World Geomorphological Landscapes

Christine Embleton-Hamann *Editor*

Landscapes and Landforms of Austria

Springer

World Geomorphological Landscapes

Series Editor

Piotr Migoń, Institute of Geography and Regional Development, University of Wrocław, Wrocław, Poland

Geomorphology – 'the Science of Scenery' – is a part of Earth Sciences that focuses on the scientific study of landforms, their assemblages, and surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of geomorphology. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations. Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us creating shapes which look improbable. Many geomorphological landscapes are so immensely beautiful that they received the highest possible recognition – they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for millions of years and include unique events. This international book series will be a scientific library of monographs that present and explain physical landscapes across the globe, focusing on both representative and uniquely spectacular examples. Each book contains details on geomorphology of a particular country (i.e. The Geomorphological Landscapes of France, The Geomorphological Landscapes of Italy, The Geomorphological Landscapes of India) or a geographically coherent region. The content is divided into two parts. Part one contains the necessary background about geology and tectonic framework, past and present climate, geographical regions, and long-term geomorphological history. The core of each book is however succinct presentation of key geomorphological localities (landscapes) and it is envisaged that the number of such studies will generally vary from 20 to 30. There is additional scope for discussing issues of geomorphological heritage and suggesting itineraries to visit the most important sites. The series provides a unique reference source not only for geomorphologists, but all Earth scientists, geographers, and conservationists. It complements the existing reference books in geomorphology which focus on specific themes rather than regions or localities and fills a growing gap between poorly accessible regional studies, often in national languages, and papers in international journals which put major emphasis on understanding processes rather than particular landscapes. The World Geomorphological Landscapes series is a peer-reviewed series which contains single and multi-authored books as well as edited volumes.

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Landscapes and Landforms of Austria

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ISSN 2213-2090 ISSN 2213-2104 (electronic)
World Geomorphological Landscapes
ISBN 978-3-030-92813-1 ISBN 978-3-030-92815-5 (eBook)
https://doi.org/10.1007/978-3-030-92815-5

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Series Editor's Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us by creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they have received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to natural forces. For centuries, or even millennia, they have been shaped by humans who modified hillslopes, river courses and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by geomorphology—'the Science of Scenery'—a part of Earth Sciences that focuses on landforms, their assemblages, the surface and subsurface processes that moulded them in the past and that change them today. The shapes of landforms and the regularities of their spatial distribution, their origin, evolution and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a new book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume covers Austria—a country which is not particularly large in terms of area, but extremely diverse in terms of geomorphology. Its territory is dominated by high-mountain landscapes of the Alps, although even these occur in many flavours, depending on the tectonic history, rock type, the extent of Pleistocene and contemporary glaciation and last but not least, human impact. But Austria has much more to offer. The north is part of the Bohemian Massif, with granite uplands dotted by bizarre rock outcrops, deeply entrenched river canyons and gorges. The extreme east, in turn, is rather low-lying, but by no means less interesting, with fascinating stories of shifting rivers and lakes to be read from landforms and sediments.

The *World Geomorphological Landscapes* series is produced under the scientific patronage of the International Association of Geomorphologists—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union and the International Union of Geological Sciences. Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which sticks to the scientific rigour, is the most appropriate means to fulfil these aims and to serve the geoscientific community. To this end, my great thanks go to the editor of the volume, Professor Christine Embleton-Hamann, who agreed to coordinate the book and ensured that the final product exceeds all possible quality requirements. I am grateful to all individual contributors who agreed to add the task of writing chapters to their busy agendas and delivered such interesting stories to read. I also acknowledge the work of all reviewers. Their hard work meant then less work for me!

On more a personal note, I am very pleased that I was able to join the team of authors and could contribute about granite landforms in northern Austria, which are little known internationally but certainly deserve broader audience. Now is time to see other aspects of Austrian geomorphological landscapes, so wonderfully presented in this volume.

Wrocław, Poland Piotr Migoń

Preface

I always found pleasure in absorbing a scenic landscape view, for instance from the top of a mountain. As a student of German and Geography in Salzburg University, two courses became influential for my further career. The first one was a class within the German language programme that dealt with aesthetic experiences. The second one was the introductory course in geomorphology that came as a revelation: the science of geomorphology actually helps you to see more landscape details, and by increasing your knowledge about their formation, it ultimately augments your appreciation of scenic landscapes. In the past, these personal experiences resulted in a habilitation thesis exploring geomorphological techniques in assessing landscape beauty, and more recently in welcoming the challenge of organizing and editing a book on the landscapes and landforms of my home country.

This book is a joint effort of the Austrian Research Association on Geomorphology and Environmental Change, whose members compiled and wrote the majority of its chapters.

Two characteristics of Austria are (i) its reputation as a tourist's paradise and (ii) its rich cultural landscape, resulting from the presence of people since prehistoric times. The World Heritage Sites of Austria are listed as cultural properties, despite the official description of two of them stressing their spectacular landscape, which was obviously overlooked in the inscription process. Austria's tourism advertising is focused on the two tourism activities that generate the highest revenues, namely skiing and city sightseeing. We want to set this right by showcasing Austria's scenic landscapes and rich geoheritage, documented and explained in its National -, Nature- and Geoparks.

A further issue was to make regional studies in German available to the international community, according to the goals of the IAG book series. The Austrian Research Association on Geomorphology and Environmental Change has several members with deep insight into the regional development of landscapes, which they publish in national journals in German. My attempt to include these regional experts turned out to be a challenge, as they naturally delivered manuscripts that were more or less word-by-word translations. To turn their efforts into a meaningful text in English, a very time-consuming communication with the authors was needed. We finally conquered it, but this endeavour caused severe delay of the publication of the book. I therefore need to express my apologies to many colleagues who delivered their manuscripts at the initial timeline and then had to wait several years for the publication.

The chapters of this book are peer reviewed. I express my personal thanks to the following members of the international community of geomorphologists, who provided expert reviews and valuable input:

Marie-Françoise André	Isabelle Gärtner-Roer	Heinz Kollmann
Gary Brierley	Stefan Glatzel	Brian Luckman
Chris Caseldine	Andrew Goudie	John Menzies
Mike Church	Philipp Häuselmann	Jan Otto
Randy Dirszowsky	Erwin Heine	Rudolf Pavuza
Ian S. Evans	Gabor Kereszturi	Ulrike Pistotnik
Monique Fort	Jasper Knight	Peter Pisut

Jean Poesen
Tony Ramsay
Andreas Rudigier
Lothar Schrott
Marcel van der Perk
Dirk van Husen
Cees J. van Westen
Kirsten von Elverfeldt

This is a better book because of their comments. I pay tribute to the series editor Piotr Migoń, who for the Austrian volume not only provided assistance and guidance, but also an original chapter on granite landforms. I am grateful to Olav Slaymaker for fruitful discussion of scientific problems, patient help with English wording problems and continuing support. I am finally indebted to the many editorial assistants at Springer who have made this endeavour possible.

Vienna, Austria
October 2021

Christine Embleton-Hamann

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Christine Embleton-Hamann is a retired professor at the Department of Geography and Regional Research at the University of Vienna. Her main interest is in alpine environments. Within this field, she focusses on human–environment interactions with research topics like human impact on geomorphic processes, assessment of the scenic quality of landscapes and geomorphological hazards. A second set of interest concerns the communication of geomorphological knowledge to a broader audience, in the pursuit of which objective she has written a well-received textbook on geomorphology. She is a former President of the Austrian Research Association on Geomorphology and served on the Executive Boards of the IAG and several IAG and IGU Working Groups.

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Part I

Introduction to the Physical Geography of Austria

Geological and Tectonic Setting of Austria

1

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).

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

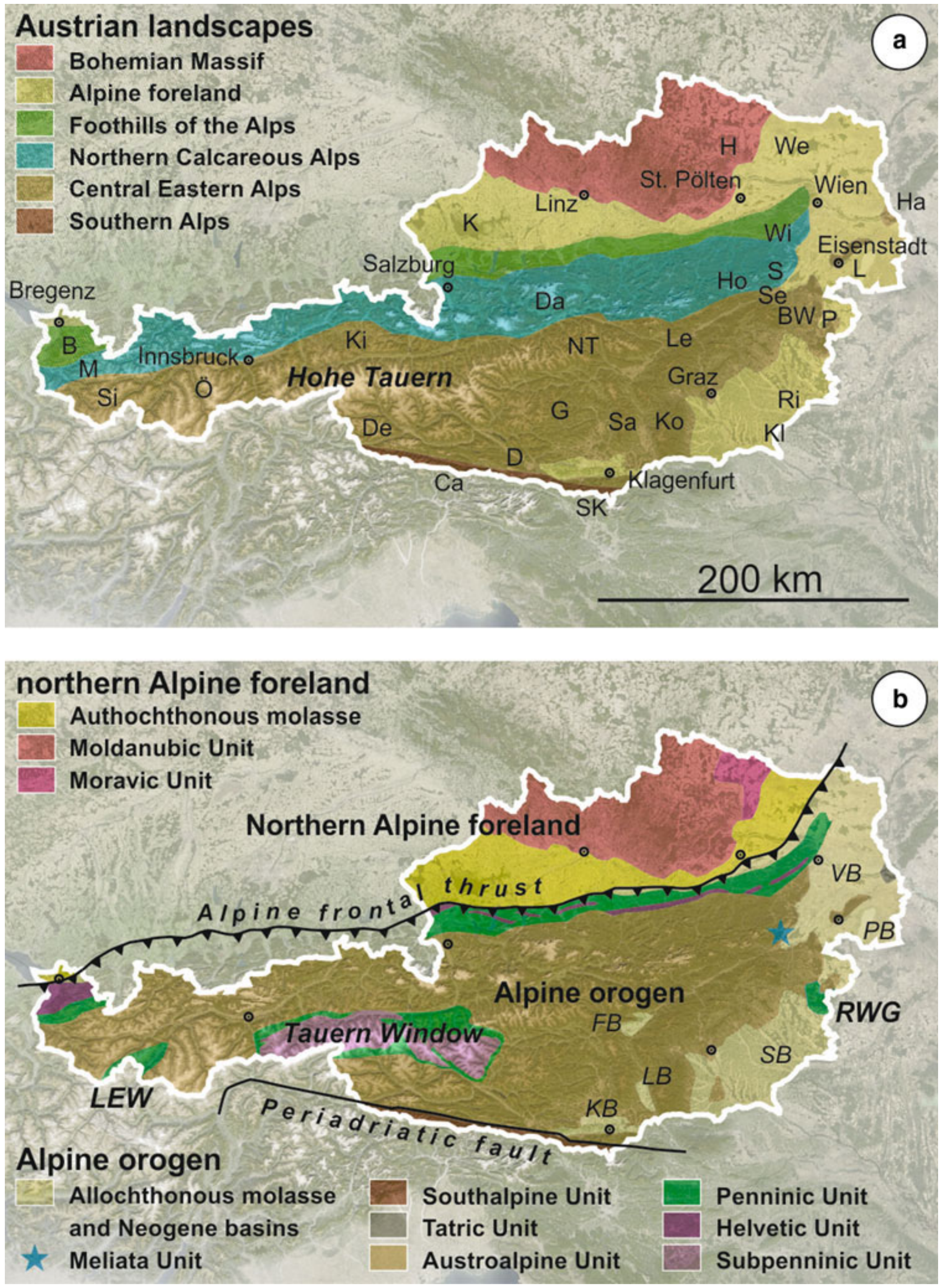

Fig. 1.1 Comparison of the distribution of landscape **a** and major tectonic **b** units in the territory of Austria. Obvious similarities of the geographical and geologic subdivisions indicate a strong influence of the geology on geomorphology. Geographic places: B = Bregenzer Wald, BW = Bucklige Welt, 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

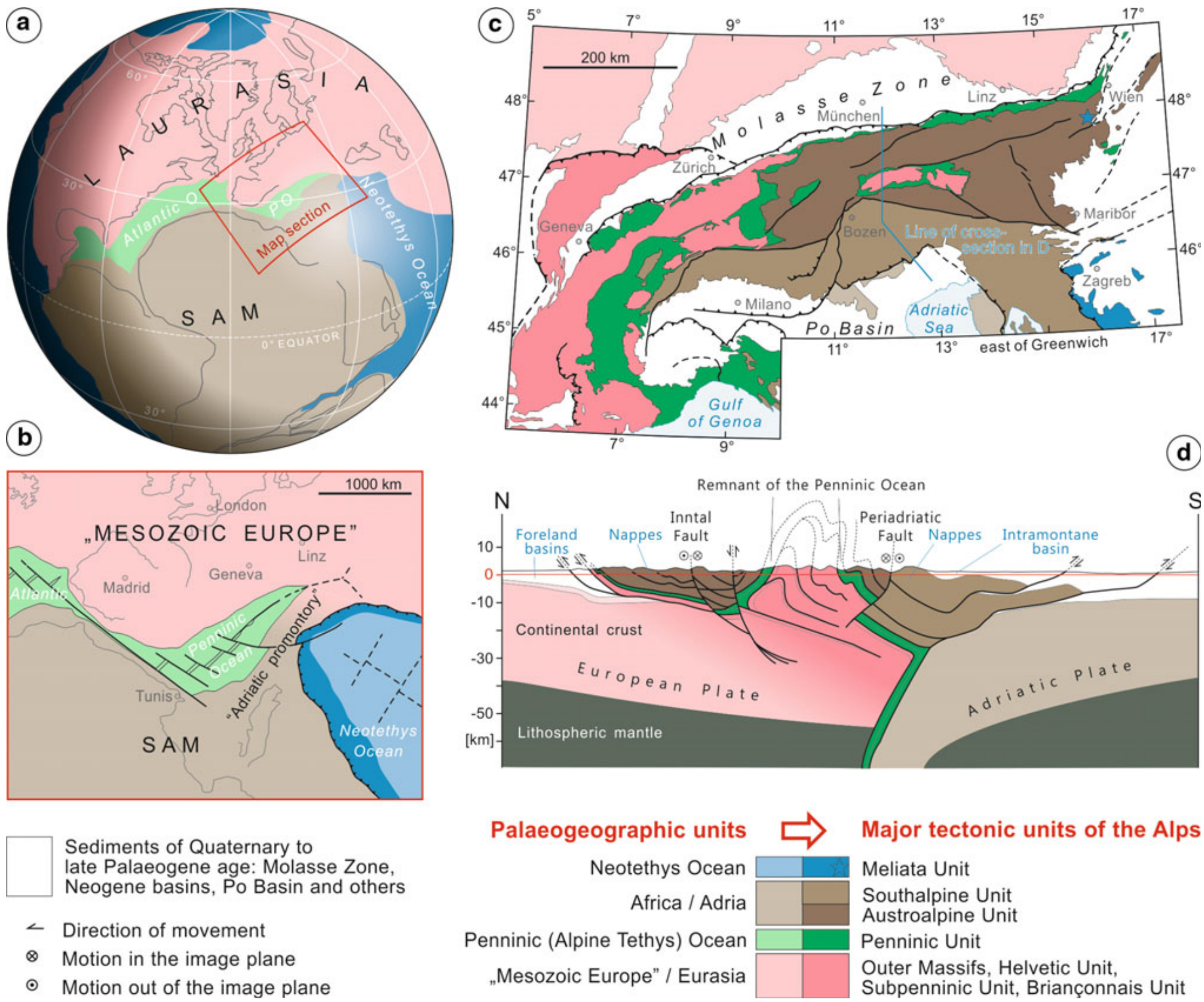

Fig. 1.2 Global **a** and regional **b** reconstructions showing the major palaeogeographic units of the Alpine realm and their transformation into the major tectonic units of the Alps, shown in map view **c** and section **d**. After Schmid et al. (2004) and Schuster et al. (2014) and references therein. 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.

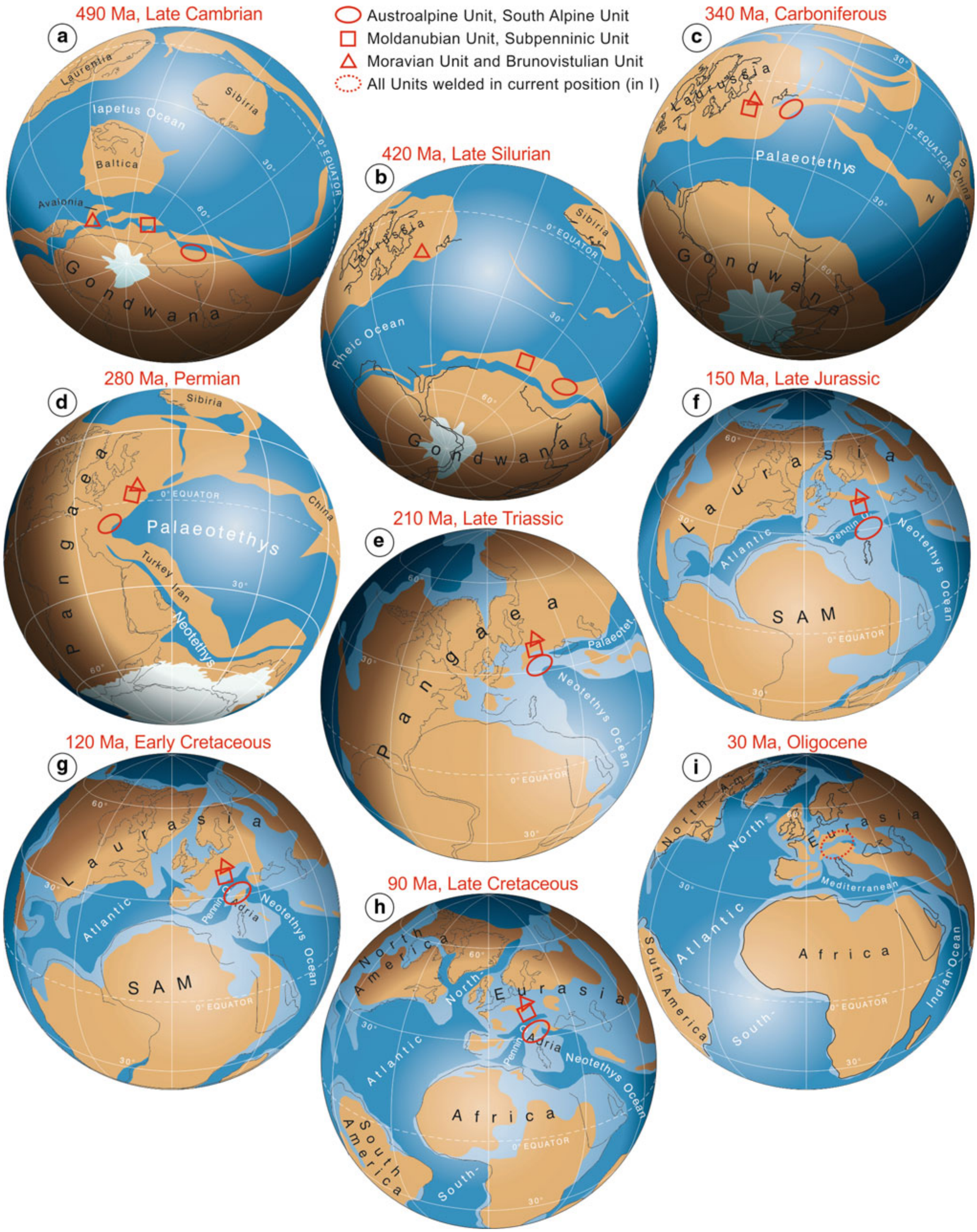

Fig. 1.3 Reconstructions of the global palaeogeography through Phanerozoic time based on Schuster et al. (2014). The positions of major continental tectonic units in the territory of Austria are shown through time. Explanation see text. SAM = southern continent assemblage that has split up since that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

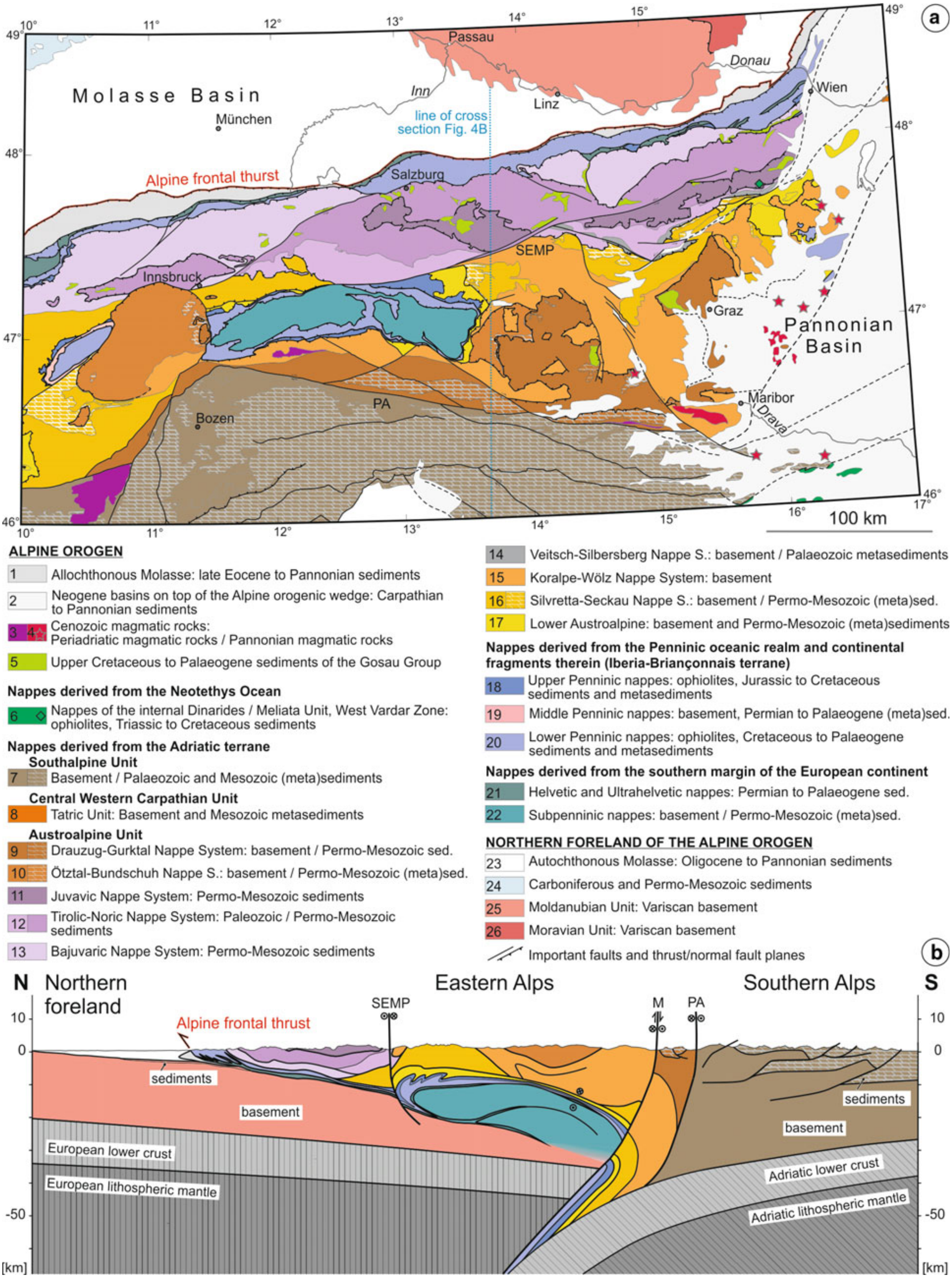

Fig. 1.4 Tectonic map **a** of the Eastern Alps and its northern foreland according to the nomenclature in Schmid et al. (2004). The numbers of the units refer to the text. Section **b** through the Eastern Alps according to Schmid et al. (2004). SEMP = Salzach-Ennstal-Mariazell-Puchberg fault, M = Mölltal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

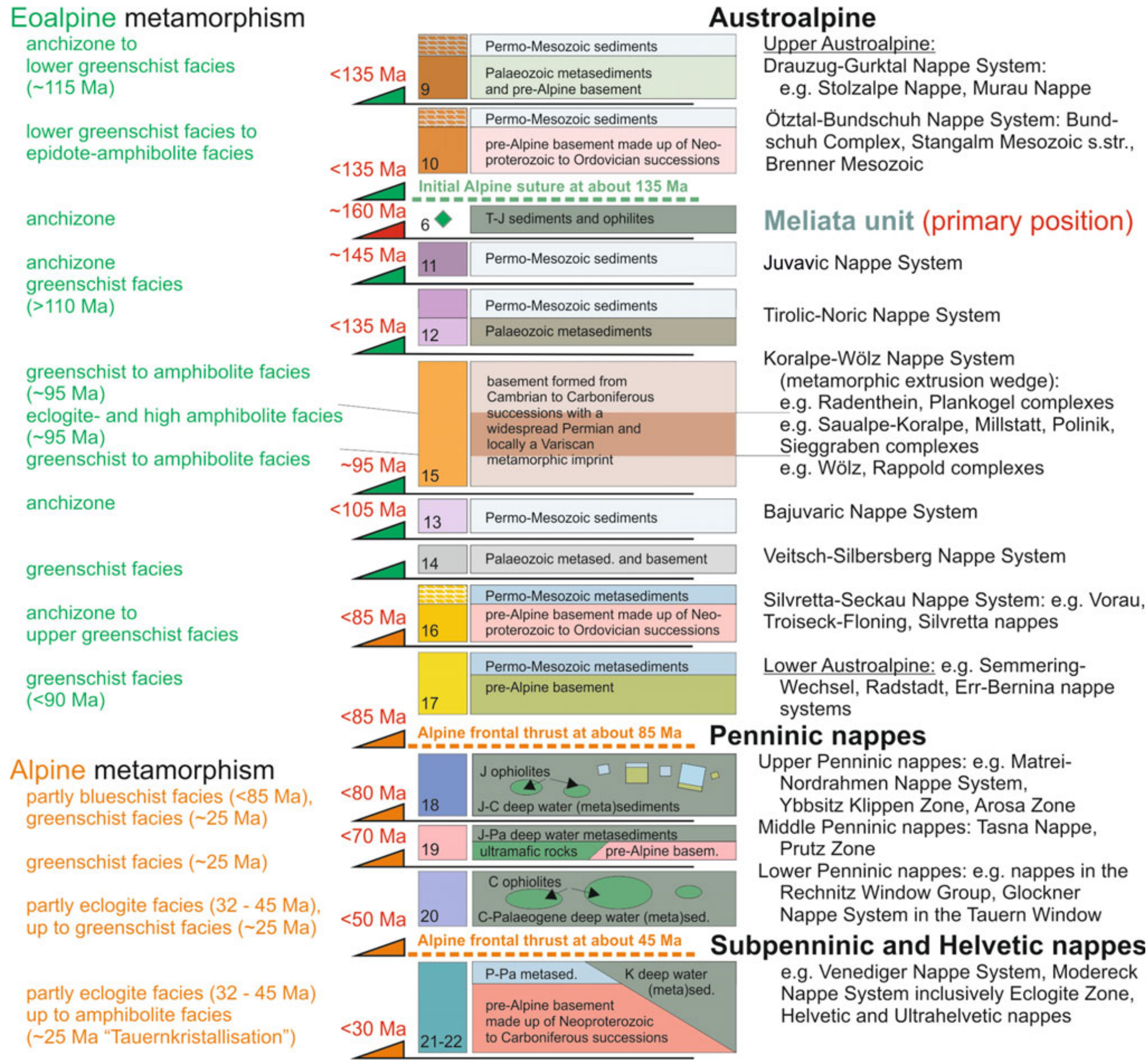

Fig. 1.5 Schematic diagram showing the tectonostratigraphic order of the major tectonic units of the Eastern Alps. Tectonic and lithostratigraphic units are listed in the left column. In the central column the major lithological content of the tectonic units is shown. Fields with numbers refer to the 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).

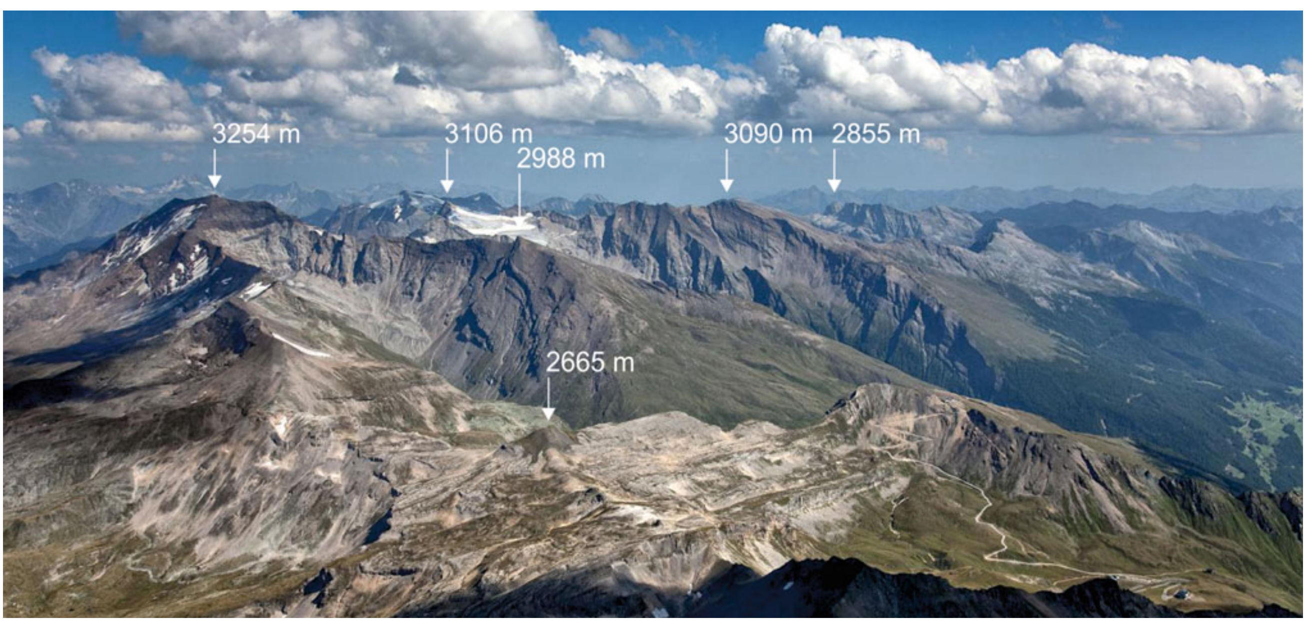

Fig. 1.6 Eastward view along the main crest of the Hohe Tauern in the Großglockner region (Salzburg/Carinthia). The crest is built up by the Venediger Nappe System of the Subpenninic Unit. Bright greyish orthogneisses occur at Sonnblick (3106 m). On top of Hocharn (3254 m) dark brownish paragneisses 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