Revised and updated translation of
Geologie der Alpen, Second Edition

Geology of the Alps

O. Adrian Pfiffner

Geology of the Alps

Geology of the Alps

Revised and updated translation of *Geologie der Alpen*,
Second Edition

O. Adrian Pfiffner

WILEY Blackwell

This second edition first published in English 2014

Edition history: Haupt Berne (1e in German, 2009); Haupt Berne (2e in German, 2010)

Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Offices
9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
111 River Street, Hoboken, NJ 07030-5774, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell.

Library of Congress Cataloging-in-Publication Data

Pfiffner, Othmar Adrian, 1947–
[Geologie der Alpen English]
Geology of the Alps / O. Adrian Pfiffner. – Revised and translated second edition.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-70813-2 (cloth) – ISBN 978-1-118-70812-5 (pbk.)
1. Geology–Alps. I. Title.
QE285.P4813 2014
554.94′7–dc23
2013050121

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: Front Cover: View of Piz Tumpiv (Canton Graubünden, Switzerland) looking WSW. The steep gully with a string of snow in the foreground marks a folded thrust fault between crystalline basement (Aar massif) and Mesozoic sediments (Cavistrau nappe). See Fig. 6-10B for explanation. Photo by O. A. Pfiffner.
Back Cover: Cross-section through the Central Alps of Switzerland showing nappe structures in Mesozoic-Cenozoic sediments and the involvement of crystalline basement (Aar, Gotthard, Verampio, Antigorio and Maggia). The deep structure of the crust is based on seismology and earthquake tomography (Diel et al. 2009), cross-section by O.A. Pfiffner 2014.
Cover design by Steve Thompson
Graphics by A. Baumeler and O.A. Pfiffner

Set in 9.5/12pt Caslon by SPi Publisher Services, Pondicherry, India

1 2014

Contents

Preface

for Anne-Marie

I have been lecturing on the 'Geology of Switzerland' at the Institute of Geological Sciences, University of Berne, since 1987. The module for students in their second year studying Earth sciences as their main or subsidiary subject forms the basis for excursions, practical work, in-depth courses on regional geology and geodynamics, as well as for Master's and Doctoral research on Alpine geology. When preparing the lectures for this module, it soon became clear to me that an explanatory text was required for the course material, in addition to illustrations. The resultant lecture notes were corrected and amended each year and I undertook a basic revision on two occasions. Over the course of recent years, the desire emerged for the production of a new version in the form of a book. This book was to extend the focus of the text and provide a more detailed illustration of the situation in the neighbouring regions of the Western and Eastern Alps. A sabbatical in the spring semester of 2008 gave me the time to research the literature, write the text and design the many illustrations. This work then continued throughout the following autumn semester, piecemeal and during my 'free' time.

The geology of the Alps is multifaceted. For a start, there are the different types of rocks – sedimentary, igneous and metamorphic – all of different ages and with manifold processes underlying their formation. In addition, plate tectonic processes, the formation of sediment basins, mountain-building or the uplift of the Alps to produce a high-altitude mountain range and its subsequent erosion are of importance. However, rock-forming processes and plate tectonics are intrinsically linked, such that structuring this material is not easy. Division along broadly chronological lines appeared to be the best solution. For this reason, after placing the Alps in a European context, the pre-Triassic basement is discussed first. The subsequent chapters focus on the Mesozoic and then on the Cenozoic building blocks. In each of these three chapters, the rock formations are presented first. This is followed by a discussion of the emergence of these rock formations in the plate tectonic framework. In all cases, the selection of the material posed a real challenge, as each of these chapters is worth a book in its own right. The final chapter on the most recent events in the Alps makes the transition to the current geological situation. The selection of material posed problems here as well and many interesting aspects have been neglected.

I was able to rely on the help of many colleagues during the realization of this book. Above all, I would like to thank Andreas Baumeler. He helped me produce the graphics, provided enormous input for the design of the illustrations, advised me on the use of colours and symbols and improved my drafts. Many of the illustrations moved back and forth between us several times before we were both happy with the end result. A book on the geology of the Alps requires a large amount of illustrative material. The publisher's willingness to accommodate our wishes and print all of the illustrations in colour was very obliging. My thanks also go to the publisher's proof-reader, Claudia Huber, and to Marco Herwegh, who checked the figures and figure legends for consistency and typographic errors. I am grateful to my colleagues at the Institute, in Switzerland and abroad, for numerous discussions and for answering my questions, of whom there are too many to name here.

Finally, I would also like to thank my wife, who has had to go without many things during the writing of the book, but who always showed great understanding for my work. I would like to dedicate this book to her.

Berne, January 2009

Comments on the second edition

After the publication of *'Geologie der Alpen'*, I was sent numerous comments. A commonly expressed wish was for the inclusion of an index. I was happy to comply with this wish in this second edition. The revision also gave me the opportunity to expand the Appendix to include a geological time scale. However, the comments I received also revealed weaknesses that have been addressed in the second edition. I am grateful, in particular, to Hanspeter Funk for his help on the correct usage of stratigraphic terms, to Marino Maggetti for pointing out errors in traces of cross-sections, to Christoph Spötl for his suggestions on ice age stratigraphy, to Wolfgang Frisch for his comment on the position of the Tauern relative to the flysch basins and to Henry Naef for prompting me to think about the deep structure in Vorarlberg. A total of over 50 illustrations have been redesigned to lesser and greater extents.

Berne, January 2010

Comments on the translation

Soon after the publication of the German version of this book, *Geologie der Alpen*, which appeared in the UTB/Haupt series I was urged to consider an English version. Many colleagues considered the book to be a standard work for the Alps that would interest an international audience amongst scientists and students. I was also encouraged to include more photographs and to expand some of the material. In particular I was asked to place more emphasis on Alpine metamorphism. Given that I had more space available I was happy to comply with these demands.

Along with the translation I updated many figures. The palaeogeographical maps showing plate configurations have undergone a major overhaul in the presentation. The cross-sections spanning the entire Alps were harmonized and now include the crustal structure as determined from earthquake tomography. At this point, I wish to thank Edi Kissling for his invaluable help in providing me with geophysical data and keeping an eye on my interpretations. To show the kinematic evolution of the Alps serial cross-sections were overhauled and a new set of cross-sections was produced for the Central Alps of western Switzerland, a classic area for nappe tectonics studied by Argand in the nineteenth century. In the chapter on the most recent history of the Alps, the inclusion of data from Italy and France provided a much more complete image of the present-day uplift pattern of the Alps. Eckhart Villinger pointed out data from the Alpine foreland to me that allowed updating the palaeogeographical maps containing the courses of the ancestral rivers draining the Alps.

The text was translated by Dr Deborah J. Curtis in cooperation with tolingo translations, Hamburg. Deborah quickly grasped what I intended to convey to the reader and spared me innumerable hours of translation that would never have reached the quality she obtained. I express my sincere gratitude to her. For the preparation of the figures, I was again able to count on the assistance of Andreas Baumeler. His eyes quickly caught the weak points that crept in with modifiying the original figures.

Berne, June 2013

1 The Alps in their Plate Tectonic Framework

▶ **Figure 1.1** Tectonic map of Europe showing mountain ranges coloured according to their age of formation and associated terranes and continents.

Rocks can be found in the Alps that range in age from one billion years to present times. The rocks themselves – sedimentary, igneous, metamorphic and unconsolidated rock – cover the entire conceivable spectrum. Many of these rocks and their formation can be understood only within the context of the geological structure of Europe and the associated plate tectonic processes. In the following therefore, the plate tectonic framework for Europe, the older mountain chains and the younger Alpine mountain ranges in Europe will be considered briefly.

1.1 Older Mountain Chains in Europe

From a geological perspective, the European continent has a highly chequered history. Although the Alps are an integral component of this continent and are, essentially, a spectacular mountain chain, their origin lies in the recent geological history of the continent. In order to understand the geological structure of Europe, the individual regions need to be classified according to the age of their consolidation. In this case, the term consolidation is taken to mean the welding of continents, following on from the motion of plates. Almost all of the mountain chains in Europe originated as a result of plate movements, where an ancient ocean was swallowed up in a subduction zone and the continental blocks subsequently collided with each other. The density of continental crust is relatively low and, therefore, buoyancy acts against it sinking to greater depths once it has entered a subduction zone. As a result, continental crust remains close to the surface and is compressed. During this process, the uppermost portions of the crust are pushed upwards and gradually build a mountain chain. This process is called orogenesis or mountain-building.

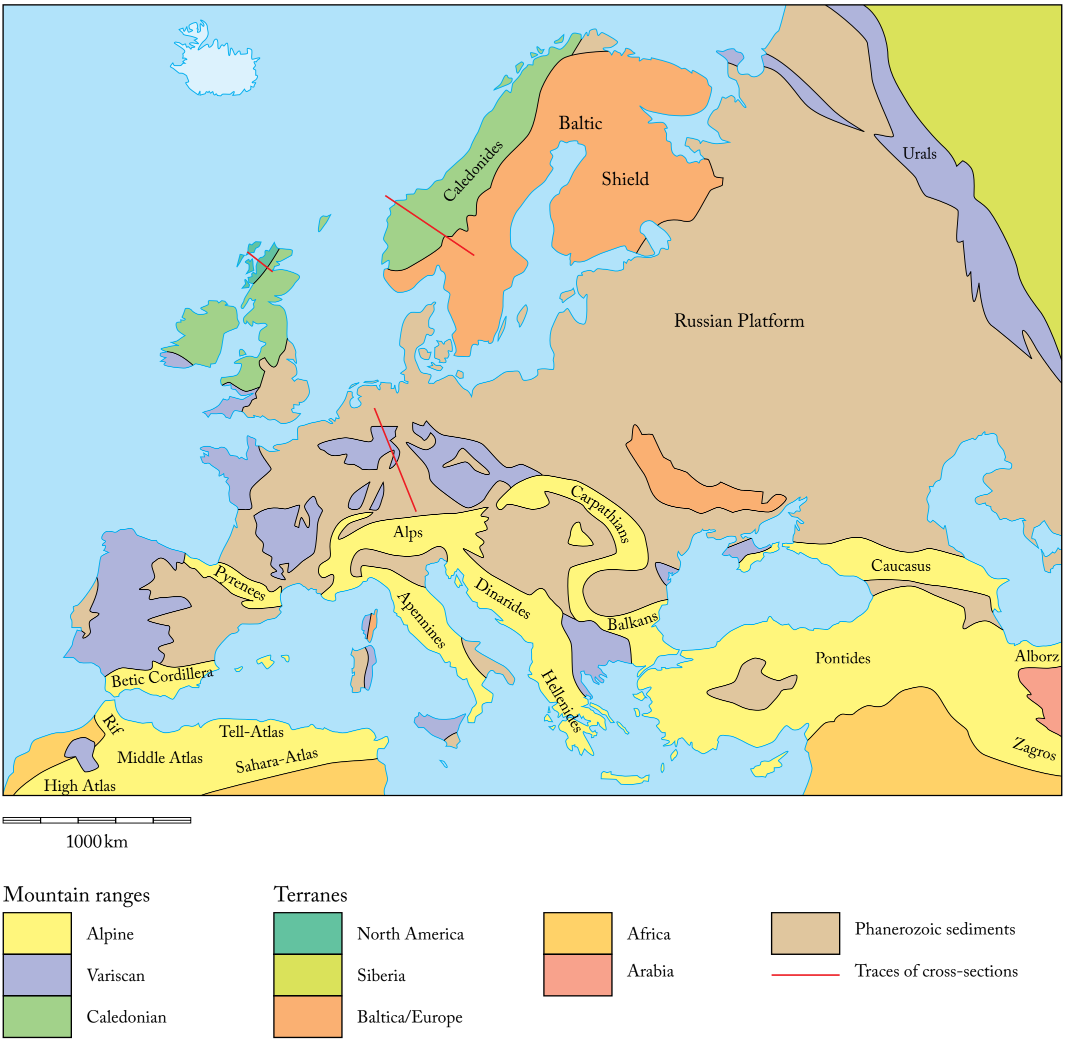
A number of such collisions between continents, or orogenies, have occurred during the geological evolution of Europe. Accordingly, we distinguish between Caledonian, Variscan and Alpine orogens. The continental plates involved in these collisions were North America, Siberia, Baltica/Europe and Africa and are also called terranes. The tectonic map in Fig. 1.1 takes this division into consideration. Europe has also been subdivided into Eo-, Palaeo-, Meso- and Neo-Europe, based on the relative ages of these orogenies. It must be noted that the terranes mentioned above contain rock units that are relics of even older, fully eroded mountain chains.

Eo-Europe is a large geological structure, a welded block that experienced no further orogenies after the Precambrian. Two geological provinces are distinguished within Eo-Europe: the Baltic Shield and the Russian Platform.

Baltic Shield

The Baltic (or Fennoscandian) Shield is a convex bulge or shield covering a large area, which is composed of a highly metamorphic crystalline basement (Baltica in Fig. 1.1). Multiple, very ancient and fully eroded mountain chains can be distinguished within these series of rock formations. The oldest rocks in the Baltic Shield are three to three and a half billion years old and were encountered in a deep drill core obtained in the region of Kola, to the south of the White Sea, as well as in Lapland.

Geology of the Alps: Revised and updated translation of Geologie der Alpen, Second Edition. O. Adrian Pfiffner.



The Russian Platform is the sedimentary cover over the Baltic Shield and is composed of Neoproterozoic non-metamorphosed sediments, overlain by Cambrian rocks as well as a series of rock formations that extend into the Cenozoic. In the southeast, the platform plunges beneath the foreland of the Caucasus, to the north of the Caspian Sea, and in the east and west, beneath the forelands of the Ural and Carpathian Mountains. The internal structure of the plate contains local depressions or basins with thick sedimentary successions as well as zones with a thin sedimentary cover. The sediments of the Russian Platform reflect the later phases of mountain-building that took place at its margins. Examples are the famous Old Red Sandstone, continental fluviatile sediments of the Middle to Late Devonian that are the erosional product from the (Caledonian) mountains in Norway and Scotland, the Permo-Triassic continental lagoon sediments in the foreland of the (Variscan)

Russian Platform

Urals and the Cenozoic continental formations in the foreland of the Caucasus and Carpathians. Sediments of the Russian Platform are usually marine deposits in the centre (with the exception of the Early Carboniferous coal swamps in the area of Moscow), but the sea retreated towards the south after the Early Cretaceous and the Russian Platform became subaerial.

Palaeo-Europe refers to the Caledonian orogen that extends across Scandinavia to Ireland. Other parts are found in Greenland and the Appalachians. This broad geographical distribution is sufficient to indicate that later plate movements fragmented this Early Palaeozoic mountain chain. Plate movements responsible for this were, for example, the opening up of the North Sea from the Permian onwards and the opening up of the North Atlantic starting in the Jurassic.

Meso-Europe includes the Variscan orogen that originated in the Late Palaeozoic. With the exception of the Urals, the Variscan mountain chain can be followed as a continuous range, which in Germany and France is generally completely eroded and covered with younger sediments, as illustrated by the island-like distribution of remnants of these mountains shown in Fig. 1.1.

Finally, **Neo-Europe** comprises a series of mountain chains that originated in the Jurassic (Turkey), in the Cretaceous (parts of the Alps and Pyrenees), but mainly in the Cenozoic. These mountain chains are often winding and arc-shaped. In addition to the Alps, good examples are the Carpathians and the Betic Cordillera–Rif–Tell–Atlas system. This arc shape is essentially due to the geometry of the plate boundaries of the different associated microplates, a point that is discussed in more detail later on. The linear mountain chains of the Pyrenees and the High and Middle Atlas share the common trait that an orogeny is mainly characterized by strike-slip motion along linear faults. In addition to the strike-slip motion, a compressive component caused a shortening of the margins of the fault lines, which was responsible for the actual 'up-folding' of these mountain chains.

A simplified illustration of Europe's plate tectonic evolution and the origins of the Caledonian and Variscan orogens is provided in Fig. 1.2. This figure shows how several continents were welded into a megacontinent, Pangaea, over the course of 300 million years.

In the Late Cambrian (500 million years ago), the southern continent, Gondwana, unified the extant land masses of South America, Africa and parts of Asia. The continents of Baltica (approximately Sweden, Finland and Russia today), Siberia and North America were surrounded by oceanic basins, in which thick sedimentary deposits accumulated. At the northern continental margin of Baltica, 1400 metres of grey and reddish arkoses, conglomerates, limestones and shales were deposited in the shallow part of the Iapetus Ocean during the Proterozoic (about 600 million years ago). The arkoses also contain tillites, that is, fossilized diamictites (glacial deposits that indicate very ancient glaciations). The Cambrian starts with a basal conglomerate that contains alum slate, that is, a dark pelite rich in iron sulphide. The marine sedimentation continued in the Ordovician–Silurian, with clay, limestone and turbidite deposits. Greenstones with gabbro and peridotite, typical rock associations in a newly developing oceanic crust, originated in the Iapetus Ocean itself. Finally, 6000 metres of Torridonian arkoses, conglomerates, sandstones, greywackes and pelites were deposited at the North American continental margin in the Proterozoic. This was followed by quartzites in the Cambrian and then thick dolostones, which continued to be deposited into the Ordovician.

The Iapetus Ocean was gradually closed through subduction and a large mountain range was formed due to the collision of Baltica with North America: the Appalachians in North America and the Caledonian orogen in Europe (Scandinavia and the Bristish Isles).

Figure 1.3 shows two cross-sections through the Caledonian mountain chain. The cross-section through the Caledonian mountain chain in Scandinavia shows how the Baltic Shield was overthrust in an easterly direction by large thrust sheets containing the Precambrian crystalline basement of the past continental margin of Baltica and its Proterozoic–Palaeozoic sedimentary cover. These crystalline nappes were thrust onto the Baltic shield over hundreds of kilometres, as can be seen from the example of the Jotun Nappe. The thin obducted nappes of Aurdal and Synfjell are mainly composed of Early Palaeozoic sediments. At the extreme east, the Oslo Graben is visible, which is a rift within the Baltic shield that is largely filled with Permian igneous rocks. In the west, towards the North Sea, there are ophiolitic rocks overlying the Jotun Nappe, relics of the Iapetus Ocean. Fragments of this ocean were not subducted during the collision between Baltica and North America, but instead incorporated into the developing mountain chain.

A certain similarity can be seen when comparing the cross-section through Scotland with that through Scandinavia. The cross-section shown in Fig. 1.3 has been adapted from

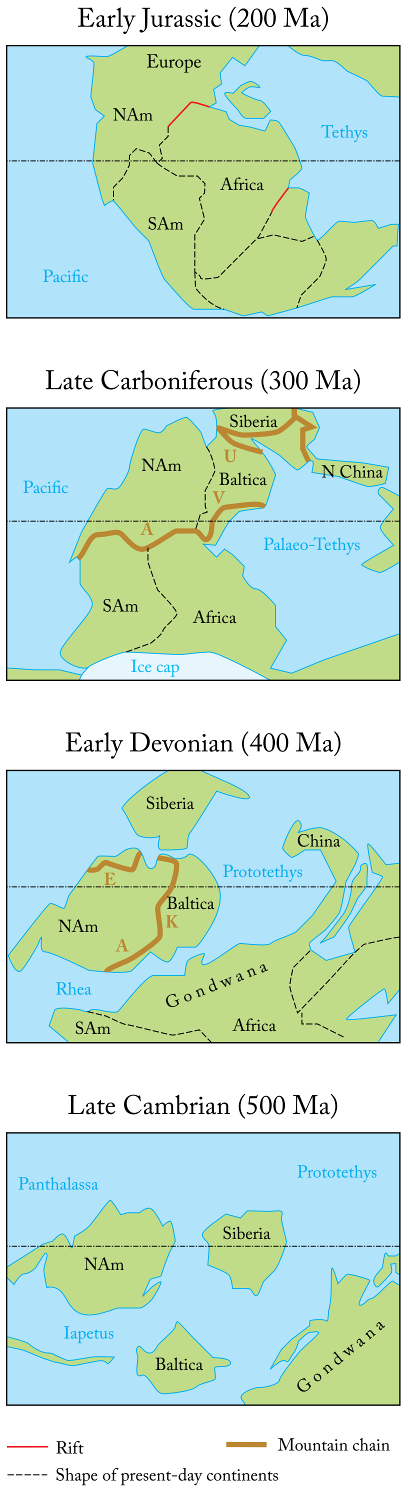
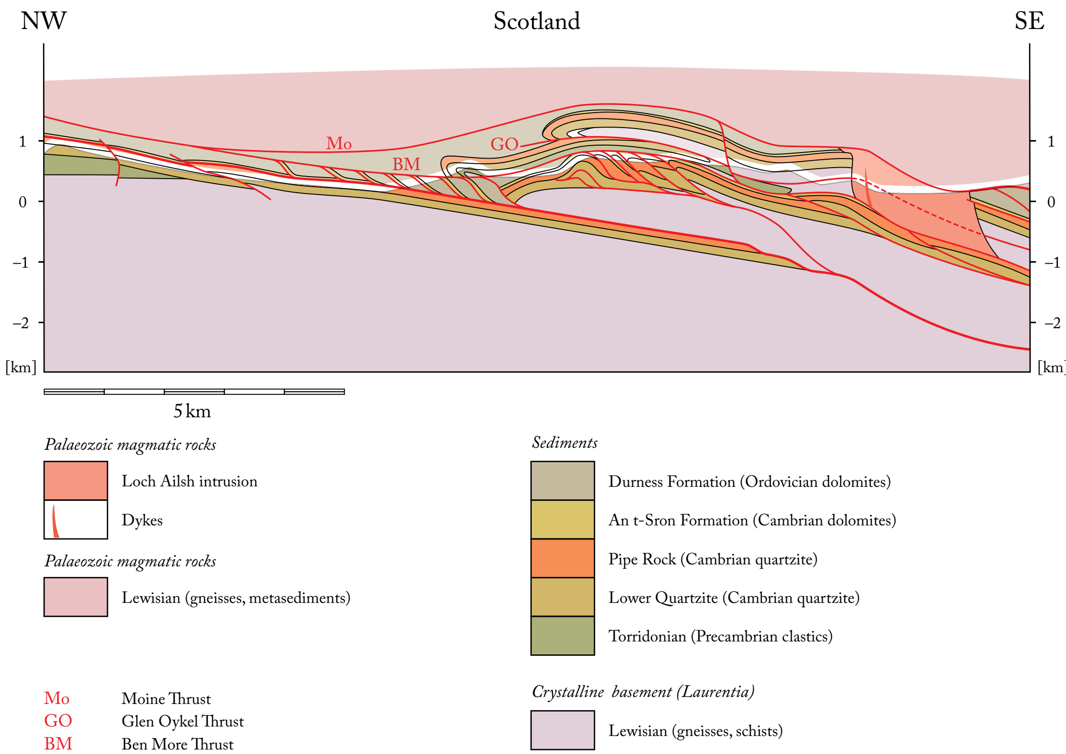
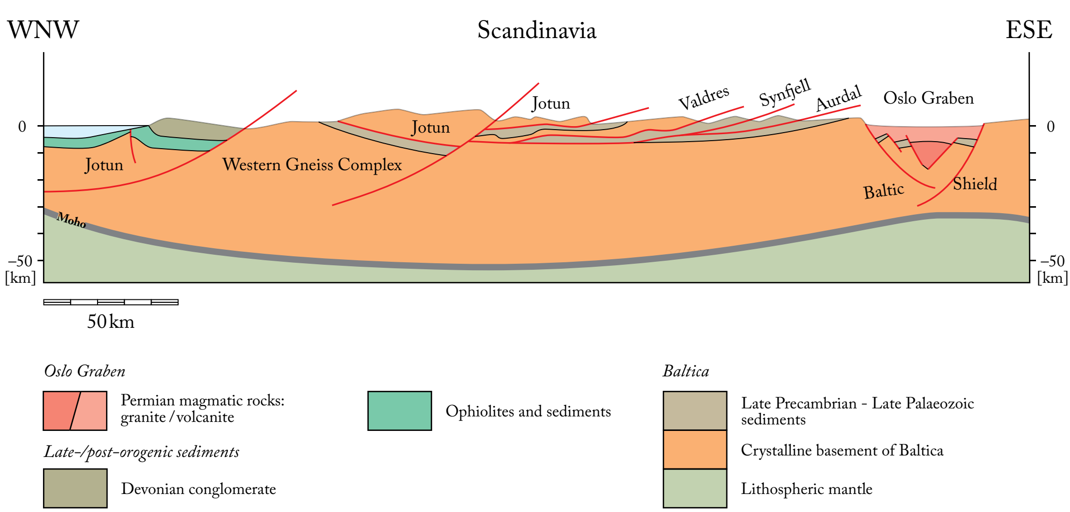


Figure 1.2 Plate tectonic evolution of Europe shown in four time slices. Positions of plates are based on Blakey (2008) and Scotese & Sager (1988). A, Appalachians; K, Caledonides; E, Ellesmere orogen; V, Variscan orogen; U, Urals; NAm, North America; SAm, South America.





Elliott & Johnson (1980). In this case, the Precambrian crystalline basement has also been included in the structure of the nappe. This 'Lewisian' basement is exposed in the Outer Hebrides in the northwest of Scotland. The 'Lewisian' has a greater affinity to the crystalline basement of the North American craton in the foreland of the Appalachians in Canada and Greenland than to the Baltic Shield. From a geological perspective, the Outer Hebrides must thus be regarded as part of North America.

The highest unit, the Moine Nappe Complex, has been almost completely eroded in this cross-section. However, the degree of metamorphism in the rocks below permits the clear conclusion that there was once a thick nappe pile overlying the currently visible rock formations (Strachan et al. 2002), because the Moine Nappe Complex exhibits a higher degree of metamorphism than the rocks below it.

The chronology of the formation of these nappes can be narrowed down based on the example of the Loch Ailsh intrusion: the Glen Oykel Thrust is cross-cut by the intrusion (so, is older), while the Ben More Thrust displaces and transports the intrusion (so, is younger) and the Moine Thrust caps the intrusion and is therefore also younger. The Loch Ailsh intrusion is dated at 434 million years ago (Silurian). It can be regarded as synorogenic, as it is located chronologically between the formation of the Glen Oykel and the Ben More or Moine thrusts.

In great contrast to Scandinavia, the nappes in Scotland (and in the Appalachians) were transported in a northwesterly direction. Overall, the Caledonian mountain chain therefore exhibits a bivergent nappe structure, a structure that is typical for mountain chains that emerge from a continent–continent collision.

The Rheic Ocean remained intact after the collision between Baltica and North America (Rhea in Fig. 1.2). The continent Gondwana, which included the land masses of South America and Africa, lay to the south of the Rheic Ocean. Towards the northeast, the Rheic Ocean met up with the Proto-Tethys Ocean, which separated the continental masses of Siberia and China. The Old Red Sandstone is the product of erosion of the Caledonian mountain chain and the Appalachians, and represents delta deposits at the margin of the continent (i.e., close to the Caledonian mountain chain). Sandy clastic sediments were also deposited at the northern margin of Gondwana (in today's Atlas). Pure limestones and shales were deposited in the Rheic and Proto-Tethys oceans in the Devonian, which are now exposed in the Eastern Alps. A microcontinent can be seen in the centre of the Rheic Ocean. Sedimentation is patchy here, indicating shallow water depth. These sediments have been preserved, for example, in the North Alpine foreland, in the Vosges, the Black Forest and in the Bohemian Massif. This microcontinental zone is also called Moldanubicum. The closure of the Rheic Ocean and collision of the continents North America–Baltica and South America–Africa led to the Variscan orogen (Fig. 1.1). The collision stages mainly occurred around the Devonian–Carboniferous transition, 345 million years ago, and then in the Early Carboniferous, 320 to 300 million years ago. In Europe, the Rhenish Schiefergebirge, the Ardennes, the Cantabrian Mountains on the Iberian Peninsula, as well as the mountainous areas in Brittany and in the Massif Central originated. On the North American side, the Southern Appalachians were uplifted. Therefore, the Appalachians have a more complex history of formation and are the product of more than one collision.

Plate convergence between Siberia and Baltica led to the uplift of the Ural

◀ **Figure 1.3** Geological cross-sections through the Caledonian orogen in Scandinavia and Scotland. In both cases, the crystalline basement is affected by thrusting and is involved in the nappe structure. Transport, however, occurred in opposite directions in Scandinavia and Scotland. Source: Based on Elliott & Johnson (1980).

Caledonides: bivergent orogen, basement involved in thrusting

Mountains (Fig. 1.2). The Proto-Tethys was reduced to an almost closed sea basin, the Palaeo-Tethys. For example, as is shown In Fig. 1.2, Baltica migrated from the Southern Hemisphere, northwards across the Equator and into the Northern Hemisphere during the period from the Late Cambrian to the Early Carboniferous. The southern tip of the welded continent underwent a glaciation in the Early Carboniferous.

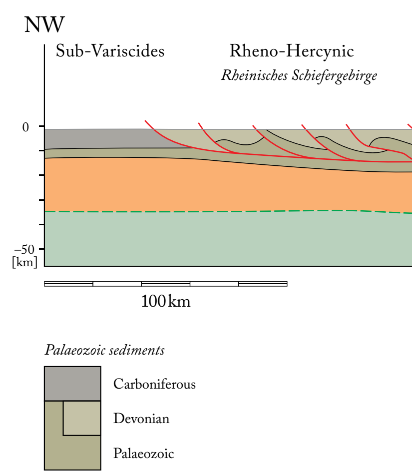
Variscides: bivergent orogen, basement involved in thrusting

The internal structure of the Variscan mountain chain in Europe is illustrated in Fig. 1.4 in a cross-section through Germany (redrawn from Matte 1991). A bivergent nappe pile was formed during the collision, which also includes the crystalline basement, similar to the case for the Caledonian mountain chain. The nappes at the continental margin of Gondwana were transported to the southeast and on the margin of Baltica to the northwest. The thick Palaeozoic sediments of the Rhenish Slate Mountains were pushed over each other like tiles and folded. The basal detachment of the nappes took place in a thick slate horizon. At the core of the orogen there is a vertically oriented fault that can be followed from Portugal to Bohemia, which probably represents a component of strike-slip motion. Even though the exposure of the core of the orogen is only patchy and is often covered by younger sediments, remnants of the Rheic Ocean can be found in a variety of locations in the form of ophiolites.

In the early Jurassic, 200 million years ago, the welded continental mass that became Pangaea had migrated further to the north and experienced a degree of anti-clockwise rotation (Fig. 1.2). The ocean between Africa and Asia became the Tethys. However, movements had now started that slowly led to the break-up of Pangaea. For example, one rift separates the Indian subcontinent from Africa and another rift opened up between Africa and the Variscan mountain chain. This rift formation and the associated ingress of the Tethys Ocean towards the west are crucial to the understanding of the geology of the Alps and are therefore discussed in more detail below.

1.2 Break-up of Pangaea and Opening of the Alpine Tethys

The plate tectonic processes during the break-up of the megacontinent, Pangaea, had a variety of effects on the Alps when they were formed later on. The small ocean basins and microcontinents that originated during this process resulted in a complicated juxtaposition of different sedimentary environments: deep-sea basins, shelf seas and submarine rises. The very different sedimentary facies representing these environments are now visible in the Alps juxtaposed vertically and laterally, in apparent complete disorder. The palaeogeographical shapes of the sedimentary basins affected the architecture



▶ **Figure 1.4** Geological cross-section through the Variscan orogen in central Europe. The crystalline basement is affected by thrusting and involved in the nappe structure. But the transport directions on either side of the orogen are opposite. Source: Matte (1991). Reproduced with permission of Elsevier.

of the Alps when these basins were closed during the formation of the Alps.

The break-up of Pangaea is illustrated in three snapshots in time in Fig. 1.5. A level of uncertainty is associated with all of these plate reconstructions, which is why these palaeogeographic maps also vary greatly from one author to the next. Figure 1.5 was simplified and redrawn from illustrations by Blakey (2008). In the Early Triassic (Keuper), 230 million years ago, Pangaea broke up along a rift that opened up between Gondwana and Laurasia. The rift originated in the Tethys, and extended along an arm of the Tethys between the continental masses of Arabia and Greece–Italy. The Palaeo-Tethys was then closed by subduction, such that the Turkish landmass was welded to Laurasia (Baltica) in the Middle Jurassic (Dogger), 170 million years ago. The eastern part of the rift shifted to the north and now separated the landmass Greece–Italy from Laurasia. This small ocean basin is referred to as the Ligurian or Piemont Ocean in Alpine geology. The rift expanded to the west and separated Africa–South America from North America. This rift was the precursor to the Atlantic and extended as far as Mexico. In the Early Cretaceous, 120 million years ago, North America and Africa drifted further apart and the Central Atlantic was born. In the north, Iberia separated from North America. The movement of Iberia was due to a spreading ridge in the west (mid-oceanic ridge of the Atlantic as it was opening up) and a transform fault to the north and to the south of Iberia. In the north, further spreading systems extended either side of Greenland. These were the forerunners for the opening up of the North Atlantic.

Figure 1.6 shows a simplified plate reconstruction for the Jurassic–Cretaceous transition (about 145 million years ago), adapted from Wortmann et al. (2001). Opinions diverge on the exact geometries of the individual basins, but the solution given in Fig. 1.6 is a combination of their essential characteristics. This shows a continental fragment extending from Iberia in a northeasterly direction and composed of Corsica–Sardinia–Briançon, which became separated from Iberia. The Corsica–Sardinia–Briançon continental

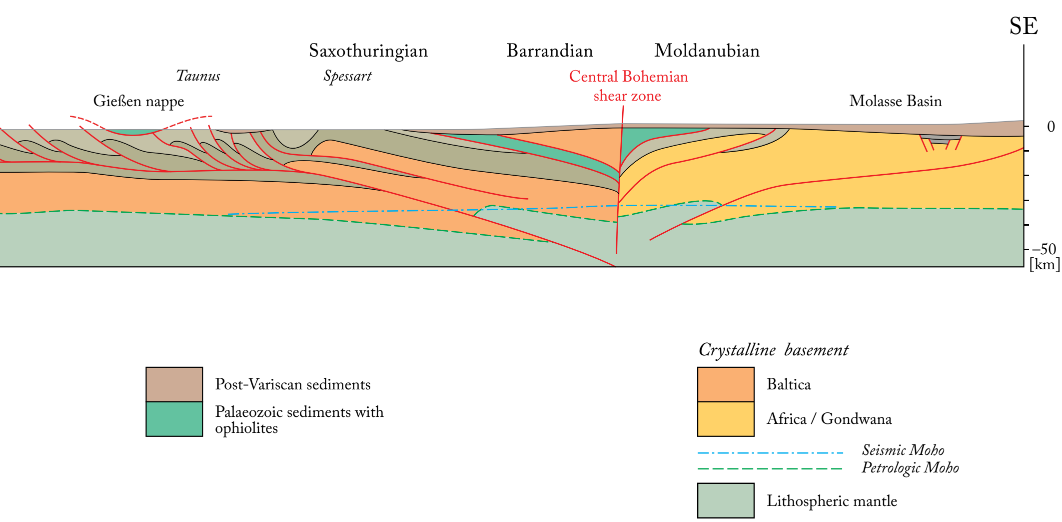


Figure 1.5 The break-up of Pangaea shown in three time slices. Positions of plates are based on Blakey (2008) and Scotese & Sager (1988). Grl, Greenland; It, Italy; Gr, Greece; Tu, Turkey; SAm, South America; Wr, Wrangellia; Mex, Mexico.

fragment corresponds to the so-called Briançon microcontinent, a submarine rise that can be traced from the Western Alps through to the Swiss Alps. The sea basin to the northwest of the Briançon microcontinent corresponds to the Valais Basin, and that in the southeast corresponds to the Penninic Ocean. A transform fault separated Iberia from Europe and acted as a local plate boundary during the drift of Iberia away from North America. Another transform fault connects the Piemont with the Penninic Ocean. The opening up of the Atlantic occurred simultaneously with an oblique opening up of the Ligurian–Piemont and Penninic oceans. The Dauphinois–Helvetic realms on the southeastern margins of Europe and the Southalpine Dolomites to the north of the Adriatic and in the Eastern Alps between the Vardar and Penninic Ocean are of particular relevance to today's Alps.

Figure 1.7 illustrates the broad palaeogeographical situation at the Barremian–Aptian transition, 125 million years ago. The reconstruction is based on Wortmann et al. (2001). The Ligurian–Piemont Ocean is characterized by multiple transform faults that indicate progressive oblique opening up of this ocean. A transform fault separates the Adriatic from the microcontinents Bakony, Austroalpine and Tiza. The Valais Basin opened up further due to the thinning of the continental margin of Baltica, or Europe, and evolved oceanic crust only in certain locations, in 'pull-apart basins'. In contrast, the Piemont Ocean had a mid-oceanic ridge that led to the formation of oceanic crust. The Adriatic continental margin and the Austroalpine microcontinent were stretched in an east–west direction by the opening up of the Piemont and the Penninic oceans. The normal faults in the future Austroalpine and Southalpine realms are evidence of this.

The Alps originated as a result of convergent plate movements between

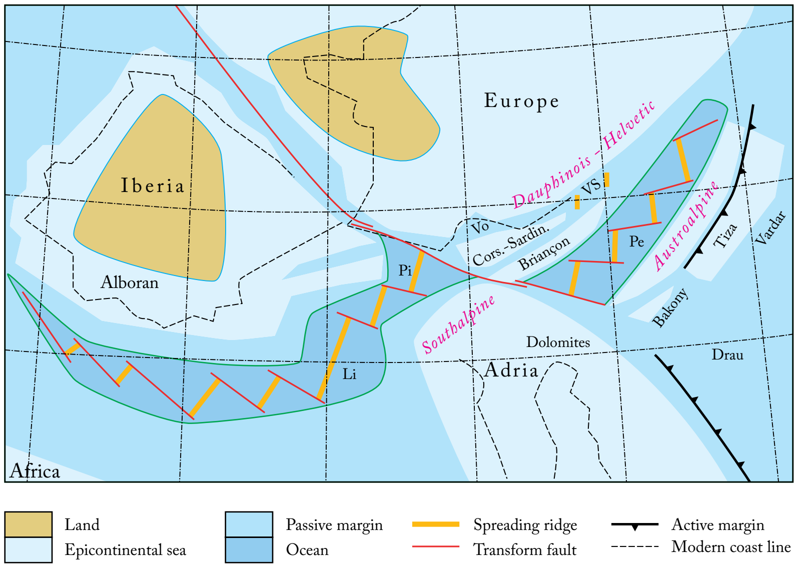


Figure 1.6 Plate reconstruction for the Berriasian (ca. 145 million years ago), simplified after Wortmann et al. (2001). The Ligurian (Li)–Piemont (Pi) Ocean stretches between the microcontinents of Iberia and Adria. It is disrupted by a transform fault and continues as the Penninic (Pe) Ocean between the Briançon and Austroalpine continental fragments. Narrow basins, the Vocontian (Vo) and Valais (VS) straddle the southern margin of the European continent. Cors-Sard, Corsica–Sardinia continental fragment. Source: Wortmann et al. (2001). Reproduced with permission of John Wiley & Sons.

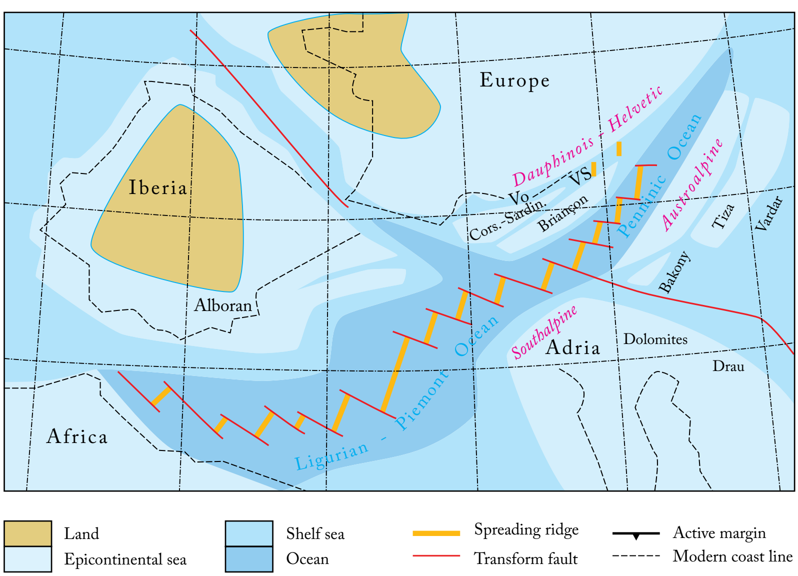


Figure 1.7 Plate reconstruction for the Barremian (ca. 125 million years ago), simplified after Wortmann et al. (2001). The Ligurian–Piemont Ocean is now wider and aligned with the Penninic Ocean. Similarly, the Southalpine and Austroalpine domains are now aligned. Cors-Sard, Corsica–Sardinia continental fragment; Vo, Vocontian basin; VS, Valais basin. Source: Wortmann et al. (2001). Reproduced with permission of John Wiley & Sons.

Baltica/Europe and Africa–Arabia. During this process, the sea basins that lay between, the Piemont Ocean and the Valais Basin, were closed up by subduction. This occurred in two separate stages. The Piemont–Penninic ocean was closed by subduction proceeding in a westerly direction in the Cretaceous, the Valais Basin by a collision in the Cenozoic between the Briançon microcontinent and the Adriatic continental margin, proceeding in a more north–south direction and, later on, between the Briançon microcontinent and the European continental margin. The complex palaeogeography illustrated in Fig. 1.7 leads us to surmise that the subduction and the collision process led to an even more complex geometry in the mountain chain that was being uplifted.

1.3 The Alpine System in Europe

The Alpine mountain ranges originated in the Cretaceous and in the Cenozoic. These ranges include, for example, the 'young' European mountain ranges (Betic Cordillera, Pyrenees, Alps, Apennines, Carpathians, Dinarides). Of note is that these mountain ranges are winding and arc-shaped. Figure 1.8 summarizes the continuing present-day motions (based on Kahle et al. 1995), which provide an insight into the plate tectonic processes during the formation of these mountain ranges. Africa is moving to the north by four millimetres and more each year. Movement in the west is slightly slower, that is, Africa is rotating anti-clockwise very slightly. Arabia is moving much faster, at 25 millimetres per year, in a northern direction. The jump in speed is taking place in a strike-slip fault that originates in the spreading ridge in the Red Sea and extends northwards through the Gulf of Aqaba, via the Dead Sea and the Sea of Galilee. The Turkish block is moving in a westerly direction by 25 millimetres per year. The plate boundary in the north of this block is to be found in the North Anatolian fault line, a seismically active dextral strike-slip fault. This drift to the west changes its direction to south-southwest in the Aegean. Its speed increases, as the Aegean is expanding in the same direction. The plate movements are revealed to be quite complicated, even just between Africa, Arabia and the Turkish block. Further north, this becomes even more complicated to understand.

In the East Carpathians, there is currently an active subduction zone that

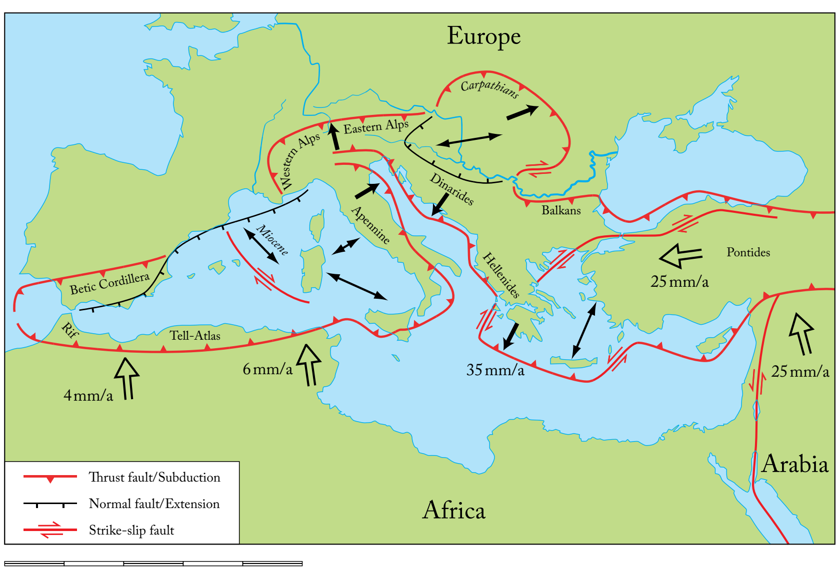


Figure 1.8 The tectonic plates in the present-day Alpine system. Open arrows with velocities (mm/a) show the direction of plate motions, simple arrows indicate directions of thrusting within the Alpine orogens. Double arrows denote areas of extension and opening of ocean basins. Source: Kahle et al. (1995). Reproduced with permission of Elsevier.

▲ **Figure 1.9** Digital elevation model of the Alps and neighbouring areas. Within the Alps, major valleys running parallel and across the orogen are clearly discernable. Large lowland areas lacking relief stretch across the foreland of the Alps. They correspond to the Rhine Graben in the north, the Bresse–Rhone Graben in the west, the Po Basin in the south and the Pannonian Basin in the east. Source: US Geological Survey.

is plunging towards the west. The Eurasian plate is sinking and simultaneously exhibiting slab retreat or roll back, that is, the plate boundary is moving towards the east in this subduction zone. As a result of this, the Pannonian Basin on the plate above is being stretched in an east-west direction. The Tiza block at the base of the Pannonian Basin is being squeezed out laterally towards the east by the pincer movement between Europe and Africa (or Apulia). However, at the same time, the Apennines and the Dinarides are also moving towards each other. Stretching and new formation of oceanic crust has been detected in the Tyrrhenian Sea in the hinterland of the active Apennines (Facenna et al. 2002). This process started about five million years ago. A little earlier, in the Miocene, the Ligurian Basin opened up under similar circumstances. At that point, the Corsica–Sardinia microcontinent separated from Europe and, during the subsequent rotation away from Europe, new oceanic crust developed in the Ligurian Sea. Therefore, movements of the smallest blocks between the two colliding continental plates also occurred in this case.

Even today, active horizontal motion can be measured in the Alps (Tesauro et al. 2005). The southern margin of the body of the Alps is moving slowly towards the north-northwest, at about 1.2 millimetres per year, and the northern margin is moving at only about 0.7 millimetres per year, but in the same direction. This indicates that the Alps are contracting by about 0.5 millimetres per year in a NNW–SSE direction.

The complicated present-day pattern of movement gives an impression of how the movements that occurred during the formation of the Alps must be envisaged. The sizes of the ocean basins and continents or microcontinents that were involved were modest in comparison with the dimensions in the classic subduction orogens of the Andes or the North American Cordillera, or in the collision mountain chains of the Himalayas or Appalachians. However, the convergent movements were qualitatively comparable and made the Alps into a mountain chain with such a highly heterogeneous structure.

1.4 Structure of the Alps

The mountainous body of the Alps extends in a wide arc from Nice to Vienna. The Po Basin lies within the arc. It is morphologically distinct due to its low altitude and minimal relief, as is made clear in the digital elevation model in Fig. 1.9. Long, narrow basins with no relief are visible outside the Alpine arc: the Rhone–Bresse Graben in the extreme southwest, the Rhine Graben in the north. In the far east of the region, the Alps disappear under the Vienna Basin.

Western Alps
Central Alps
Eastern Alps

Along this mountain chain, the Alps are subdivided into the Western Alps, Central Alps and Eastern Alps. The Eastern Alps run more or less east–west and their western boundary is located on an approximate line through St Margrethen–Chur–Sondrio. In the Central Alps, the course of the mountain chain changes from east–west to almost north–south. The Western Alps run from north to south, but form a tight arc round the western end of the Po Basin. The boundary between the Central and Western Alps is diffuse. Some authors therefore only subdivide the Alps into the Western Alps and the Eastern Alps. While the three-part division is preferred here, this is simply due to the internal structures, which are hereby easier to classify in a comprehensible manner.

Across this mountain chain, the Alps are subdivided into tectonic units that belong to specific palaeogeographical domains. The palaeogeographical affiliation is defined by the Mesozoic sedimentary environment in these units. Based on this structure, we can distinguish a belt of sedimentary rocks that belong to the European continental margin and are exposed in the extreme external regions of the Alps, that is, extreme west and north. These rock formations are referred to as 'Dauphinois' and 'Helvetic'. A second belt of sedimentary rocks, summarized using the term 'Penninic', is located in a more central position, that is, it lies further to the east or south. The associated Mesozoic sediments were deposited in marine basins between the European and Adriatic continental margins. A third belt of sedimentary rocks is to be found mainly in the most internal location, towards the Po Basin. These units are referred to as 'Austroalpine' and 'Southalpine' and are allocated to the Adriatic continental margin. In general, the Penninic units lie on top of the Helvetic and the Austroalpine unit on top of the Penninic. All these units are actual nappe complexes that were transported hundreds of kilometres from their substratum in the form of relatively thin sheets of rock. Figure 1.10 shows the distribution of these nappe complexes throughout the Alps.

The Austroalpine nappe complex makes up almost the entire Eastern Alps. It is only at the outer margins in the north and east that Penninic and Helvetic nappes can still be recognized in the footwall of the Austroalpine nappes. In the centre of the Eastern Alps, in the Tauern Window, the Austroalpine nappe complex is eroded, such that a spectacular view of the Penninic and Helvetic nappes lying below is revealed. A smaller, but otherwise equivalent, window is found slightly to the west, in the Lower Engadin. Further to the west, the Austroalpine nappe complex is almost fully eroded in the Central Alps. However, small erosional remnants, called klippen or outliers, remain as evidence for the original distribution. The largest of these klippen is to be found in the region of the Dent Blanche.

The Southalpine nappe complex and the adjacent Dolomites to the east are separated from the Austroalpine nappe complex by a major fault, the peri-Adriatic fault system. This continues eastwards into the Karawanks, where it separates the Dinarides from the Eastern Alps. The Southalpine nappe complex, the Dolomites and the Dinarides, were tectonically independent of the Austroalpine nappe complex. Only the affinity of the Mesozoic sediments to the Adriatic continental margin constitutes a common element.

The distribution of the Penninic nappe complex also reveals a large klippen in the region of the Central Alps, on the northern margin of the Alps. This is to be found in the French–Swiss Prealpine and in the Chablais region in France. Further smaller klippen are to be found in central Switzerland. These klippen also provide evidence that the Penninic nappes once covered large parts of the Alps.

The Jura Mountains are visible in Fig. 1.10 at the outermost margin of the Central Alps. At the end of nappe formation in the Alps, this banana-shaped mountain range was compressed, folded and pushed to the northwest.

Younger, Cenozoic basins demarcate the edge of the Alps. In the north of the Alps, the Molasse Basin extends from Vienna, via Munich into the Swiss Central Plateau and peters out in a westerly direction. The Molasse Basin is a foreland basin that developed in the Oligocene–Miocene after Alpine nappe formation and was then filled with clastic deposits from the uplifting Alps. In the course of the most recent nappe movements, the Molasse Basin was mainly compressed at its southern margin and even pushed to the northwest in the region of the Jura Mountains.

The rift system with the Rhine Graben and the Rhone–Bresse Graben is visible outside the Jura. The two rift basins are connected to each other by a transform fault system. Basement uplifts exposing crystalline rocks flank the rift basins on both sides: the Black Forest and Vosges, and the Massif Central and Massif de la Serre.

Finally, the Po Basin is visible in the south of the Alps, a foreland basin shared by the Alps and the Apennines. Clastic sediments up to ten kilometres thick were deposited in this basin in the Cenozoic. The basin fill was partially affected by the Alpine nappe movements, resulting in fold and thrust structures.

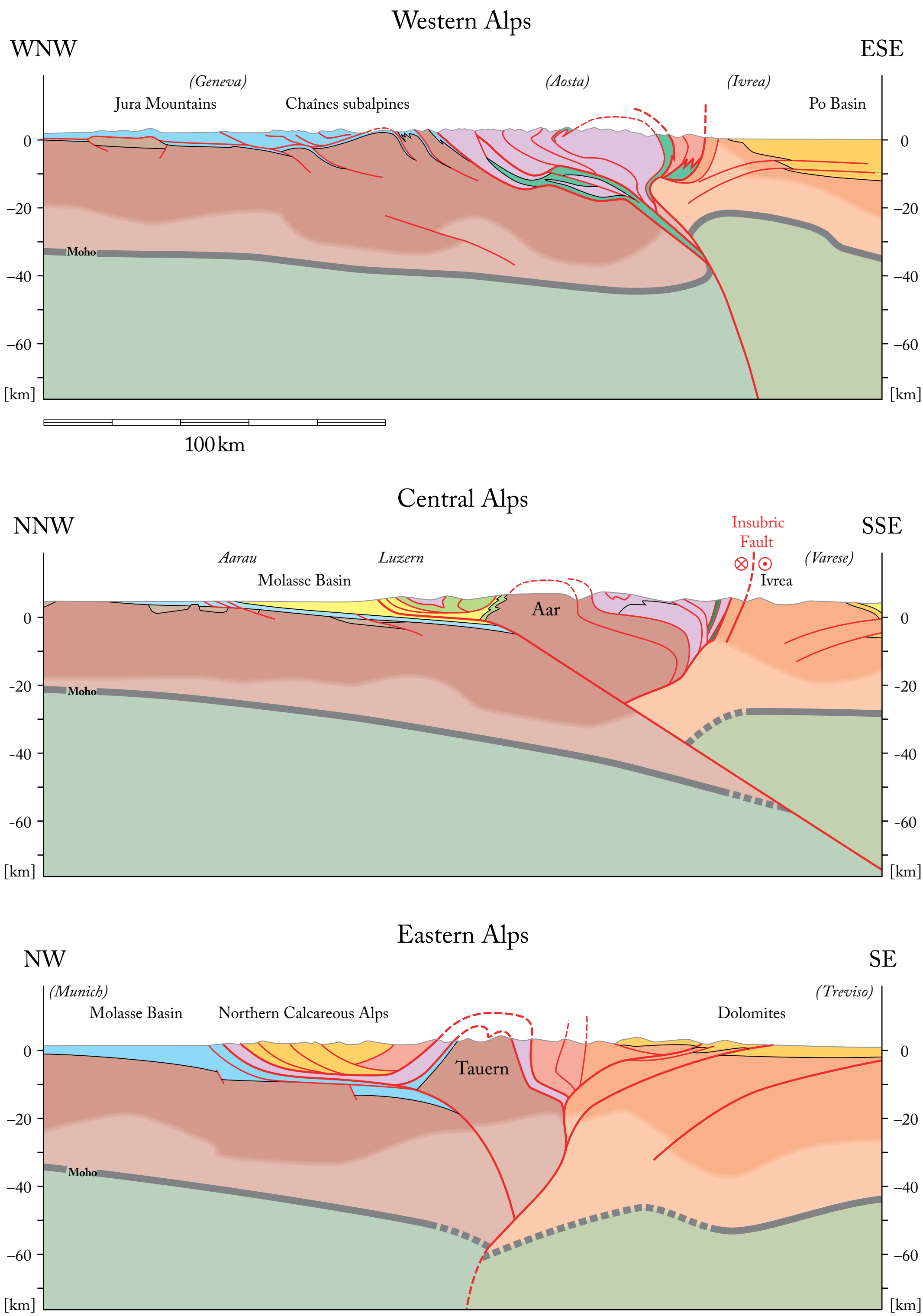
Figure 1.11 shows three schematic, simplified cross-sections through the Alps. These show commonalities and differences between the West, Central and Eastern Alps. All three cross-sections are based on insights gained from reflection seismic investigations conducted within the framework of three large national and international research programmes. The cross-section through the Western Alps is

▶ **Figure 1.10** Simplified tectonic map of the Alps and their foreland. The Jura Mountains, and Dauphinois–Helvetic nappe system are part of the European continental margin, the Austroalpine and Southalpine nappe systems represent the Adriatic margin. The Penninic nappe system in between is derived from the Valais basin, the Briançon microcontinent and the Penninic Ocean. Two tectonic windows (inliers) in the Engadin and Tauern prove that the Penninic and Helvetic nappes have a subsurface continuation towards the east. On the other hand, klippen (outliers) of Austroalpine units at the transition between the Central and Western Alps indicate the former extension of the Austroalpine nappes towards the west. A, B and C indicate the locations of the cross-sections shown in Fig. 1.11.

European margin
Piemont Ocean
Adriatic margin

based on the Franco-Italian project ECORS-CROP (Nicolas et al. 1990, Roure et al. 1996, Schmid & Kissling 2000), that through the Central Alps on the Swiss National Research Project, NFP 20 (Pfiffner et al. 1997) and, finally, the cross-section of the Eastern Alps is based on the Germano-Austro-Italian

project TRANSALP (TRANSALP working group 2002, Lüschen et al. 2004). The structure of the lower crust has been determined from controlled-source seismology, as well as local earthquake tomography studies by Waldhauser et al. (2002), Diel et al. (2009) and Wagner et al. (2012).


Western Alps
WNW
ESE
(Geneva)
Jura Mountains
Chaînes subalpines
(Aosta)
(Ivrea)
Po Basin
0
−20
−40
−60
[km]
Moho
100 km
Central Alps
NNW
SSE
Insubric Fault
Aarau
Molasse Basin
Luzern
(Varese)
Ivrea
Aar
0
-20
-40
-60
[km]
Moho
Eastern Alps
NW
SE
(Munich)
Molasse Basin
Northern Calcareous Alps
(Treviso)
Dolomites
Tauern
0
−20
−40
−60
[km]
Moho