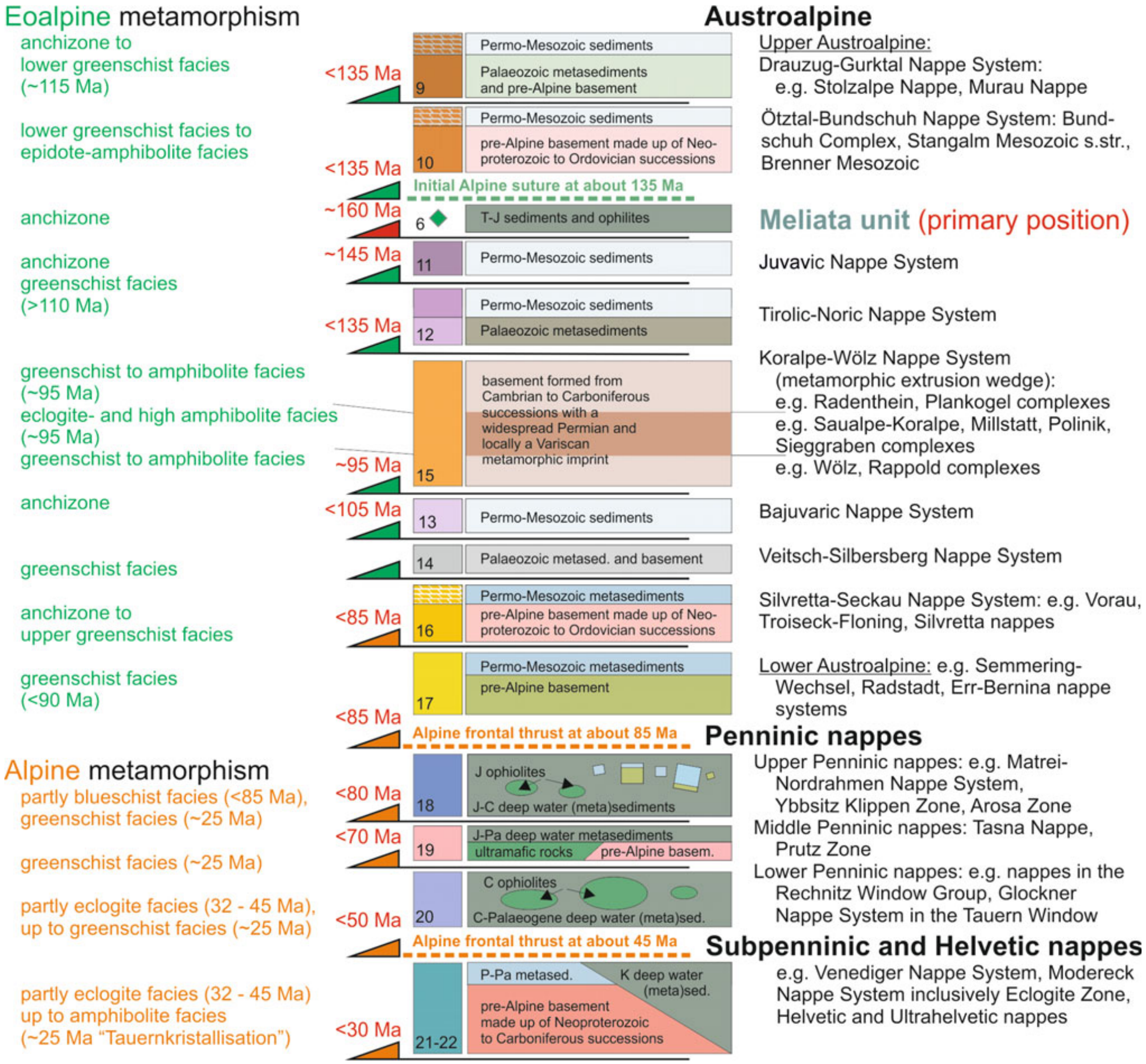


Fig. 1.5 Schematic diagram showing the tectonostratigraphic order of the major tectonic units of the Eastern Alps. Tectonic and lithostratigraphic units are listed in the left column. In the central column the major lithological content of the tectonic units is shown. Fields with numbers refer to the numbers of the tectonic units in the text and the colour in Fig. 1.4. Red numbers at left indicate the time of incorporation into the Alpine orogenic wedge. The metamorphic grade during the Eoalpine (Cretaceous) and Alpine (Cenozoic) events and the time of peak metamorphism is given in the right column. Note, the Meliata Unit is not part of the Austroalpine Unit, its primary emplacement was on top of the Juvavic and Tirolic-Noric nappe systems. T = Triassic, J = Jurassic, C = Cretaceous, Pa = Palaeogene

sands and clays, some fossil-rich, occur that formed in a beach or shallow water environment. The central part is dominated by sands and clays from a deeper basin, influenced by intense stream currents. In the south, coarser-grained clastic sediments derived from the Alpine nappes are present. The youngest (Pannonian, c. 7 Ma) part of the sedimentary pile consists of fluvial gravels derived from the Alps, which contain coal layers in the Kobernausser Wald (Upper Austria). Because of its composition of soft sediments, the area of the Autochthonous Molasse shows a smooth hilly landscape with larger outcrops restricted to valleys and localities affected by anthropogenic activity.

1.3.2 Units in the Alps

The tectonic lowermost element of the Alps is the Allochthonous Molasse. It is overlain by the Subpenninic and

Helvetic nappes derived from the European continental margin and the Penninic nappes that developed from the Penninic oceanic realm. The highest part of the Alpine nappe pile is made up of the Austroalpine, Tatric and Southalpine units that originate from the Adriatic terrane and also includes slices of the Meliata Unit derived from the Neotethys Ocean. Since the Oligocene, two types of magmatic rocks formed and Neogene basins developed on top of the Alpine orogenic wedge (wedge shaped Alpine nappe pile overlying the Eurasian and Adriatic plates).

1.3.2.1 Allochthonous Molasse and Units Derived from the European Continental Margin

The **Allochthonous Molasse** (1) is made up of sediments from the northern Alpine foreland basin that were deformed, sheared-off and incorporated into the Alpine orogenic wedge before the middle Miocene (until 15 Ma). It consists of conglomerates, sands and clays (Wessely 2006) forming the most external foothills along the northern margin of the Alps.

The **Subpenninic nappes** (22) developed in the Oligocene (c. 34–23 Ma) from thinned continental crust of the distal European margin (e.g. Froitzheim et al. 1996; Kurz et al. 2001) and represent ductily deformed basement and cover nappes, which lost contact with their lithospheric mantle (Schmid et al. 2004). They are characterized by a basement consisting of partly migmatitic paragneisses and amphibolites with Neoproterozoic to Carboniferous protolith ages, intruded by large masses of deformed Variscan granitoids ("Zentralgneise"). Post-Variscan transgressive sediments were deposited on top of these gneisses at different times between the late Carboniferous and the Cretaceous. Typical is a sequence with Permian and Early Triassic clastics, Middle Triassic carbonates ("Seidelwinkel Trias") and Late Triassic rauhwacke and quartzites. In other nappes, Late Jurassic marbles derived from shallow water limestones (Hochstegen Formation) appear directly on the Variscan basement. During their Alpine tectonometamorphic overprint, the Subpenninic nappes experienced greenschist to amphibolite facies metamorphic conditions in the Eocene to Miocene (45–15 Ma). The structurally lower nappes dominated by thick basement form the Venediger Nappe System, whereas nappes nearly exclusively composed of Permian to Cretaceous metasediments are referred to as Modereck Nappe System (Schmid et al. 2013). The latter also includes the so-called eclogite zone, which additionally contains material derived from the Penninic Ocean and developed in a subduction and accretion channel (Kurz and Froitzheim 2002). It experienced an eclogite facies imprint in the Eocene (c. 35 Ma). In the Hohe Tauern region, within the so-called Tauern Window, the Subpenninic nappes build up some of the highest peaks like Großvenediger (3662 m) or Hochalmspitze (3360 m). Typically, they form very steep cliffs of bright coloured, blocky orthogneisses ("Zentralgneise") (Fig. 1.6).

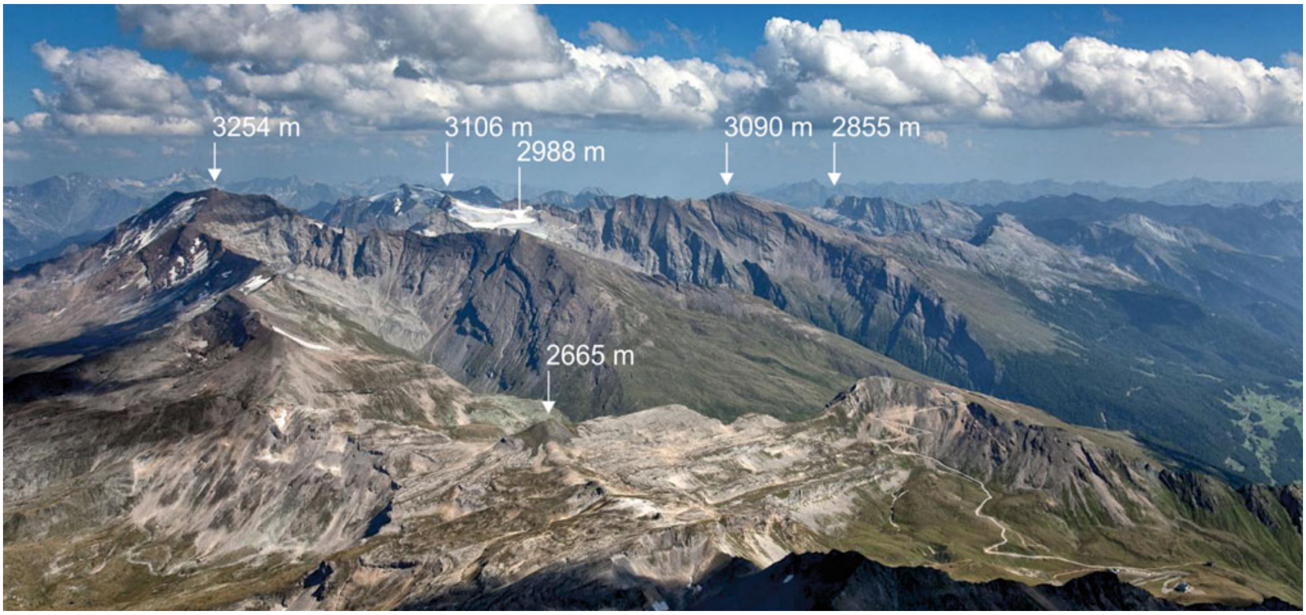


Fig. 1.6 Eastward view along the main crest of the Hohe Tauern in the Großglockner region (Salzburg/Carinthia). The crest is built up by the Venediger Nappe System of the Subpenninic Unit. Bright greyish orthogneisses occur at Sonnblick (3106 m). On top of Hocharn (3254 m) dark brownish paragneisses are visible. Overlying brownish-grey Jurassic and Cretaceous schists (Bündnerschiefer Group) of the Penninic and Subpenninic units are visible at Gjaidtroghöhe (2988 m) and Sandkopf (3090 m). Further up in the tectonic succession Subpenninic metasedimentary rocks including bright coloured Triassic carbonates around Rossschartenkogel (2665 m) and at Rote Wand (2855 m) follow. Photo from: www.alpengeologie.org

In the Oligocene, the **Helvetic and Ultrahelvetic nappes** (21) were detached from the distal European margin to form a thin-skinned fold and thrust belt. They are composed of Jurassic to Eocene (200–35 Ma) cover sequences, which can be subdivided with respect to their depositional depth. The Helvetic nappes sensu stricto comprise mostly carbonaceous shelf sediments up to a few hundred metres in thickness, whereas the Ultrahelvetic nappes consist of thin pelagic sediments from the deeper continental slopes (Oberhauser 1980). In the Bregenzer Wald (Vorarlberg), the Helvetic nappes form a hilly to mountainous area with an elevation between 450–2100 m, whereas the Ultrahelvetic units only appear as thin slices intercalated between Penninic nappes of the Rhenodanubian flysch zone (see below).

1.3.2.2 Nappes Derived from the Penninic Oceanic Realm

The Penninic nappes developed in the Late Cretaceous to Palaeogene (85–35 Ma) from an oceanic realm with continental fragments (terranes) therein. Based on their palaeogeographic origin and structural position, they are subdivided into the Upper, Middle and Lower Penninic nappes.

In the Palaeogene, the **Lower Penninic nappes** (20) formed from material of the northern part of the Penninic oceanic basin (Valais oceanic domain). They consist of Cretaceous ophiolites including serpentinized slices of ultramafic mantle rocks and a basaltic oceanic crust overlain by thick, Cretaceous to Eocene (135–45 Ma) flyschoid sequences (e.g. Rhenodanubian Group, Bündnerschiefer Group), which are dominated by siliciclastic or carbonaceous material. Unmetamorphosed Lower Penninic nappes build up the Rhenodanubian flysch zone along the northern margin of the Alps. Similar rocks, partly with an Eocene–Oligocene (45–35 Ma) blueschist to eclogite facies high pressure imprint and a Miocene (c. 25 Ma) greenschist facies overprint, appear in the central part of the Lower Engadine Window, the Glockner Nappe System of the Tauern Window and in the nappes of the Rechnitz Window Group.

The **Middle Penninic nappes** (19), mainly derived from the Briançonnais terrane, consist of Variscan metamorphic basement and a cover sequence with Permian fluvial to shallow marine clastics, a carbonate-rich Triassic shallow water sequence and Jurassic to Cretaceous deep-water sediments, deposited on a deep marine swell. In Austria, greenschist metamorphic Middle Penninic nappes are only present in the Lower Engadine Window in Tyrol.

Rocks that are derived from the southern part of the Penninic Ocean (Piedmont-Ligurian oceanic domain) as well as from the accretionary wedge along the southern margin of the oceanic basin towards the Adriatic terrane make up the **Upper Penninic nappes** (18). They are composed of Jurassic ophiolite slices comprising serpentinized ultramafic mantle rocks, gabbros and basalts within Late Jurassic and Cretaceous deep marine shales and flyschoid sediments (Froitzheim and Manatschal 1996). Sequences with serpentinized, exhumed mantle rocks that are directly overlain by Jurassic radiolarites and pelagic limestones are typical. Unmetamorphosed Upper Penninic slices occur in the border zone between the Rhenodanubian flysch zone and the Austroalpine nappes of the Northern Calcareous Alps (Arosa Zone, Ybbsitz klippen belt; Oberhauser 1980; Decker 1990). Further, blueschist and/or greenschist metamorphic units form the uppermost tectonic elements within the Lower Engadine and Tauern windows (e.g. Matrei Zone, Reckner Complex).

The flyschoid sequences of the Rhenodanubian flysch zone build up gentle hills along the northern margin of the Alps. Within the tectonic windows, the soft schists of the Bündnerschiefer Group cause gentle surfaces even on very steep slopes. Above the tree line, they are brownish coloured and vegetated by grass (Fig. 1.6). The stronger rocks of the ophiolite slices often protrude as cliffs forming the peaks of prominent mountains such as Großglockner (3798 m).

1.3.2.3 Nappes Derived from the Adriatic Terrane

The Austroalpine, Tatric and Southalpine are units that formed from the Mesozoic Adriatic terrane. In general, the crustal sequence of the Adriatic terrane is made up of three different types of pre-Mesozoic basement (Raumer et al. 2013) that is covered by Mesozoic sediments.

The first pre-Mesozoic basement type is dominated by biotite-plagioclase-paragneisses with intercalations of micaschists and amphibolites that developed from Neoproterozoic to Cambrian successions (1000–485 Ma). In part, they experienced a Cambro-Ordovician tectonometamorphic imprint (Neubauer 2002) and contain abundant intrusions of deformed Cambro-Ordovician (540–460 Ma) granitoids. They are affected by an amphibolite facies Variscan imprint at 380–300 Ma with minor associated granitic intrusions (Mandl et al. 2017). This basement type is typical for the Silvretta-Seckau and Ötztal-Bundschuh nappe systems. The second basement type is built up of muscovite-rich micaschists and paragneisses, typically containing intercalations of marbles, quartzites and amphibolites, that have a Cambrian to Carboniferous (540–300 Ma) depositional age. These sequences are often characterized by a first metamorphic imprint and related magmatism in the Permian (285–250 Ma), and they are frequent in the Koralpe Wölz Nappe System. Thirdly, there are weakly metamorphosed Palaeozoic sequences, for example, in the Southalpine Unit. They were deposited in a shelf environment and show a fossil record from the Ordovician to the early Carboniferous (485–340 Ma) (Schönlaub 1979). The Ordovician part is dominated by siliciclastics and felsic volcanics (e.g. Blasseneck porphyroid). In the Silurian, limestones are more common and there are some intercalations of basaltic metavolcanic rocks. Thick carbonate platform sediments and related intra-basin sediments including some basaltic extrusives are characteristic for the Devonian. From the early Carboniferous, some carbonaceous successions are preserved, but an increasing amount of clastic sediments reflects the Variscan event. Locally preserved late-orogenic Carboniferous sediments and Permian clastic sediments with salt and gypsum deposits in some units complete the depositional cycle.

The Mesozoic cover successions (Tollmann 1977; Mandl 2000) include famous units like the Northern Calcareous Alps. They start with Lower Triassic fluvial or shallow marine siliciclastic sediments and are overlain by Middle Triassic dark coloured limestones deposited in an euxinic marine environment. Above this follows the deposition of carbonate platform sediments (Wetterstein platform) in reef and lagoonal facies. After a short break with siliciclastic influx in the early Upper Triassic, limestones and dolomites of a second carbonate platform continue the sequence (Hauptdolomit-Dachsteinkalk platform). Contemporaneously, there are Middle to Upper Triassic sedimentary piles of pelagic limestones deposited on the slope towards the Neotethys Ocean (Hallstatt-facies sediments). Variegated sequences of Jurassic pelagic carbonates, olistolithes and radiolarites and some reef limestones were deposited due to increasing tectonic activity related to the opening of the Penninic Ocean and the beginning of closure of the Neotethys Ocean (Missoni and Gawlick 2010). Lower Cretaceous synorogenic clastic sediments including conglomerates and sandstones formed in foreland basins of the initial Alpine orogenic wedge (Roßfeld and Losenstein formations). Finally, Upper Cretaceous to Palaeogene conglomerates, shales, coals and reef limestones as well as turbiditic slope sediments (Gosau Group, 5) developed in piggy-back basins on top of the moving Austroalpine nappes (Faupl and Wagreich 2000).

The **Austroalpine Unit** forms a complex nappe stack that includes all three types of basement discussed above as well as its Mesozoic cover. Based on the structural position this unit is subdivided into Lower and Upper Austroalpine subunits that both are further subdivided into nappe systems (Schmid et al. 2004, Froitzheim et al. 2008). A schematic column, including the metamorphic grades according to Schuster et al. (2004), is given in Fig. 1.5.

The Lower Austroalpine Subunit (17) was derived from the continental margin towards the Penninic Ocean and was affected by extension and nappe stacking during the opening and closing of this domain, respectively. Being the structurally lowest part of the Austroalpine nappe pile, it occurs as a thin sleeve around the Penninic windows and in the Semmering area (Lower Austria/Styria). The Lower Austroalpine nappes and tectonic zones are mostly composed of crystalline basement with Neoproterozoic to Ordovician protolith ages and Permo-Mesozoic metasediments. They were sheared-off in the middle Late Cretaceous (c. 80 Ma) and experienced a lower greenschist facies metamorphic imprint during the Alpine event.

The Upper Austroalpine Subunit represents an Eoalpine nappe pile stacked in the Early to middle Late Cretaceous (135–85 Ma). Its lowermost part is the Silvretta-Seckau Nappe System (16) consisting of a basement with a dominating Variscan metamorphic imprint and remnants of Permian to Triassic cover sequences. During the Eoalpine orogenic event, it was overprinted by sub-greenschist to amphibolite facies conditions.

To the north, the Silvretta-Seckau Nappe System is overlain by the Veitsch-Silbersberg Nappe System (14), which consists of slivers of Variscan metamorphic basement rocks and Permo-Carboniferous sequences with a greenschist facies Alpine overprint. Above, the Juvavic (13), Tirolic-Noric (12) and Bajuvaric (11) nappe systems follow. These are composed of an up to 3200-m-thick pile of unmetamorphosed or lowermost greenschist facies metamorphic Permian and Mesozoic sediments and form the Northern Calcareous Alps. Additionally, the Tirolic-Noric Nappe System comprises a thick lower greenschist facies and fossiliferous Palaeozoic sequence. These Palaeozoic rocks as well as those from the Veitsch-Silbersberg Nappe System are often referred to as the Greywacke Zone. Its mostly schistose rocks form a relatively smooth landscape, e.g. in the area around Kitzbühel (Tyrol). The thick Mesozoic piles form the Northern Calcareous Alps with the typical bright coloured cliffs in between the Montafon (Vorarlberg) and the Wienerwald (Lower Austria) (Fig. 1.7a).

To the south, the Silvretta-Seckau Nappe System is overlain by three nappe systems that form the crystalline basement axis in large parts of Austria. The Koralpe-Wölz Nappe System (15) represents the Eoalpine metamorphic extrusion wedge. Its Permo-Mesozoic cover was completely stripped off during an early phase of the Eoalpine orogenic event (in the Early Cretaceous) and therefore it consists exclusively of polymetamorphic basement nappes with a Permian amphibolite high-temperature/low pressure and an Eoalpine pressure-dominated metamorphic overprint. The metamorphic grade of the latter is greenschist to eclogite facies in the individual nappes. The Ötztal-Bundschuh Nappe System (10) shows a similar lithological composition as the Silvretta-Seckau Nappe System but is positioned above the Koralpe-Wölz Nappe System. On top, there is the Drauzug-Gurktal Nappe System (9), which is made up of a Variscan metamorphic basement, anchizonal to greenschist

Fig. 1.7 Field photographs of typical landscapes in the central Eastern Alps. **a** View from above the Salzach Valley towards the town of Bischofshofen and the Tennengebirge (highest peak 2430 m, Salzburg). The area is built up by the Tirolic-Noric Nappe system of the Austroalpine unit. Palaeozoic schistose rocks (formerly known as Greywacke zone) build up the gentle hills in the foreground, whereas the bright coloured rock walls of the Tennengebirge are formed by Triassic platform carbonates (Northern Calcareous Alps). The plateau on top of the mountains represents the Oligocene Dachstein palaeosurface. **b** View from above the Gurk Valley (Carinthia) to the villages Gurk and Straßburg in the foreground and the Saualpe and Zirbitzkogel (2396 m) in the background. The hilly area in front consists of phyllite of the Drauzug-Gurktal Nappe System, whereas the mountains in the background are built up by micaschists and paragneisses of the Koralpe-Wölz Nappe system (both are part of the Upper Austroalpine subunit). As the Gurktal region formed an ice-free oasis during the Pleistocene glaciation periods (see van Husen 2011), the relatively gentle topography in the foreground preserves several Pre-Pleistocene planation surfaces that can be used to derive stages of the uplift history. Photos from: www.alpengeologie.org

facies Palaeozoic metasedimentary sequences and by unmetamorphosed Permian to Triassic sediments (Rantitsch and Russegger 2000). Within the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems, the Eoalpine metamorphic grade decreases upwards from epidote–amphibolite facies at the base to diagenetic conditions at the top of the nappe pile.

The last three nappe systems form the principal basement units in the central and southern part of the Eastern Alps.

In the west, they build up high and rough mountains in the Silvretta (Vorarlberg/Tyrol) and Ötztal (Tyrol) areas, whereas further to the east, the topography is lowering via the Niedere Tauern (Salzburg/Styria), Gurktaler Alps (Carinthia/Styria; Fig. 1.7b), Saualpe and Koralpe mountains (Styria), as far as the hills of the Bucklige Welt (Styria/Lower Austria/Styria). Dependent on the elevation, the character of the landscape formed by these units differs. Typically, isolated occurrences of Permo-Mesozoic sequences appear as bright coloured, cliffy rock formations within the rather smooth topography formed by the monotonous basement rocks.

The **Tatric Unit** (8) is a tectonic element from the Central Western Carpathians, which reaches into the territory of Austria in the hills of the Hainburger Berge (Lower Austria/Burgenland). It is built up of Variscan metamorphic basement intruded by early Carboniferous granites and a Permo-Mesozoic cover series. Today, these rocks remain little deformed and are overprinted only by anchizonal or lowermost greenschist facies conditions during the Cretaceous Eoalpine event.

In contrast to all Alpine units described above, the **Southalpine Unit** (7) is considered to represent a southern external retro-arc orogenic wedge (Schmid et al. 1996). The Southalpine nappes were mobilized in the Eocene, and in the territory of Austria, they are composed of Variscan weakly metamorphosed, fossiliferous Palaeozoic rocks and Permo-Triassic sequences. The Alpine overprint reaches anchizonal conditions. They form rough mountain ranges including the Carnic Alps (Fig. 1.8a) and the South Karawanken (Carinthia).

1.3.2.4 Slices Derived from the Neotethys Oceanic Realm

The **Meliata Unit** (6) of the Eastern Alps consists of remnants from the Neotethys Ocean. It forms only small slices originally obducted onto the Adriatic continental margin in the Middle Jurassic (c. 160 Ma). Today, it is squeezed between Austroalpine nappes in the eastern part of the Northern Calcareous Alps. The Meliata Unit comprises serpentinites, basic volcanic rocks and Triassic olistolithes as well as radiolarites embedded in Jurassic turbidites. They show a sub-greenschist facies metamorphic imprint. These rocks can be correlated to those of the Meliata zone in the Western Carpathians (Mandl 2000). Material from the Neotethys Ocean is also present as detritus in Austroalpine units included in several Cretaceous formations (Faupl and Wagreich 2000), and in the “Haselgebirge”, an evaporite tectonite at the base of the Juvavic and Tirolic-Noric nappe systems (Schorn et al. 2013).

1.3.2.5 Eocene to Miocene Magmatism

The **Periadriatic intrusions** (3) comprise calc-alkaline tonalites, granodiorites and granites and minor alkaline basaltic dikes present along the Periadriatic fault (e.g. Rieserferner pluton; Deferegger Alps/Carinthia). They are late Eocene to early Oligocene (40–28 Ma) in age and related to the break-off of the subducted slab from the distal European margin at depth (Davies and von Blankenburg 1995). Their intrusion is closely associated with contemporaneous strike-slip movements along the Periadriatic fault. Miocene to Quaternary volcanic rocks (18.0–1.9 Ma) related to the **Pannonian magmatism** (4) developed in the course of the extensional tectonics during the formation of the Pannonian Basin (Fodor et al. 2008; Lukács et al. 2018). In a first phase, more acidic trachytes, dacites and andesites were extruded, whereas a second phase is characterized by alkaline andesitic to basaltic rocks, e.g. at Klöch/Styria or Pauliberg/Burgenland (cf. Chap. Geomorphological Evidence of Past Volcanic Activity in the Southeast of Austria).

1.3.2.6 Oligocene and Neogene Basins Within the Alps

Remnants of Oligocene sedimentary sequences (34–23 Ma) occur on top of the plateaus of some mountains in the eastern Northern Calcareous Alps (e.g. Hochschwab, Dachstein). They are referred to as the Augenstein Formation and represent relics of locally more than 1000-m-thick sedimentary piles of quartz-rich gravels that formed in the southern continuations of the Molasse Basin (Frisch et al. 2001; Kuhlemann 2007). Also, along the Inntal Fault, a sequence dominated by conglomerates and sandstones is preserved.

Neogene basins on top of the Alpine orogenic wedge (2) occur in the eastern part of the Eastern Alps and in the neighbouring Western Carpathians and Pannonian region. They are mostly filled by clastic sediments generated during the lateral extrusion of the Eastern Alps in the Miocene (Ratschbacher et al. 1989). Most of these basins developed as half-grabens or pull-apart basins along active faults. Some, like the Vienna Basin, show a polyphase evolution with a piggy-back geometry reactivated as a pull-apart basin (Decker et al. 2005). Of special interest is the Klagenfurt Basin, which is a foreland basin of the overriding Karawanken today (Nemes et al. 1997), but originated as a pull-apart basin (cf. Chap. Klagenfurt Basin: A Large Basin in the Alps). All basins show individual sedimentary successions, generally starting in the Carpathian (17.5 Ma), with clastic detritus from the surroundings and intercalated coal deposits (e.g. Fohnsdorf Basin, Leoben Basin, Sachsenhofer et al. 2010). The Pannonian, Styrian, Vienna and Lavanttal basins contain

Fig. 1.8 Field photographs of typical landscapes. **a** View along the Gail Valley close to Villach towards the west (Carinthia). Within the Gail Valley the Periadriatic fault is located. This fault was active in the Oligocene and during the Miocene lateral extrusion of the Eastern Alps. North of it, the Austroalpine Unit with Mount Dobratsch (2166 m) is visible. The steep rock walls at its southern side consist of Triassic platform carbonates. In the south, the Southalpine Unit composed of Palaeozoic sediments of the Carnic Alps (Ca) and Triassic carbonates in the Julic Alps (Ju) in Slovenia and Italy, is visible. **b** View eastward over the Styrian Basin with the castle of Riegersburg (c. 350 m altitude) in the foreground. The castle is located on top of Miocene volcanic rocks related to the Pannonian magmatism. The gentle hills in the surrounding are formed by Neogene sediments of the Styrian Basin. Photos from: www.alpengeologie.org

marine Badenian to Sarmatian successions with more coarse-grained fan and coastal sediments at the margins and sand and clay in the central part. In many places the sediments are interlayered by volcanic rocks related to the Pannonian magmatism. Early Pannonian sediments developed in a brackish environment. Fluvial conglomerates and sands form the youngest deposits (Harzhauser and Tempfer 2004; Gross et al. 2007).

Where Quaternary sedimentation or planation progressed (e.g. Marchfeld in the Vienna Basin east of Vienna), the basins show flat topography, but more frequently they are characterized by a smooth topography due to young uplift, erosion and a superimposed drainage system. In the Styrian Basin, the pipes of the volcanic centres form steep hills representing the highest elevations of the region (e.g. Klöch or Riegersburg/Styria; Fig. 1.8b).

1.4 Mantle Structure Beneath the Eastern Alps

The processes in the Earth's mantle have an important influence on the elevation of the Earth's surface with respect to both isostatically supported and dynamic topography (e.g. Friedrich et al. 2018). Therefore, a summary of our knowledge about the mantle structure beneath the Eastern Alps is given. Much of this information was obtained from the TRANSALP project that produced a deep seismic reflection profile in a traverse across the Alps from Munich to Treviso in 1998 and 1999 (e.g. Lüschen et al. 2004). More insight can be expected in the near future as the large-scale geophysical AlpArray project (AlpArray Seismic Network 2015) is processed at present.

The Mohorovičić discontinuity (MOHO)—the boundary between the crust and the lithospheric mantle—is at a depth of about 30–35 km to the north of the Alpine arc and becomes generally deeper towards the south (Fig. 1.9a). In the west, it dips steeply and can be traced until 60 kms depth, where it disappears below another MOHO surface. The latter is bent around an east–west trending axis with a hinge at 25–30 km depth below the Po Basin. Its northern limb dips below the Alps and the southern one below the Apennines. Towards the east, from East Tyrol onward, the gap between the MOHO surfaces decreases and finally disappears in the Pannonian Basin, where the MOHO is generally at about 26 km depth (Ziegler and Dèzes 2006). The MOHO that descends below the Alpine orogen in the north belongs to the Eurasian Plate, whereas that in the south

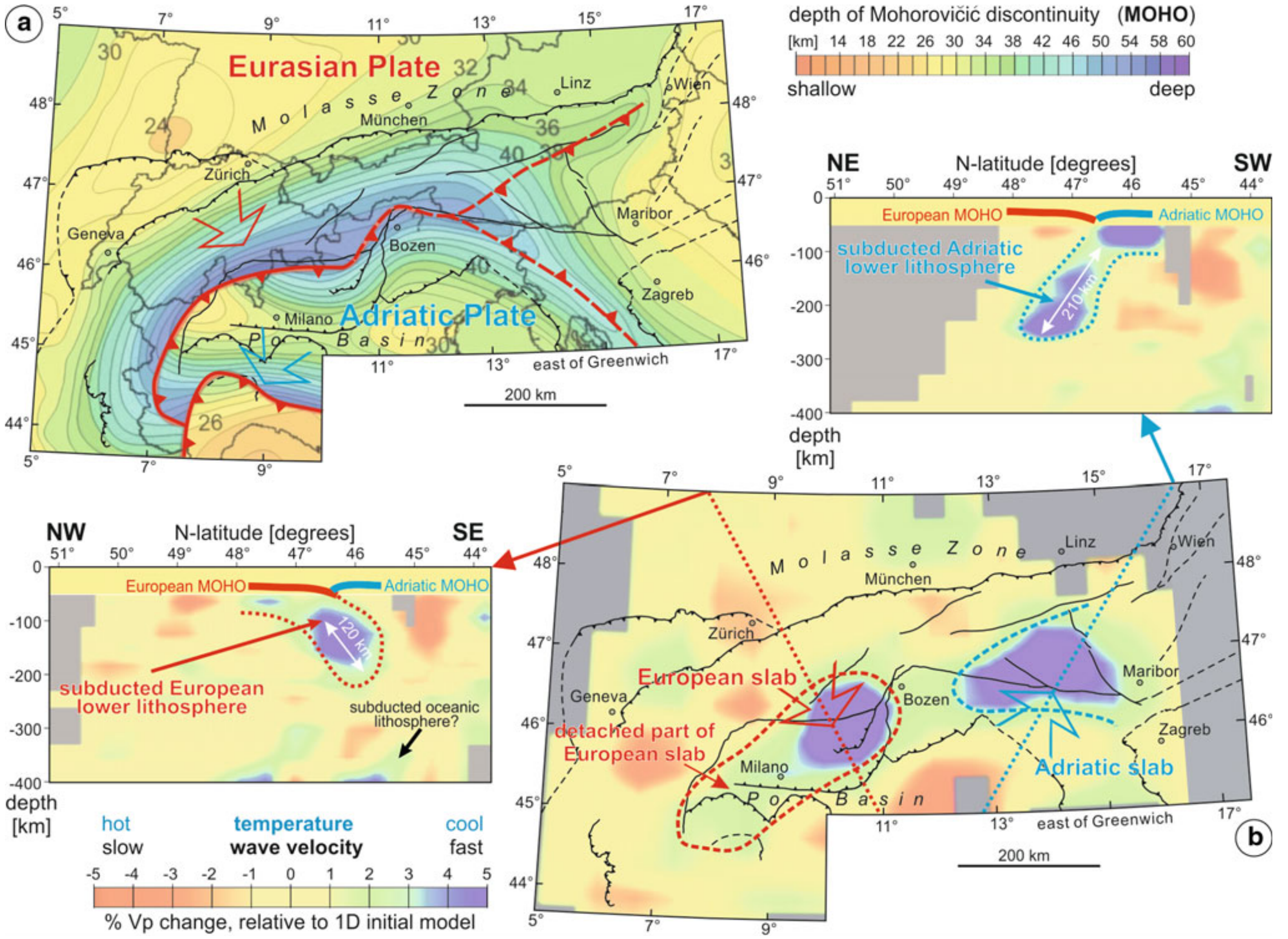


Fig. 1.9 Geophysical information on the deep structure of the Alps and surrounding areas shown for the same area as the tectonic map of Fig. 1.2c. The map **a** shows the depth of the MOHO discontinuity (Ziegler and Dèzes 2006). It may be seen that the MOHO of the Eurasian Plate dips southward and that of the Adriatic Plate dips northward below the Alpine orogenic wedge. In the west, the Adriatic Plate overrides the Eurasian Plate, whereas the situation is more diffuse in the east. Map and sections in **b** image the teleseismic mantle tomography (Lippitsch et al. 2003). Map view shows the P-wave velocity structure beneath Alps in 150 km depth. Based on the sections Schmid et al. (2004) argue for a European slab of lithospheric mantle below the western part of the Alpine arc, whreas in the eastern part an Adriatic slab is interpreted. For further explanation see text

reflects the Adriatic Plate. This indicates overriding of the Adriatic Plate onto the European Plate in the west, but a diffuse situation in the east. This may be the consequence of the Miocene east–west extension.

Teleseismic tomography data (e.g. from the ALPASS project; Brückl et al. 2007) indicate a mass of material with faster wave velocities (colder areas) below the Alpine arc (Fig. 1.9b). However, there are two cold spots, one below Lombardy and the second below East Tyrol and Carinthia. They indicate slabs of subducted lithospheric mantle hanging down deep (>200 km) into the asthenospheric mantle. While there is no doubt that the western slab is belonging to the Eurasian Plate, there is an ongoing discussion about the eastern slab, whether it belongs to the Eurasian or Adriatic Plate (Lippitsch et al. 2003; Mitterbauer et al. 2011).

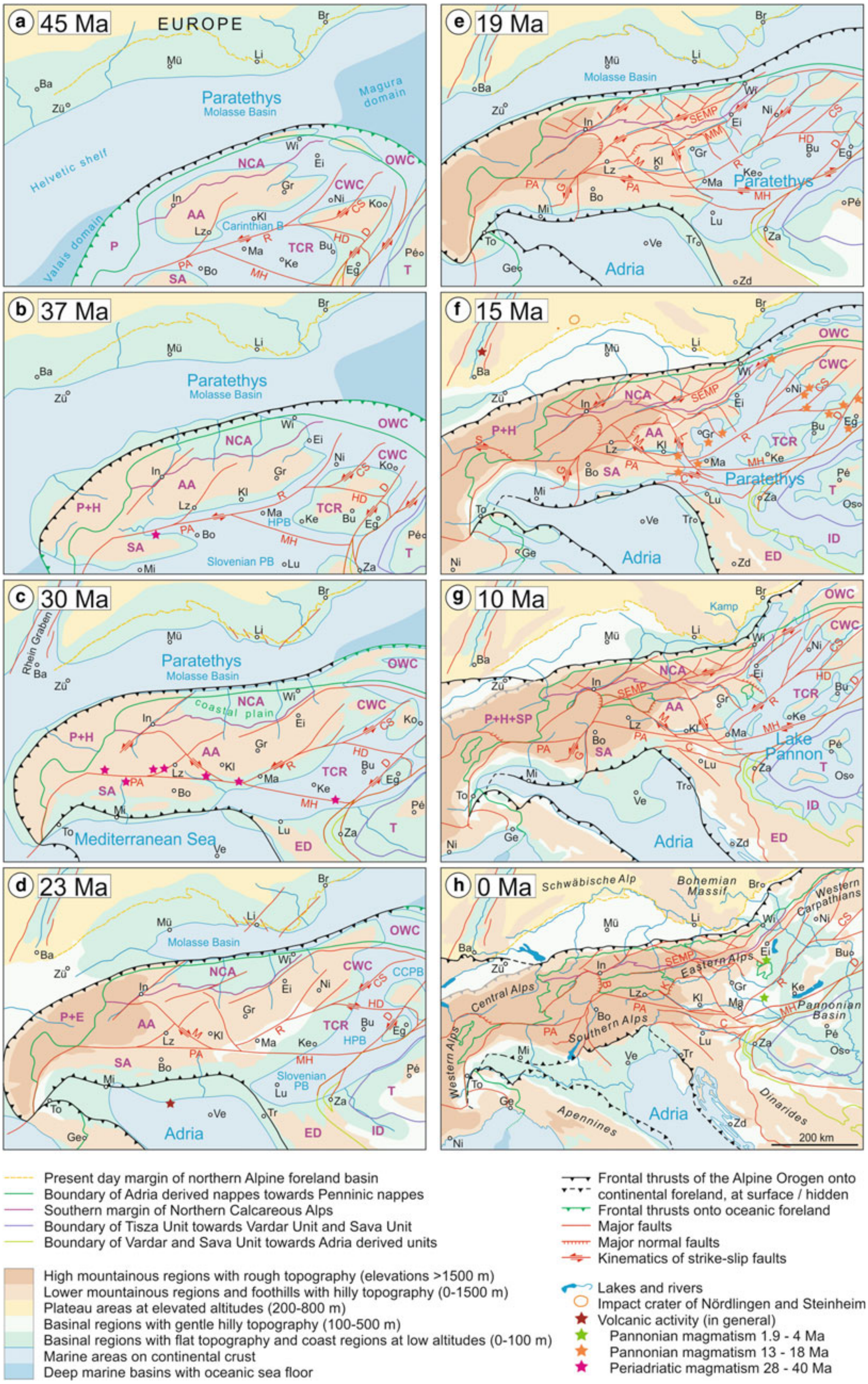
In any case, these slabs are heavy and compensate the increased thickness of light continental crust accumulated in the Alpine orogenic wedge, which is indicated by the greater MOHO depth in this area. Changes in the thickness of the crust (e.g. due to erosion) as well as changes in the thickness of the lithospheric mantle (e.g. due to thermal erosion or slab break-off) have a major influence on the elevation of the area because of isostatic rebound.

1.5 Evolution of the Landscape

This section describes the evolution of surface topography and the distribution of land and sea in the Austrian territory from the Eocene to the present (Fig. 1.10). In this context, it is important to note that there is an important change in the nomenclature of geographic places in the Eocene. This is because the Mesozoic oceanic basins were completely dismembered at that time. Therefore, for the time afterwards, Paratethys is now the name for the sea to the north and on top of the Alpine orogenic wedge, whereas the Mediterranean Sea is the sea to the south.

In the middle Eocene (c. 45 Ma), the morphology, the distribution of land and sea and the spatial relationships between geographic points on the Earth's surface were very different from today. The Penninic oceanic lithosphere, formerly located to the north of the Alpine orogenic wedge, was now mostly subducted and the wedge started overriding the southern margin of the Eurasian continent with the rate of a few millimetres per year (Fig. 1.10a, 45 Ma). The flexural foreland basin (Molasse Basin) was filled by the Paratethys sea. The Paratethys got wider towards the east where it was partly floored by some remnants of Penninic oceanic lithosphere (Magura domain) in the area of the Carpathian arc and the Pannonian Basin. To the north of the Molasse Basin, flat low-lying topography characterized the southern margin of the European continent. The climate was warm and forests covered the land. Further south, in the region of the Alps, there was an island arc, but little is known about the distribution of land and sea in this area. Thermochonological data indicate that most of the Alpine metamorphic units were still at several kilometres depth and only a few isolated areas were already exhumed in the earliest Palaeogene (Hejl 1997). The preservation of up to 50 Ma old low-temperature geochronological ages in these regions suggests that erosion rates and probably topography were generally low.

During the late Eocene and Oligocene (37.8–23.0 Ma), the Alpine orogenic wedge moved continuously northward causing topographic loading at the European southern margin (Frisch et al. 1998). The result was continuing subsidence and a northward shift of the northern shoreline and of the axis of the Paratethys sea arm that paralleled the orogenic front (Fig. 1.10b; 37 Ma). In the late Eocene, the subducted lithospheric mantle slab from which all the Alpine nappes were detached, broke off from the Eurasian plate some hundreds of kilometres below the western parts of the Alps and sank into the asthenospheric mantle. This slab break-off (von Blankenburg and Davies 1995) caused important changes to many tectonic and geomorphic processes. Due to isostatic rebound from the removed heavy burden at depth, first rapid surface uplift of the range began and a moderate mountain range developed between the Western Alps and around the Inn Valley (Fig. 1.10c; 30 Ma). The Molasse Basin immediately to the north of this region also rose and marine sedimentation terminated west of Munich in the late Oligocene (Fig. 1.10d; 23 Ma). The eastern part of the Alps stayed at low altitude and formed a low-lying peninsula into the Paratethys Sea. This peninsula included the Western Carpathians, which also rose above sea level at this time. The build up of topography caused the onset of erosion and exhumation of many rocks that lie at the surface today (Kuhlemann et al. 2001). The southern part of the Eastern Alps (areas in Styria, Carinthia and Burgenland) was hilly, with rivers draining towards the north where the area of the Northern Calcareous Alps formed a coastal plain with fluvial gravel fans (Frisch et al. 2000, 2001). Remnants of these gravel plains (Augenstein Formation) are still preserved on top of the plateaus of the Northern Calcareous Alps, for example, on the Dachstein Plateau. Along the axis of the peninsula, the Periadriatic fault was active with a sinistral sense of shear until c. 30 Ma (Mancktelow et al. 2001). Granites intruded into the fault zone and especially in the western part, volcanoes erupted. Along the southern margin of the Bohemian Massif between Linz and Amstetten, the coast line was structured with sand beaches and cliffs that formed along reactivated Variscan faults. Further east, mud


a 45 Ma
EUROPE
Paratethys
Molasse Basin
Magura domain
Helvetic shelf
Valais domain
NCA
AA
CWC
OWC
TCR
Carinthian B
P
SA
PA
MH
T
b 37 Ma
Paratethys
Molasse Basin
P+H
HPB
Slovenian PB
c 30 Ma
Rhein Graben
Paratethys
Molasse Basin
coastal plain
Mediterranean Sea
ED
d 23 Ma
Molasse Basin
P+E
CCPB
HPB
Slovenian PB
Adria
ID
e 19 Ma
Molasse Basin
SEMP
Paratethys
Adria
f 15 Ma
Paratethys
Adria
g 10 Ma
Kamp
P+H+SP
Lake Pannon
Adria
h 0 Ma
Schwäbische Alp
Bohemian Massif
Western Carpathians
Eastern Alps
Central Alps
Southern Alps
Western Alps
Pannonian Basin
Apennines
Dinarides
Adria
200 km
Present day margin of northern Alpine foreland basin
Boundary of Adria derived nappes towards Penninic nappes
Southern margin of Northern Calcareous Alps
Boundary of Tisza Unit towards Vardar Unit and Sava Unit
Boundary of Vardar and Sava Unit towards Adria derived units
High mountainous regions with rough topography (elevations >1500 m)
Lower mountainous regions and foothills with hilly topography (0-1500 m)
Plateau areas at elevated altitudes (200-800 m)
Basinal regions with gentle hilly topography (100-500 m)
Basinal regions with flat topography and coast regions at low altitudes (0-100 m)
Marine areas on continental crust
Deep marine basins with oceanic sea floor
Frontal thrusts of the Alpine Orogen onto continental foreland, at surface / hidden
Frontal thrusts onto oceanic foreland
Major faults
Major normal faults
Kinematics of strike-slip faults
Lakes and rivers
Impact crater of Nördlingen and Steinheim
Volcanic activity (in general)
Pannonian magmatism 1.9 - 4 Ma
Pannonian magmatism 13 - 18 Ma
Periadriatic magmatism 28 - 40 Ma

◀ **Fig. 1.10** Palaeogeographic reconstructions showing the landscape evolution of the Eastern Alps and surrounding areas since the Eocene. Changes in the spatial relationships between geographic points at the Earth's surface are indicated by geologic marker lines (see legend) and selected cities. The figure was constructed from the integrated information of Hejl (1997), Frisch et al. (2001), Rögl (2001), Wagner et al. (2010, 2011), Legrain et al. (2015), Kováč et al. (2016), Bartosch et al. (2017), Dertnig et al. (2017), Schmid et al. (2017) and several others. Explanation see text. Abbreviations: cities (Black) Ba = Basel, Bo = Bozen, Br = Brno, Bu = Budapest, Eg = Eger, Ei = Eisenstadt, Ge = Genova, Gr = Graz, In = Innsbruck, Ke = Keszethely, Kl = Klagenfurt, Ko = Košice, Li = Linz, Lu = Lubliana, Lz = Lienz, Ma = Maribor, Mi = Milano, Mü = München, Ni = Nice, Nt = Nitra, Os = Osijek, Pé = Pécs, To = Torino, Tr = Trieste, Ve = Venezia, Wi = Wien, Za = Zagreb, Zd = Zadar, Zü = Zürich. Major faults (red) B = Brenner normal fault, C = Celje fault, CS = Central Slovak fault, D = Darno fault, G = Giudicaria fault, HD = Hurbanovo-Diósjenő fault, I = Inntal fault, K = Katschberg normal fault, L = Lavanttal fault, M = Mölltal fault, MM Mur-Mürz fault, PA = Periadriatic fault, R = Rába fault, S = Simplon fault, SEMP = Salzach-Ennstal-Mariazell-Puchberg fault. Major geologic units (violett) CAA = Austroalpine nappes of the Central Eastern Alps, CWC = Central Western Carpathians, ED = External Dinarides, H = Helvetic nappes, ID = Internal Dinarides, NCA = Northern Calcareous Alps, OWC = Outer Western Carpathians, P = Penninic nappes, SA = Southalpine Unit, SP = Subpenninic nappes, T = Tisza Unit, TCR = Transdanubian Central Range. Marine basins (blue) HPB = Hungarian Palaeogene Basin, SPB = Slovenian Palaeogene Basin, CCPB = Central Carpathian Palaeogene Basin

plains with mangrove forests existed. The hinterland was drained by a precursor of the Kamp River, which entered via the Horn Basin (Steininger and Steiner 2005).

The evolution during the early Miocene (Egerian–Eggenburgian–Ottnangian, 23.0–17.5 Ma) was characterized by ongoing convergence between the Adriatic and Eurasian plates and west-directed subduction of the last remnants of Penninic oceanic lithosphere in the east. This subduction zone rolled rapidly eastward, opening up space within the Carpathian arc (Royden et al. 1983, Ren et al. 2012). Continental units coming in from the sides filled this space, for example the Alpine orogenic wedge, which experienced eastward lateral extrusion (Ratschbacher et al. 1991, Robl et al. 2008a, Wölfler et al. 2011). This lateral extrusion caused formation of large orogen-parallel strike-slips faults (Fig. 1.10e; 19 Ma) with sinistral motion in the north of the range (e.g. Inntal fault, SEMP fault, Mur-Mürz fault) and dextral motion in the south (e.g. Lavanttal fault, Mölltal fault, Periadriatic fault; Fig. 1.8a). North–south shortening in front of the Adriatic indenter caused thickening of the crust in the area around the Tauern Window and contemporaneous east–west extension led to crustal thinning in the eastern part of the Eastern Alps and the Pannonian region (Ratschbacher et al. 1989). Rapid exhumation in response to both, topography induced erosion and extension along north–south striking detachments like the Brenner and Katschberg normal faults commenced (Wölfler et al. 2011, 2012). The formerly north–south running drainage systems began to orient themselves along the newly formed east–west striking faults (Frisch et al. 1998, Robl et al. 2008a, Bartosch et al. 2017). These tectonic processes resulted in frequent changes in the distribution pattern of the sea. A global circum-equatorial seaway was established in the Eggenburgian (20.5–18.5 Ma) and caused warming of the climate (Rögl 1999) and thermophile fauna migration from the Indian Ocean. Sea level rise caused marine transgression of the Paratethys in the area around Horn in the southeastern Waldviertel. At the end of the Eggenburgian the circum-equatorial current was cut off and the climate got cooler. The Paratethys lost its contact with the Indian Ocean. However, due to further loading by the propagating Alpine orogenic wedge onto the Eurasian plate, a sea arm north of the Alps redeveloped that connected the Paratethys to the Mediterranean Sea. In the Ottnangian (at c. 18 Ma), overthrusting of the orogenic wedge onto the Eurasian Plate terminated along the northern front of the Eastern Alps, as ongoing convergence was now accommodated within the wedge. This caused further uplift of the area. Contemporaneously, the global sea level subsided due to the growth of the Antarctic ice shield. As a consequence, the western part of the Molasse Basin in Bavaria and in Upper Austria lost its marine ingression. In the east, the Paratethys became isolated and the salinity dropped dramatically, with lethal consequences for most species of the marine fauna. At that time, the Eastern Alps still had a very moderate morphology in the west and only a hilly landscape in the east.

During the middle Miocene (Carpathian–Badenian–Sarmatian, 17.5–11.6 Ma) the Tauern Window was rapidly exhumed (Wölfler et al. 2011; Fox et al. 2016) and the increasing relief of the range caused rapid erosion providing the Molasse Basins with substantial quantities of sediments (Kuhlemann et al. 2001). Cooling ages of this time are widespread in Austria, indicating final exhumation of most regions along the central axis of the Alps (Fox et al. 2016). Exhumation was accompanied by successive surface uplift that was interrupted by stagnation phases accounting for the origin of planation surfaces like the Nockberge surface (Hejl 1997). The hilly landscape in the eastern part of the Eastern Alps was now cut by distinct east–west oriented drainage systems along the newly established orogen-sized strike-slip faults (Fig. 1.10f; 15 Ma). Pull-apart basins that formed along these faults were filled by local gravel and often turned into swampy areas with alluvial forests (e.g. Tamsweg, Lavanttal, Trofaiach basins). Early forms of the Mur and Drau transported material into the Vienna and Styrian basins in the east. Due to tilting of the Koralpe (Legrain et al. 2015), large clastic fans developed along the western margin of the Styrian Basin. In the Styrian and Pannonian basins stratovolcanoes formed (e.g. Riegersburg; Gross et al. 2007). In response to the tectonic activity and sea level rise due to global temperature increase at the end of the Carpathian (c. 16.5 Ma), the Paratethys sea was re-connected to the global ocean (Rögl 1999). However, its shape was very different from before, as most of the basins that had formed on top of the orogenic wedge and the Alpine foreland basin east of the Bohemian Massif were flooded. In the Sarmatian (13.0–11.5 Ma), the Paratethys was finally isolated from the Indian Ocean and formed an inland sea reaching as far as the Caspian Sea in the east. Volcanic activity, especially in the eastern part of the Pannonian Basin, caused changes in water chemistry and faunal depletion. In the northern part of the Vienna Basin, colonies of seal populated an island at Steinberg near Zistersdorf (Lower Austria). For the last time, a shallow sea arm extended 40 km westward along the Zaya Valley into the Alpine foreland basin. Broad mudflats existed along its coast (Steininger and Steiner 2005). The western part of the Styrian Basin rose above sea level (Gross et al. 2007). Along the retreating shores, brackish environments were established. In the late Sarmatian, further uplift of the Alpine area caused the final retreat of the inland sea from the Alpine foreland basin. Large volumes of clastic material were transported into the Molasse, Vienna and Styrian basins and up to 100-m-thick gravel fan sediments were deposited. Warming climate and less fresh water input caused increased salinity and saturation in calcium carbonate so that oolithes developed along the wide coastal beaches. At the end of the Sarmatian, the climate got cooler again, the Vienna and Styrian basins fell dry and rivers cut into the sedimentary basin fill.

The time span of the late Miocene (Pannonian–Pontian, 11.6–5.3 Ma) is characterized by final retreat of the Paratethys Sea (Rögl 1999) due to inversion of the Pannonian Basin. However, in the early Pannonian (c. 11.0 Ma) a last ingression of the Paratethys still reached the Vienna and Styrian basins (Fig. 1.10g; 10 Ma). After that, the Pannonian, Vienna and Styrian basins were isolated from the Paratethys and a brackish environment was established. This stage is referred to as Lake Pannon. General consensus holds that this basin inversion was caused by the cessation of subduction underneath the Carpathian arc in connection with the onward extrusion of the Alps to the east (e.g. Bada et al. 2007). The Vienna Basin formed a large embayment as the northwestern part of Lake Pannon at this time. A proto-Danube, with a catchment area reaching to Salzburg and Upper Austria came in from the west and deposited a large alluvial fan from Krems, via Hollabrunn to Mistelbach. In the Styrian Basin, a deltaic fan formed from the Feistritz Valley, whereas there was no fan from the Mur Valley at this time (Schuster et al. 2016). In the late Pannonian (c. 8.5 Ma), Lake Pannon retreated from the Styrian and Vienna basins. In the latter, the Danube entered north of the Leiser Mountains. Large areas in the basins were vast floodplains with meandering main channels, rivulets and stagnant lakes embedded in floodplain forests. At about 7.0 Ma the floodplain forests were replaced by steppe (Harzhauser and Tempfer 2004).

Since the Miocene–Pliocene transition (c. 5.3 Ma), a remarkable new phase of rock uplift started that involved at least 500 m (e.g. Wagner et al. 2010; Legrain et al. 2014, 2015). This rock uplift caused surface uplift of the eastern end of the Alps to its present elevation and hundreds of metres of erosion in the surrounding basins, the Molasse Basin and the Styrian Basin, where the net surface uplift remained therefore small (Ebner and Sachsenhofer 1995; Genser et al. 2007). It also uplifted the Bohemian Massif by several hundreds of metres. Because of the long wavelength of this event, the causes for this rejuvenation of uplift are thought to be in the mantle (Baran et al. 2014; Legrain et al. 2014). Changes of the base level caused modelling of different landscapes dependent on the distribution of different lithologies. Rivers like the Danube (Wachau), Kamp or Thaya now began to cut gorges into the hard rocks forming the relatively flat but elevated topography of the Bohemian Massif, whereas in the area of the Molasse Basin a gentle hilly landscape developed from the weak sediments (Baumann et al. 2018). In the Alps, the stepwise uplift led to a series of planation events that are recorded as a series of successive level surfaces at different altitudes (Fig. 1.7b). The elevation of these levels is lower than that of the Miocene Nockberge surface and higher than the Pleistocene glacial terraces. They can be found in many regions at the eastern end of the Alps, for example, in the Koralpe, the Grazer Bergland, the Gurktal Alps and the Niedere Tauern (Winkler-Hermaden 1955; Wagner et al. 2011; Dertnig et al. 2017). From the Pliocene onward, important changes of the river systems can be deduced. For example, in the late Pliocene (c. 2.6 Ma), the Danube left the Vienna Basin in between the Hainburg Mountains and Leithagebirge into the Pannonian Basin, whereas the Morava entered the Pannonian Basin between the Little Carpathians and the Hainburg Mountains. Later on, in the Pleistocene, a tributary of the Morava River, captured the Danube and since that time both rivers leave the Vienna Basin through a gap between the Little Carpathians and Hainburg Mountains. Further south, another river coming in from the Pannonian Basin between Hainburg Mountains and Leithagebirge captured the Leitha River (Zámolyi et al. 2016). The river Mur that had flown across the Semmering Pass into the Vienna Basin now was captured by a small drainage near Graz and started flowing south towards the Styrian Basin.

The morphology established during the Pliocene was significantly modified during the Pleistocene glaciation periods (van Husen 2000, Robl et al. 2008b, 2015). In many parts of Austria, glaciers lowered the topography by up to several hundreds of metres. At the easten end of the Alps, however, several mountains (reaching up to 2000 m above sea level; Fig. 1.10h) were not affected by pervasive glaciation (Koralpe, parts of the Seckauer Tauern, Schneeberg, etc.). They preserved morphological features that are relicts of the surface uplift history since the Eocene (e.g. Winkler-Hermaden 1955, Frisch et al. 1998, Wagner et al. 2010, Legrain et al. 2014, 2015). Therefore, Eastern Austria forms an ideal study area for investigating the pre-Pleistocene landscape evolution of the entire Alps and for addressing modern reseach questions. Such questions are the relative importance of glacial erosion versus deep tectonic forcing on modern erosion rates and uplift in a mountain belt (e.g. Dixon et al. 2016), or the stages of mountain development from uplift to a steady state of uplift & erosion to final erosion (e.g. Hergarten et al. 2010).

References

AlpArray Seismic Network (2015) AlpArray seismic network (AASN) temporary component. AlpArray working group. Other/Seismic Network. https://doi.org/10.12686/alparray/z3_2015

Bada G, Horvath F, Dövenyi P, Szafian P, Windhoffer G, Cloetingh S (2007) Present-day stress field and tectonic inversion in the Pannonian basin. Glob Planet Change 58:165–180

Baran R, Friedrich AM, Schlunegger F (2014) The late miocene to holocene erosion pattern of the Alpine foreland basin reflects Eurasian slab unloading beneath the western Alps rather than global climate change. Lithosphere 6(2):124–131. https://doi.org/10.1130/L307.1

Bartosch T, Stüwe K, Robl J (2017) Topographic evolution of the Eastern Alps: the influence of strike-slip faulting activity. Lithosphere 9(3):384–398

Baumann S, Robl J, Prasicek G, Salcher B, Keil M (2018) The effects of lithology and base level on topography in the northern alpine foreland. Geomorphology 313:13–26

Brückl E, Bleibinhaus F, Gosar A, Grad M, Guterch A, Hrubcová P, Keller GR, Majdanski M, Sumanovac F, Tiira T, Yliniemi J, Hegedüs E, Thybo H (2007) Crustal structure due to collisional and escape tectonics in the Eastern Alps region based on profiles Alp01 and Alp02 from the ALP 2002 seismic experiment. J Geophys Res 112:B06308. https://doi.org/10.1029/2006JB004687

Davies JH, von Blanckenburg F (1995) Slab breakoff: a model of lithospheric detachment and its test in the magmatism and deformation of collisional orogens. Earth Planet Sci Lett 129:85–102

Decker K (1990) Plate tectonics and pelagic facies: late Jurassic to early cretaceous deep-sea sediments of the Ybbsitz ophiolite unit (Eastern Alps, Austria). Sed Geol 67:85–99

Decker K, Peresson H, Hinsch R (2005) Active tectonics and quaternary basin formation along the Vienna basin transform fault. Quaternary Sci Rev 24:305–320

Dertnig F, Stüwe K, Woodhead J, Stuart FM, Spötl C (2017) Constraints on the Miocene landscape evolution of the eastern Alps from the Kalkspitze region, Niedere Tauern (Austria). Geomorphology 299:24–38

Dixon JL, von Blanckenburg F, Stüwe K, Christl M (2016) Glaciation's topographic control on Holocene erosion at the eastern edge of the Alps. Earth Surf Dynam 4:895–909. https://doi.org/10.5194/esurf-4-895-2016

Ebner F, Sachsenhofer RF (1995) Paleogeography, subsidence and thermal history of the Neogene Styrian basin (Pannonian basin system, Austria). Tectonophysics 242:133–150

Faccenna C, Becker TW, Auer L, Billi A, Boschi L, Brun JP, Capitanio FA, Funiciello F, Horvàth F, Jolivet L, Piromallo C, Royden L, Rossetti F, Piromallo C (2014) Mantle dynamics in the Mediterranean. Rev Geophys 52(3):283–332

Faupl P, Wagreich M (1992) Cretaceous flysch and pelagic sequences of the Eastern Alps: cretelations, heavy minerals, and paleogeographic implications. Cretaceous Res 13:387–403

Faupl P, Wagreich M (2000) Late Jurassic to Eocene palaeogeography and geodynamic evolution of the eastern Alps. Mitt Österr Geol Ges 92:79–94

Finger F, Schubert G (2015) Die Böhmische Masse in Österreich: was gibt es Neues? Abh Geol BA 64:167–179

Finger F, Hanžl P, Pin C, Von Quadt A, Steyrer HP (2000) The Brunovistulian: avalonian precambrian sequence at the eastern end of the central European variscides? Geol Soc Lon Spec Pub 179 (1):103–112

Fodor LI, Gerdes A, Dunkl I, Koroknai B, Pècskay Z, Trajanova M, Horwàth P, Vrabec M, Jelen B, Balogh K, Frisch W (2008) Miocene emplacement and rapid cooling of the Pohorje pluton at the Alpine-Pannonian-Dinaric junction, Slovenia. Swiss J Earth Sci 101:255–271

Fox M, Herman F, Willett SD, Schmid SM (2016) The exhumation history of the European Alps Inferred from linear inversion of thermochronometric data. Am J Sci 316(6):505–541. https://doi.org/10.2475/06.2016.01

Franke W (2000) The mid-European segment of the variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. Geol Soc Lond Spec Pub 179:35–61. https://doi.org/10.1144/GSL.SP.2000.179.01.05

Friedrich AM, Bunge HP, Rieger SM, Colli L, Ghelichkhan S, Nerlich R (2018) Stratigraphic framework for the plume mode of mantle convection and the analysis of interregional unconformities on geological maps. Gondwana Res 53:159–188. https://doi.org/10.1016/j.gr.2017.06.003

Frisch W (1979) Tectonic progradation and plate tectonic evolution of the Alps. Tectonophysics 60:121–139

Frisch W, Kuhlemann J, Dunkl I, Brügel A (1998) Palinspastic reconstruction and topographic evolution of the Eastern Alps during late tertiary tectonic extrusion. Tectonophysics 297:1–15. https://doi.org/10.1016/S0040-1951(98)00160-7

Frisch W, Székely B, Kuhlemann J, Dunkl I (2000) Geomorphological evolution of the eastern Alps in response to miocene tectonics. Z Geomorph 44(1):103–138

Frisch W, Kuhlemann J, Dunkl I (2001) The Dachstein paleosurface and the Augenstein formation in the northern Calcareous Alps—a mosaic stone in the geomorphological evolution of the eastern Alps. Int J Earth Sci 90:500–518

Fritz H, Dallmeyer RD, Neubauer F (1996) Thick-skinned versus thin-skinned thrusting: rheology controlled thrust propagation in the variscan collisional belt (The southeastern Bohemian Massif, Czech Republic—Austria). Tectonics 15(6):1389–1413

Froitzheim N, Manatschal G (1996) Kinematics of Jurassic rifting, mantle exhumation, and passive margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Geol Soc Am Bull 108:1120–1133

Froitzheim N, Schmid SM, Frey M (1996) Mesozoic paleogeography and the timing of eclogite facies metamorphism in the Alps: a working hypothesis. Eclogae Geol Helv 89:81–110

Froitzheim N, Plasienka D, Schuster R (2008) Alpine tectonics of the Alps and western Carpathians. In: McCann T (ed) The geology of central Europe. The Geological Society of London. https://doi.org/10.1144/CEV2P.6

Fuchs G (1976) Zur Entwicklung der Böhmischen Masse. Jb Geol BA 119:45–61

Fuchs G, Matura A (1976) Zur geologie des Kristallins der Böhmischen Masse. Jb Geol BA 119:1–43

Fügenschuh B, Seward D, Mancktelow N (1997) Exhumation in a convergent orogen: the western Tauern window. Terra Nova 9:213–217

Genser J, Neubauer F (1989) Low angle normal faults at the eastern margin of the Tauern window (Eastern Alps). Mitt Österr Geol Ges 81:233–243

Genser J, Cloetingh SAPL, Neubauer F (2007) Late orogenic rebound and oblique Alpine convergence: new constraints from subsidence analysis of the Austrian Molasse basin. Glob Planet Change 58:214–223

Gerdes A, Wörner G, Henk A (2000) Post-collisional granite generation and HT-LP metamorphism by radiogenic heating: the variscan south bohemian Batholith. J Geol Soc 157(3):577–587

Gross M, Fritz I, Piller WE, Soliman A, Harzhauser M, Hubmann B, Moser B, Scholger R, Suttner TJ, Bojar BP (2007) The neogene of the styrian basin—guide to excursions. Joannea Geol Paläont 9:117–193

Handy MR, Schmid SM, Bousquet R, Kissling E, Bernoulli D (2010) Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. Earth Sci Rev 102:121–158

Harzhauser M, Tempfer PM (2004) Late Pannonian wetland ecology of the Vienna basin based on molluscs and lower vertebrate assemblages (Late Miocene, MN 9, Austria). Courier-Forschungsinstitut Senkenberg 246:55–68

Hauer F (1867) Geologische Übersichtskarte der österreichisch-ungarischen Monarchie nach den Aufnahmen der K.K. Geol R.-A., M. 1:576.000. 12 Blatt. Geol RA, Wien

Hejl E (1997) Cold spots during the Cenozoic evolution of the eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics 272:159–173

Hergarten S, Wagner T, Stüwe K (2010) Age and prematurity of the Alps derived from topography. Earth Planet Sci Lett 297:453–460

Janák M, Froitzheim N, Yoshida K, Sasinková V, Nosko M, Kobayashi T, Hirajima T, Vrabec M (2015) Diamond in metasedimentary crustal rocks from Pohorje, eastern Alps: a window to deep continental subduction. J Metam Geol 33:495–512

Janák M, Froitzheim N, Lupták B, Vrabec M, Krogh-Ravna EJ (2004) First evidence for ultrahigh-pressure metamorphism in Pohorje, Slovenia: tracing deep continental subduction in the eastern Alps. Tectonics 23:TC5014. https://doi.org/10.1029/2004TC001641

Kober L (1938) Der geologische Aufbau Österreichs. Springer, Wien

Kossmat F (1927) Gliederung des variszischen Gebirgsbaues. Abh Sächs Geol LA 1:1–39

Kováč M, Plašienka D, Soták J, Vojtko R, Oszczypko N, Less G, Ćosović V, Fügenschuh B, Králiková S (2016) Paleogene palaeogeography and basin evolution of the western Carpathians, northern Pannonian domain and adjoining areas. Glob Planet Change 140:9–27

Kroner U, Romer RL (2013) Two plates—many subduction zones: the Variscan orogeny reconsidered. Gondwana Res 24(1):298–329

Kuhlemann J (2007) Paleogeographic and paleotopographic evolution of the Swiss and eastern Alps since the Oligocene. Glob Planet Change 58:224–236

Kuhlemann J, Frisch W, Dunkl I, Szekely B (2001) Quantifying tectonic versus erosive denudation by the sediment budget: the Miocene core complexes of the Alps. Tectonophysics 330:1–23

Kurz W, Neubauer F, Genser J, Unzog W, Dachs E (2001) Tectonic evolution of Penninic units in the Tauern window during the Paleogene: constraints from structural and metamorphic geology. In: Piller WE, Rasser MW (eds) Paleogene of the eastern Alps. Österr Akad der Wissensch, Schriftenreihe der Erdwissenschaftlichen Kommission 14:347–375

Kurz W, Froitzheim N (2002) The exhumation of eclogite–facies metamorphic rocks—a review of models confronted with examples from the Alps. Int Geol Rev 44:702–743

Legrain N, Stüwe K, Wölfler A (2014) Incised relict landscapes in a never glaciated part of the Eastern Alps. Geomorphology 221:124–138. https://doi.org/10.1016/j.geomorph.2014.06.010

Legrain N, Dixon J, Stüwe K, von Blanckenburg F, Kubik P (2015) Post-Miocene landscape rejuvenation at the eastern end of the Alps. Lithosphere 7(1):3–13. https://doi.org/10.1130/L391.1

Linner M (Sep 2013) Metamorphoseentwicklung und Deckenbau des Moldanubikums mit Fokus auf den Raum Melk—Dunkelsteinerwald. In: Gebhardt H (ed) Arbeitstagung 2013 der Geol Bundesanstalt, Melk 23.-27. Wien, pp 43–56

Linzer HG, Decker K, Peresson H, Dell'Mour R, Frisch W (2002) Balancing lateral orogenic float of the eastern Alps. Tectonophysics 54:211–237

Lippitsch R, Kissling E, Ansorge J (2003) Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. J Geophys Res 108. https://doi.org/10.1029/2002JB002016

Lukács R, Harangi S, Guillong, M. Bachmann O, Fodor L, Buret Y, Dunkl I, Sliwinski J, von Quadt A, Peytcheva I, Zimmerer M (2018) Early to mid-miocene syn-extensional massive silicic volcanism in the Pannonian basin (East-Central Europe): Eruption chronology, correlation potential and geodynamic implications. Earth Sci Rev. https://doi.org/10.1016/j.earscirev.2018.02.005

Lüschen E, Lammerer B, Gebrande H, Millhan K, Nicolich R, TRANSALP working group (2004) Orogenic structure of the eastern Alps, Europe, from TRANSALP deep seismic reflection profiling. Tectonophysics 388:85–102

Mancktelow NS, Stöckli DF, Grollimund B, Müller W, Fügenschuh B, Viola G, Seward D, Villa IM (2001) The DAV and Periadriatic fault system in the eastern Alps south of the Tauern window. Int J Earth Sci 90:593–622

Mandl GW (2000) The Alpine sector of the Tethyan shelf—examples of Triassic to Jurassic sedimentation and deformation from the northern Calcareous Alps. Mitt Österr Geol Ges 92:61–78

Mandl G, Ondrejickova A (1993) Radiolarien und conodonten aus dem Meliatikum im Ostabschnitt der NKA (A). Jb Geol BA 136(4):841–871

Mandl M, Kurz W, Haunzenberger C, Fritz H, Klötzli U, Schuster R (2017) Pre-Alpine evolution of the Seckau complex (Austroalpine basement / Eastern Alps): constraints from in-situ LA-ICP-MS U-Pb zircon geochronology. Lithos 296:412–430. https://doi.org/10.1016/j.lithos.2017.11.022

Matte P (1986) Tectonics and plate tectonic model for the variscan belt in Europe. Tectonophysics 126:329–374

Missoni S, Gawlick HJ (2010) Evidence for Jurassic subduction from the northern Calcareous Alps (Berchtesgaden; Austroalpine, Germany). Int J Earth Sci 100:1605–1631

Mitterbauer U, Behm M, Brückl E, Lippitsch R, Guterch A, Keller GR, Koslovskaya E, Rumpfhuber EM, Sumanovac F (2011) Shape and origin of the East-Alp slab constrained by the ALPASS teleseismic model. Tectonophysics 510:195–206

Nemes F, Neubauer F, Cloetingh S, Genser J (1997) The klagenfurt basin in the Eastern Alps: an intra-orogenic decoupled flexural basin? Tectonophysics 282:189–203

Neubauer F (2002) Evolution of late Neoproterozoic to early Palaeozoic tectonic elements in central and Southeast European Alpine mountain belts: review and synthesis. Tectonophysics 352:87–103

Neubauer F, Handler R (2000) Variscan orogeny in the eastern Alps and Bohemian Massif: how do these units correlate? Mitt Österr Geol Ges 92:35–59

Neubauer F, Genser J, Handler R (2000) The Eastern Alps: result of a two-stage collision process. Mitt Österr Geol Ges 92:117–134

Oberhauser R (1980) Der Geologische Aufbau Österreichs. Springer, Wien-New York

Peresson H, Decker K (1996) The tertiary dynamics of the northern eastern Alps (Austria): changing paleostresses in a collisional plate boundary. Tectonophysics 272:125–157

Petrakakis K (1997) Evolution of Moldanubian rocks in Austria: review and synthesis. J Metam Geol 15:203–222

Pischinger P, Kurz W, Übleis M, Egger M, Fritz H, Brosch FJ, Stingl K (2008) Fault slip analysis in the Koralm Massif (Eastern Alps) and consequences for the final uplift of "cold spots" in Miocene times. Swiss J Geosci. https://doi.org/10.1007/s00015-008-1277-x

Rantitsch G, Russegger B (2000) Thrust-related very low grade metamorphism within the Gurktal nappe complex (Eastern Alps). Jahrb Geol BA 142(2):219–225

Ratschbacher L, Frisch W, Neubauer F, Schmid SM, Neugebauer J (1989) Extension in compressional orogenic belts: the eastern Alps. Geology 17:404–407

Ratschbacher L, Merle O, Davy P, Cobbold P (1991) Lateral extrusion in the eastern Alps: Part 1. Boundary conditions and experiments scaled for gravity. Tectonics 10:245–256. https://doi.org/10.1029/90TC02622

Ren Y, Stuart GW, Houseman GA, Dando B, Ionescu C, Hegedüs E, Radovanović S, Shen Y, South Carpathian Project Working Group (2012) Upper mantle structures beneath the Carpathian–Pannonian region: implications for the geodynamics of continental collision. Earth Planet Sci Lett 349:139–152

Robl J, Stüwe K, Hergarten S, Evans L (2008) Extension during continental convergence in the eastern Alps: the influence of orogen-scale strike-slip faults. Geology 36:603–606

Robl J, Hergarten S, Stüwe K (2008) Morphological analysis of the drainage systems in the eastern Alps. Tectonopys 460:263–277

Robl J, Prasicek G, Hergarten S, Stüwe K (2015) Alpine topography in the light of tectonic uplift and glaciation. Glob Planet Change 127:34–49. https://doi.org/10.1016/j.gloplacha.2015.01.008

Rögl F (2001) Mid-Miocene circum-Mediterranean paleogeography. Ber Inst Geol Paläont Karl-Franzens-Univ Graz 4:49–59

Rögl F (1999) Mediterranean and Parathetys. Facts and hypotheses of an Oligocene to miocene paleogeography (Short overview). Geol Carpath 50(4):339–349

Royden L, Horvath F, Rumpler J (1983) Evolution of the Pannonian basin system: 1. Tectonics Tectonics 2(1):63–90. https://doi.org/10.1029/TC002i001p00063

Rupp C, Linner M, Mandl GW (2006) Erläuterungen zur Geologischen Karte von Oberösterreich 1:200.000. Geologische Bundesanstalt, Wien

Sachsenhofer RF, Gruber W, Dunkl I (2010) Das Miozän der Becken von Leoben und Fohnsdorf. J Alp Geol 53:9–38

Scharf A, Handy MR, Favaro S, Schmid SM, Bertrand A (2013) Modes of orogen-parallel stretching and extensional exhumation in response to microplate indentation and roll-back subduction (Tauern Window, Eastern Alps). Int J Earth Sci. https://doi.org/10.1007/s00531-013-0894-4

Schmid SM, Pfiffner OA, Froitzheim N, Schönborn G, Kissling E (1996) Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics 15:1036–1064

Schmid SM, Fügenschuh B, Kissling E, Schuster R (2004) Tectonic map and overall architecture of the Alpine orogen. Eclogae Geol Helv 97:93–117

Schmid SM, Scharf A, Handy MR, Rosenberg CL (2013) The Tauern window (Eastern Alps, Austria)—a new tectonic map, cross-sections and tectonometamorphic synthesis. Swiss J Geosc 106:1–32

Schmid SM, Kissling E, Diehl T, van Hinsbergen DJ, Molli G (2017) Ivrea mantle wedge, arc of the western Alps, and kinematic evolution of the Alps-Apennines orogenic system. Swiss J Geosc 110(2):581–612

Schönlaub HP (1979) Das Paläozoikum in Österreich. Verbreitung, Stratigraphie, Korrelation, Entwicklung und Paläogeographie nicht metamorpher und metamorpher Abfolgen. Abh Geol BA 33:1–124

Schorn A, Neubauer F, Genser J, Bernroider M (2013) The Haselgebirge evaporitic mélange in central northern Calcareous Alps (Austria): Part of the Permian to lower Triassic rift of the Meliata ocean? Tectonophysics 583:28–48

Schuster R, Stüwe K (2008) Permian metamorphic event in the Alps. Geology 36:603–606

Schuster R, Stüwe K (2010) Die Geologie der Alpen im Zeitraffer. Mitt Nat Ver Steiermark 140:5–21

Schuster R, Koller F, Hoeck V, Hoinkes G, Bousquet R (2004) Explanatory notes to the map: metamorphic structure of the Alps—metamorphic evolution of the eastern Alps. Mitt Österr Miner Ges 149:175–199

Schuster R, Nievoll J, Rupp C, Ćorić S, Ilickovic T (2016) Neogene sedimente und landschaftsentwicklung im Umfeld der Kartenblätter GK50 Blatt 103 Kindberg und 135 Birkfeld. Arbeitstagung Der Geologischen Bundesanstalt 2015:127–143

Schuster R, Daurer A, Krenmayr HG, Linner M, Mandl GW, Pestal G, Reitner JM (2014) Rocky Austria. Geology of Austria—short and colorful. 2nd edn. Geologische Bundesanstalt, Wien

Sedgwick A, Murchison RI (1832) XVIII. A sketch of the structure of the Eastern Alps; with sections. Trans Geol Soc Lond 2–3:301–420. London

Stampfli GM, Borel GD (2004) The transmed transsects in space and time: constraints on the paleotectonic evolution of the Mediterranean domain. In: Cavazza W, Roure F, Spakman W, Stampfli GM, Ziegler PA (eds) The TRANSMED Atlas: the Mediterranean region from crust to mantle. Springer, p 141

Steininger H, Steiner E (2005) Meeresstrand am Alpenrand—Molassemeer und Wiener Becken. Verlag publication PN 1 Bibliothek der Provinz (Weitra)

Stüwe K, Homberger R (2012) High above the Alps. A bird's eye view of geology. Weishaupt, Gnas

Stüwe K, Schuster R (2010) Initiation of subduction in the Alps: continent or ocean? Geology 38(2):175–178

Suess E (1912) Die moravischen fenster und ihre Beziehung zum Grundgebirge des Hohen Gesenke. Denkschr Kk Akad Wiss, Math-Naturwiss Cl 88:541–631

Suess E (1909) Das Antlitz der Erde, vol 3. Temsky & Freytag, Prag-Wien-Leipzig

Tenczer V, Stüwe K (2003) The metamorphic field gradient in the eclogite type locality. J Metam Geol 21:377–393

Thöni M (2006) Dating eclogite-facies metamorphism in the eastern Alps—approches, results, interpretations: a review. Mineral Petrol 88:123–148

Tollmann A (1977) Geologie von Österreich, vol 1. Die Zentralalpen. Deuticke, Wien

van Husen D (2000) Geological processes during the quaternary. Mitt Österr Geol Ges 92:135–156

van Husen D (2011) Quaternary glaciations in Austria. In: Ehlers J, Gibbard PL, Hughes PD (eds) Development in quarternary sciences, vol 15. pp 15–28

von Blankenburg F, Davies HJ (1995) Slab breakoff: a model for syncollisional magmatism and tectonics in the Alps. Tectonics 14:120–131

von Raumer JF, Bussy F, Schaltegger U, Schulz B, Stampfli GM (2013) Pre-Mesozoic Alpine basements—their place in the European paleozoic framework. Geol Soc Am Bull 125(1–2):89–108

Wagner T, Fabel D, Fiebig M, Häuselmann P, Sahy D, Sheng X, Stüwe K (2010) Young uplift in the nonglaciated parts of the eastern Alps. Earth Planet Sci Lett 295:159–169

Wagner T, Fritz H, Stüwe K, Nestroy O, Rodnight H, Hellstrom J, Benischke R (2011) Correlation of cave levels, stream terraces and planation surfaces along the river Mur—timing of landscape evolution along the eastern margin of the Alps. Geomorphology 134:62–78. https://doi.org/10.1016/j.geomorph.2011.04.024

Wessely G (2006) Geologie der Österreichischen Bundesländer—Niederösterreich. Geologische Bundesanstalt, Wien

Winkler-Hermaden A (1955) Ergebnisse und Probleme der quartären Entwicklungsgeschichte am östlichen Alpensaum außerhalb der Vereisungsgebiete. Denkschr Akad Wiss, Math-Naturw Kl 110 (8):1–180

Wölfler A, Stüwe K, Danisik M, Evans NJ (2012) Low temperature thermochronology in the eastern Alps: implications for structural and topographic evolution. Tectonophysics. https://doi.org/10.1016/j.tecto.2012.03016

Wölfler A, Kurz W, Fritz H, Stüwe K (2011) Lateral extrusion in the eastern Alps revisited: refining the model by thermochronological, sedimentary and seismic data. Tectonics 30 TC4006. https://doi.org/10.1029/2010TC002782

Zámolyi A, Salcher B, Draganits E, Exner U, Wagreich M, Gier S, Fiebig M, Lomax J, Surányi G, Zámolyi F (2016) Latest Pannonian and quaternary evolution at the transition between eastern Alps and Pannonian Basin: new insights from geophysical, sedimentological and geochronological data. Int J Earth Sci 106(5):1695–1721

Ziegler PA, Dèzes P (2006) Crustal evolution of western and central Europe. Geol Soc Lond Mem 32(1):43–56

Ralf Schuster is a research scientist at the Geological Survey of Austria and private lecturer at the University of Vienna. His research focuses on geological mapping, geochronology and tectonics of the Eastern Alps and surrounding regions.

Kurt Stüwe is a professor for Earth Sciences at the University of Graz in Austria. He has worked in many branches of the Earth Sciences and has conducted research projects on mountain forming processes on all continents. In recent years he has focused on neotectonic- and geomorphological questions, mostly with a modelling approach.