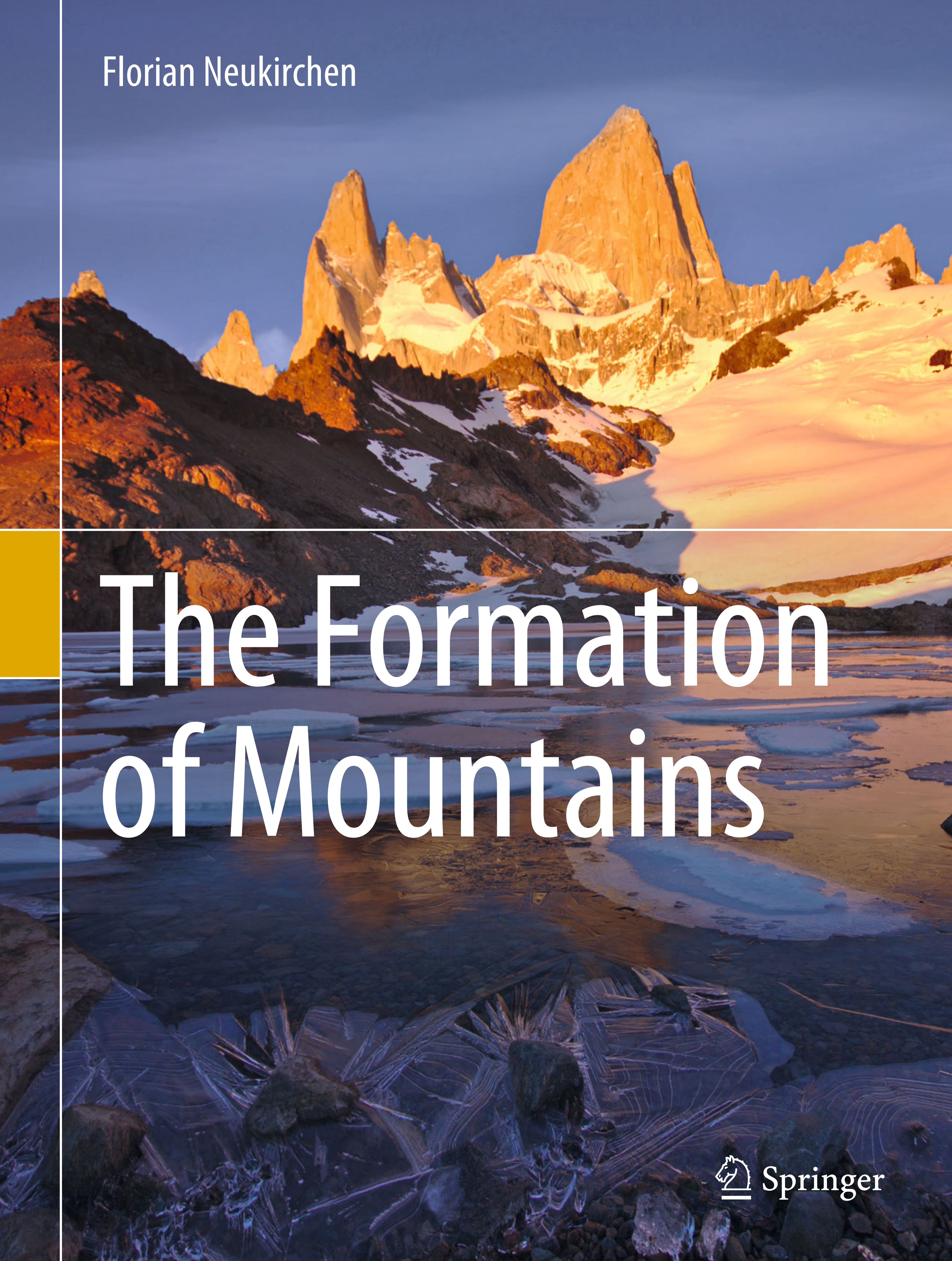
Florian Neukirchen

The Formation of Mountains



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Preface

The processes that create and shape mountains are just as fascinating as the resulting landscapes. This book invites you on a geological journey around the world. Popular travel destinations are explained in detail, making it a kind of guide book for travellers interested in earth sciences. It also unearths many surprises that are not covered in classic textbooks. The latest findings from disciplines such as tectonics, petrology, sedimentology, geomorphology, seismology, volcanology and plate tectonics are incorporated.

The target group is everyone who likes to be in the mountains, for example, for hiking, mountaineering or climbing. Therefore, I also explain basic concepts and technical terms. However, the book is also suitable for students of geography and geosciences, especially when preparing for a trip and to look beyond the horizon of one's own discipline. The chapters build on each other didactically; those who are not yet familiar with the basics of geology should therefore follow the order of the chapters. I explain technical terms the first time they are used; they can also be looked up in the glossary.

More than 10 years have passed since the first edition of *Bewegte Bergwelt* was published in German. Since then, geology has evolved; there are new seismic profiles, new datings and many other interesting studies. The present translation is based on the completely revised, updated and expanded second edition.

The idea for this book matured about 15 years ago on a 13-month journey through Asia. One of my long treks was the Annapurna Circuit in Nepal. The mountain villages on the northern side of the Annapurna massif have a Tibetan flair: colourful prayer flags flutter in the wind, prayer wheels and whitewashed chortens line the way, and the rain shadow of the mountains usually means dryness. However, as I approached Manang, supposedly the driest place in the region, it started to rain. The rain turned to snow towards evening, and heavy snowfall continued without interruption for the next 3 days, making the ascent to the pass Thorung La (5416 m) impossible for the time being. Wild rumours circulated among the trekkers about the situation further up, and many made their way back in frustration. Others, like me, stayed in the village by the warm stove, waiting for better weather. They asked me, the geoscientist, about mountain building in general and the Himalayas in particular. Some questions were pretty good. I couldn't answer all of them, so at home I researched more details in scientific journals.

Similar situations were repeated later on other treks all over the world. Surprised, I soon realised that there was no easy-to-understand book that compiled all the amazing phenomena and geological peculiarities of the world's mountains that I could recommend to all the interested climbers, hikers and nature lovers. I only found books that were either too general to understand regional peculiarities or were limited to a single region such as the Alps. Yet it is precisely the similarities that make even a complicated mountain range like the Alps more understandable. The processes that took place there, one after the other and side by side, we can first visualise with simpler examples. The idea of writing this book thus took on a more and more concrete form. In addition, I became more and more serious about my hobby of travel photography. With each trip, more photos from all over the world accumulated, which now make up the majority of the figures in this book.

I find it more exciting than any inventory of rock formations to be able to visualise the processes that contributed to the formation of a mountain range. Since I primarily want to explain how something happens and why, I decided to structure the book according to the most important processes and not regionally. However, a mountain range always has a long geological history in which very different processes took place one after the other. This inevitably leads to breaks in the narrative when the development of a mountain range continues in another chapter.

In the cited literature, I rely mainly on reviews and on particularly exciting new articles. These naturally build on a long history of research, which can be looked up in the cited literature, but I also mention some classic papers that have led to a revolutionary change in geological understanding.

I would like to thank all those who contributed to this book. Very helpful were comments and suggestions from Stefan M. Schmid (University of Basel), Wolfgang Frisch (University of Tübingen), Thomas Glade (University of Vienna), Felix Keller (Academia Engiadina), Jurgis Klaudius and Michael Neubauer as well as Carola, Hans and Randi Neukirchen, who read parts of the manuscript before the publication of the first German edition. I thank all the photographers who provided their excellent pictures from regions I did not visit myself. I thank all the reviewers of the German edition for their praise and constructive criticism.

Berlin, Germany
March 2022

Florian Neukirchen

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About the Author

Florian Neukirchen is a geoscientist and non-fiction author. After his studies in Freiburg, he worked on alkaline rocks at the University of Tübingen. Research trips led him to Oldoinyo Lengai in Tanzania, through the High Atlas in Morocco and to the Ilimaussaq intrusion in Greenland. On his travels around the world, he visited many mountain ranges, climbed some peaks or carried a backpack and a camera on long-distance treks to the best viewpoints. He currently lives and writes in Berlin. He published *The World of Mineral Deposits* (2020), as well as several books on geology in German.

Tschingelhörner (2849 m) with the rock window Martinsloch. This is where the nappe structure of the Alps was first recognised. Along the clearly visible Glarus Thrust, older sediments were pushed as thrust sheet over younger sediments (© Florian Neukirchen 2010)

1 The Structure of Mountains

"Because it's there." That was George Mallory's answer to the question why he wanted to climb the highest mountain in the world (Fig. 1.1). The Everest pioneer had an accident a few hundred metres below the summit during his third expedition in 1924. Even though he did not conquer the summit, his legendary saying made him immortal.

Since time immemorial, mountains have fascinated people: large and mighty, visible from afar and yet unapproachable (Figs. 1.2 and 1.3), another world in front of which one feels small and insignificant and yet close to heaven. It is no wonder that countless myths surround them—that the gods cavort on the peaks, that giants and trolls live there or witches dance. No religion can do without its sacred mountains. But the peaks also exert a magical attraction on people who want to penetrate this mythical world and challenge the gods. The myths have not diminished as a result. On the contrary, with every first ascent and every misfortune, new myths are added.

"Because it is there". Why do mountains exist at all? Myths also surround their formation, and even today, despite intensive research, nowhere near all questions have been answered. Nevertheless, we have a relatively good picture of the processes that take place during mountain formation. It is the picture of a dynamic planet that is constantly changing, an Earth whose continents "wander", whose mountains rise and are eroded again, whose oceans become wider and wider and also disappear again.

A mountain range like the Himalayas or the Alps is formed when two continents move towards each other and collide. This sounds almost banal and self-evident to our ears. But we have to remember that little more than half a century ago, the continents did not move at all, at least in most people's imagination.

Mountains also form when oceanic crust is pushed under a continental margin. Under the Andes (Fig. 1.4) with their smoking volcanoes, the "crustal plate" of the Pacific submerges into the Earth's interior, the ocean slowly becomes smaller and smaller (Chap. 4). However, mountains are not only formed by collision and compression but also by the opposite, by extension (Sect. 6.2). Still others rise into the sky in places where, even by geological standards, tectonic quiescence prevailed for long periods of time. In the case of the tepui in Venezuela (Sect. 2.6.4), the last mountain building was longer ago than the development of life forms that are more complex than sea anemones, for example.

Some mountains are part of a mountain range composed of countless peaks; others rise solitarily from a plain. They can be very high and still look like a hill. Others are low but impress with their steep cliffs. There are ridges and tables, cones and gentle hills, pinnacles, needles and ridges, towers, horns and pyramids. Mountains are so diverse (Figs. 1.1, 1.3, 1.4, 1.5 and 1.6) that it is not at all easy to define a mountain in a generally valid way. The entries in the dictionaries are less meaningful than what each of us already has in mind as an idea. The processes by which mountains are formed and given their shape are as varied as the mountain shapes.

High topography is not always related to orogenesis (i.e., the processes of mountain building), and an episode of mountain building (orogeny) does not always lead to particularly high topography. This sounds confusing, but for geologists "orogenesis" is not uplift and, thus, the formation of the mountain ranges themselves but rather movements in the Earth's interior and the formation of the structures that make up the architecture of mountain ranges: tectonic movements, for example, that displace rock units against each other; molten rock that solidifies into granite; sediments that are transformed into metamorphic rocks at depth. Uplift only begins with a delay, and it must be faster than the simultaneous erosion for a mountain range to rise.

Geologists have been roaming the mountains "with hammer and mind" for centuries. They read the rocks like a book and try to decipher the secrets of the Earth. When they find fossils such as corals, shells and ammonites, this not only allows them to make statements about life forms that have long been extinct but also about the sea in which the

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Fig. 1.1 Mount Everest (8848 m) with Nuptse (7861 m), Lhotse (8516 m), Makalu (8485 m), Cholatse (6440 m) and Taboche (6542 m) from the Renjo La pass in Nepal, with the village of Gokyo at the lake (© Florian Neukirchen 2013)

sedimentary rock in question was deposited. The temperature at which a claystone was transformed into glittering mica schist can be calculated from the chemical composition of the minerals. The compositions of basalt or granite give clues as to where these melts were formed and what happened to them on the way up. The waves of an earthquake can give insights into the unreachable interior of the Earth, much like a doctor can look into a human body with ultrasound. Increasingly sophisticated methods—including large measuring devices and experiments in laboratories, seismic campaigns across the mountains and measurements by satellites—allow better and better insights into the construction of the mountains and the processes taking place. From all these puzzle pieces, a picture emerges that traces the development of a mountain range.

How, for example, can high-pressure rocks from a depth of 100 km reach the surface (Sect. 7.6) and eventually lie next to sediments that have always been there? Does the climate have an effect on mountain building (Sects. 3.5.3 and 7.1.5)? Why are there huge gaps in the Andean segment of the so-called ring of fire without a single volcano (Sects. 4.2.2 and 4.2.4)? And what does the term "fold mountains" mean anyway? It is still sometimes used to describe mountain belts such as the Alps but, in fact, it is rather misleading. If we push a tablecloth from two sides towards the centre of the table, it becomes folded. This is how simple the formation of mountains was imagined a long time ago. But it doesn't take much to realise that this model cannot be easily applied to the Earth's crust. An average continent is 30 km thick. If you try the same experiment with a mattress, you will suspect that a continent would have to produce gigantic folds with a wavelength of hundreds of

Fig. 1.2 Vysoká (2547 m) in the High Tatras, morning atmosphere during the ascent to Rysy from the Slovak side (© Florian Neukirchen 2018)

Fig. 1.3 Cerro Torre (3128 m) in Patagonia from the Argentinian side. The steep granite tower, a mushroom-shaped overhanging glacier at the summit and, above all, the notoriously bad weather are a challenge even for professional mountaineers (© Florian Neukirchen 2012)

kilometres—much broader than the folds we can observe in the Alps. In fact, such mountain ranges don't look much like folds at all. Geologists puzzled over it for quite a long time. In the Glarus Alps, they found a structure early on where the solution seemed to suggest itself, but they resisted for a long time because it seemed too far-fetched.

1.1 The Riddle of the Glarus Thrust

In the mountains of eastern Switzerland, in the canton of Glarus between the Rhine Valley near Chur and Lake Walen, a striking line stands out, dividing the mountains razor-sharp into two storeys of obviously completely different rocks (Fig. 1.7). Particularly well known are the Tschingelhörner, whose peaks consist of dark sandstones and conglomerates overlying light limestone and grey flysch. Flysch (Sect. 2.4.6) is alternating bedding of sandstone and claystone that was deposited in the sea when the Alps were just beginning to rise in the Tertiary. For a long time, this line was a great mystery of geology, because the sandstones, greywackes and conglomerates above the line are much older than the flysch below. They were deposited in a desert landscape as early as the Permian. The detritus originated from the erosion of the older Variscan Mountains, which once stretched across the whole of Europe but had already been largely flattened at that time. Greywacke is a type of sandstone that contains many rock fragments and clay particles. Conglomerate is gravel that has solidified into a rock. Quite a lot of time has passed from the Permian to the Tertiary, about 200 million years. The whole age of the dinosaurs lies in between. The light-coloured limestone, which lies between flysch and sandstone at the Tschingelhörnern, comes from this time period, from the late Jurassic.

It goes without saying that younger rocks cannot be deposited below older ones. Rather, the older ones must have been subsequently pushed over the younger ones. In the process, they have covered a distance of 40–50 km (Fig. 1.8). This fault is known as the Glarus Thrust (*Glarner Hauptüberschiebung*) and it is only one of many overthrusts in the Alps, which consist of a whole stack of displaced thrust sheets that are also called nappes.

But, as clearly as this thrust fault can be seen in the field, it took quite a long time for geologists to come to terms with the idea that such a thing could be possible. This was at a time when the theory of plate tectonics was far from being invented. Horizontal movements of such proportions were still unimaginable; only vertical uplift and subsidence were thought of. It was once believed, for example, that the mountains were raised by magma rising from the Earth's interior. This idea was supported by the fact that granites, i.e., magma that had solidified in the depths, were often found along the central axis of the mountain ranges. In the middle of the 19th century, an alternative explanation emerged. It was believed that the Earth was shrinking due to cooling, and the formation of the mountains was imagined to be something like the wrinkles on a shrivelled apple. The oceans were thought to be basins collapsed by this contraction. And to explain why marine sediments are found in the mountains, there had to be cycles of uplift and subsidence somehow.

Already 200 years ago, the Swiss polymath Hans Conrad Escher von der Linth (1767–1823) painted the Tschingelhörer (Fig. 1.9). Like many of his contemporaries, Escher occupied himself with very different things; he worked as a

Fig. 1.4 Parinacota (6348 m) is one of the countless volcanoes in the Andes. View from Lago Chungara in Lauca National Park, Chile (© Florian Neukirchen 2010)

Fig. 1.5 These mountains on the Tibetan Plateau lie on the edge of a large undrained basin with Lake Nam Tso at an altitude of more than 4700 m (© Florian Neukirchen 2005)

civil engineer in river regulation, he was a silk manufacturer, cartographer and painter, politician and geologist at the same time. As a good observer, he wondered about the greywacke overlying limestone, which contradicted even the theory of that time. According to this theory, whole regions rose and subsided regularly, alternating between sea and mountains. Sandstones, greywackes and conglomerates are the erosion debris of an older mountain range, because they can hardly have reached the mountain peaks from the basin in the Alpine foothills. Escher von der Linth concluded that they must be older than the limestones deposited in a sea.

Hans Conrad Escher's son, Arnold Escher (1807–1872), became the first professor of geology in Zurich. Using fossils, he was able to determine the relative ages of the rocks, with the unequivocal result that at the Tschingelhörnern the older sediments indeed overlay the younger ones. He already suspected that the older rocks had been thrust over the younger ones. He took his British colleague Sir Roderick Impey Murchison up there, and he too was immediately convinced that it must be an enormous overthrust. That was in 1849, but Escher rejected the revolutionary idea; he was afraid of not being taken seriously. No one would believe

Fig. 1.6 The mountains on the Lofoten archipelago (Norway) were sculpted by glaciers. They rise directly from the sea like the teeth of a saw. View from Hermansdalstind (1029 m) on the Reinefjord and several mountain lakes, with the mainland on the horizon (© Florian Neukirchen 2009)

Fig. 1.7 The Glarus Thrust at the Tschingelhörner. Much older sediments from the Permian ("Verrucano") were pushed over younger sediments, over a light-coloured limestone from the Jurassic (at the Tschingelhörner below the thrust) and flysch (at the pass on the right side below the limestone) from the Tertiary (© Florian Neukirchen 2010)

him that mountains had been literally moved and over enormous distances. To explain the dilemma of the upside-down age sequence, he thought up a strangely shaped double fold that defied all imagination and mechanics. His successor Albert Heim adopted this idea and made excellent drawings of it (Fig. 1.10).

It was not until half a century later that the idea of displaced thrust sheets was able to gain acceptance, but others than the Swiss earned the credit. Besides the Austrians who discovered the Tauern window, it was, above all, the Frenchman Marcel Bertrand (1886–1907) who put the pieces of the puzzle together, explained the Tauern window to the Austrians (Exner 2003) and developed the "outrageous fantasy" that the Alps are built up by nappes or thrust sheets.

Window (Fig. 1.11) is the geological term for an area in which a hole has been eroded into a nappe, so to speak, in which the lower units found underneath the overthrust emerge on the surface. In Austria, Hohe Tauern and Zillertal Alps together form such a window (Sect. 8.3.4). Due to its rectangular shape, it actually resembles a window frame

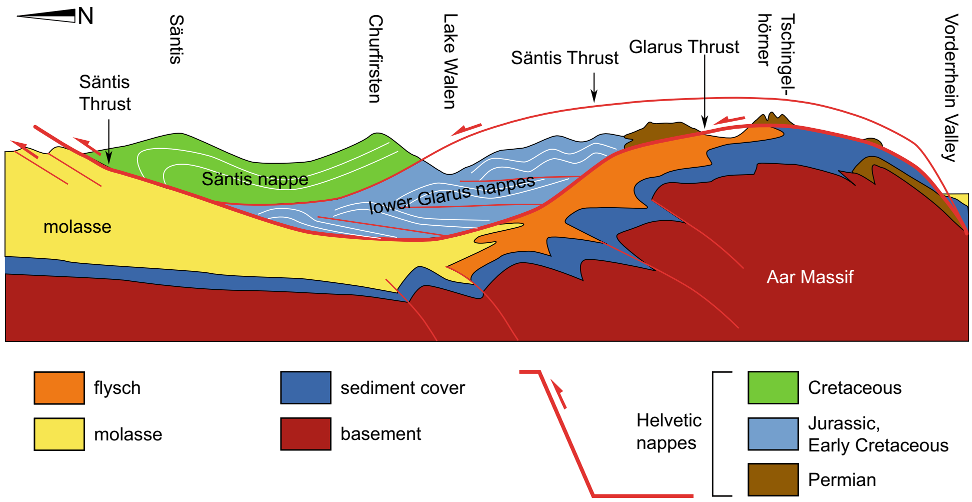

Fig. 1.8 In a late phase of the formation of the Alps, the sediments of the European continental margin were sheared off and pushed northwards along the Glarus Thrust. In the process, they overran Tertiary flysch (deposited only during mountain building in the disappearing ocean basin) and the molasse (the erosional debris of the Alps in the foreland basin). The overthrust was deformed into a horizontal S by the subsequent rise of the Aar massif

through which one can look into the deeper nappes. In the Tauern window, the lower thrust sheets consist of rocks that once lay in the deep basin of the Penninic Ocean, which disappeared due to mountain building, while the upper nappe that was thrust over them was once part of the continental margin south of the ocean. A klippe or outlier is the counterpart of a window. In this case, the upper nappes have largely been eroded, leaving only isolated, free-standing remnants. The first klippen to be recognised as such are in the Préalpes of western Switzerland, where a nappe of rocks originating from the open sea lie above sediments from the former European continental margin. These outliers were found by the Swiss geologist Hans Schardt, who noticed that these rocks matched rocks that occur today, only much further south. The name klippe (German for cliff) comes from the fact that the Lucerne geologist Franz Joseph Kaufmann still believed in 1876 that such rocks were rocky islands in a sea in which the surrounding rocks were deposited.

Marcel Bertrand was finally put on the right track by a seminal book by the Austrian geologist Eduard Suess (1831–1914). In his work *Die Entstehung der Alpen* ("The Origin of the Alps"), published in 1875, Suess established that horizontal movements caused by lateral constriction had a greater influence in the formation of mountain ranges than vertical uplift caused by a force acting from within the Earth. The contraction theory with the shrivelled apple had just emerged, and it was to provide the mechanism. Suess initially thought of folds. Bertrand took the thought further: If there are horizontal movements, then overthrusts are also possible.

In an article from 1884, Bertrand first applied this idea to the Glarus Thrust. Without ever having been to Glarus, he showed that an overthrust explains the structures there much better than the confused idea of a double fold—to which Albert Heim, the "Pope" of Swiss geology, nevertheless continued to stubbornly cling. Bertrand and several Frenchmen and Austrians, among them Eduard Suess, now developed the theory that the Alps were built up of superimposed thrust sheets, of rock packages that had shifted one on top of the other. A little later, similar nappes of the ancient Caledonian Mountains were described in Scotland and Scandinavia. The same structure was then found again and again in other mountains—Bertrand was on the trail of the structure of almost all high mountains.

If two continents collide, one tries to thrust over the other. But, since two continents cannot simply be pushed over each other, a whole system of thrust faults develops, where individual nappes are sheared off and moved over the rocks beneath them. The individual nappes may have travelled enormous distances, typically dozens of kilometres, but some have even been displaced by well over 100 km. Stacking one sheet on top of the other results in a significant horizontal shortening of the affected crust, which is of course accompanied by a simultaneous thickening. At the very top, now lies the margin of one continent dissected into nappes; in the middle, nappes of the remains of the ocean that disappeared between the two continents; and below that, the sediments of the other continental margin dissected into nappes. Underneath the nappe pile lies what is still more or less in place from the continental margin. The overthrusting of these nappes took place deep below the Earth's surface.

Fig. 1.9 The watercolour entitled "Das Martinsloch" by Hans Conrad Escher von der Linth from 1812 shows the Glarus Thrust at the Tschingelhörner (© Escher von der Linth, Wikimedia, in the public domain)

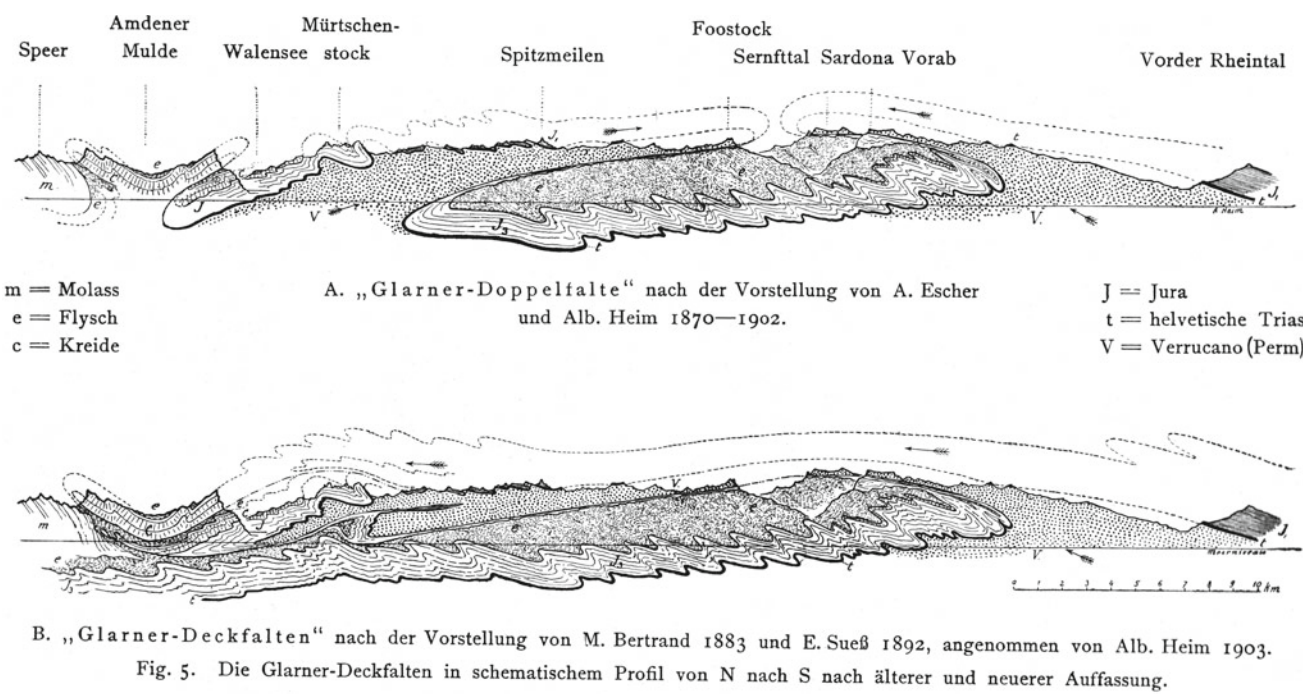

Fig. 1.10 Drawing by Albert Heim: Above, the "Glarus double fold" as proposed by Arnold Escher. It was intended to solve the puzzle of the reversed age sequence without overthrusting. Below: Marcel Bertrand's reinterpretation as the Glarus Thrust (from Heim 1921)

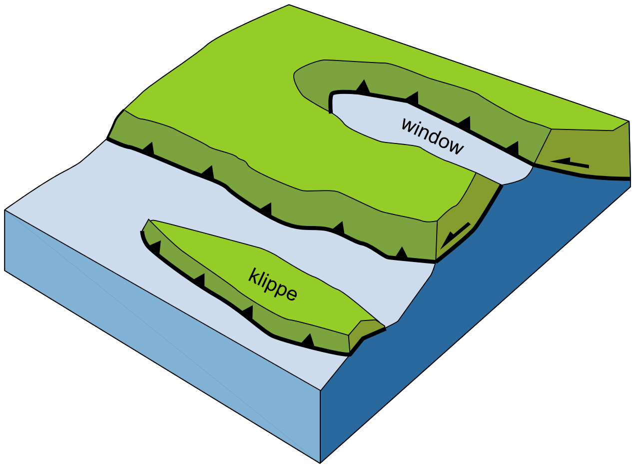

Fig. 1.11 Overthrust with window and klippe (outlier)

The rise to a mountain range follows later; it is an effect of the compensatory buoyancy experienced by the thickened crust (Sect. 3.5). Since it is not folds but the thrusts and nappes that is the decisive structure, geologists today prefer to speak of "overthrust mountains" rather than "fold mountains".

Even if it was a Frenchman who came up with the idea of the nappe stack, a little later Swiss people such as Hans Schardt (1858–1931) and Emile Argand (1879–1940) also contributed to the understanding of the nappe structure of the Alps. Subsequently, Switzerland got its laurels in a completely different way: The Glarus Thrust was elevated to the rank of a World Natural Heritage Site by UNESCO. This was not only because generations of geologists have racked their brains here but also because an overthrust can be seen here, as well as hardly anywhere else, from the "root zone" of the nappe to its front. We really should take another closer look.

The young flysch still lies where it was deposited on the almost unmoved part of Europe. The light-coloured limestone directly below the overthrust had probably been sheared off from its base somewhat earlier. During thrusting, this rock package was carried away and slid a little way over the flysch. Somewhat north of the Tschingelhörner, however, it almost disappears. The limestone there is only a 1–2 m thin, strongly deformed band that marks the thrust fault. Also at the Tschingelhörner site, the uppermost metre of limestone bordering the fault is strongly deformed.

The Permian greywackes above the fault are part of a nappe of sediments that once lay as a thick pile on the European shelf, i.e., the continental margin flooded by a shallow sea. They originate from an area that once lay south of the Vorderrhein Valley, but this region disappeared into the depths due to mountain building. The area of origin of a nappe is what we call the root zone. There, it was sheared off and pushed towards the north. On top of the Permian sediments, of course, there were once younger sediments, a thick stack of limestones from the Mesozoic, which in turn were sheared off and shifted as further nappes. In places, these thrust sheets still lie above or to the north of the Glarus nappe; they are mainly found north of Lake Walen towards the margin of the Alps. The nappes of sediments that once lay on the European shelf are the lowest units of the nappe stack of the Alps; they are all grouped together under the term Helvetic nappes. In Switzerland, these units run in a broad belt through the northern part of the Alpine arc. Above the Helvetic nappes, there are other nappe systems which I will discuss in Chap. 8.

The Glarus Thrust thus separates the almost immobile margin of Europe from the Helvetic nappe stack. In profile, it looks like a recumbent S. It rises steeply from the Vorderrhein Valley (root zone), reaches an altitude of more than 3000 m and then plunges again until it disappears below the surface. It continues deep below Lake Walen and only emerges once more below the other Helvetic nappes in the northern foothills of the Alps near Säntis. The S-shape is a later structure; originally the overthrust was a slightly inclined ramp. During transport, such a nappe is naturally exposed to internal stresses, especially at the very front. This is where we find most of the folds, which certainly also exist in overthrust mountains.

But how can these nappes be moved at all over such distances, along a razor-sharp line, without breaking? This is where the highly deformed limestone at the base of the fault plays a role. Movement was confined to this limestone, which acted as a kind of lubricant. Investigation of this limestone showed that it was deformed at a temperature of about 350 °C (Ebert et al. 2007), under conditions where it behaved ductilely, i.e., could be deformed almost like plasticine. Displacement at the fault occurred at the corresponding depth of just over 10 km.

With the Alps, we have immediately ventured into a particularly complicated mountain range. We should take a look at simpler examples before we examine them in detail in Chap. 8. First, however, we need the most important basics. Let's pick up the hot lead that rocks can be ductile. After all, this contradicts our everyday experience.

Autochthon and Allochthon

Rocks that are still in the same place where they were formed are called autochthonous. In the context of mountain building, this refers to rocks that were not moved as a tectonic nappe, i.e., the foreland and the units below the nappe stack.

Allochthonous are rocks (or minerals etc.) that have been transported from another place. In tectonics, this term refers to the nappes. Parautochthon stands for nappes that have only been moved over a short distance.

1.2 Rocks and Dough

If there is anything that is solid and rock hard, it is surely a stone. When we hold one in our hands, we can hardly imagine that it could be deformable or even serve as a lubricant. It is no problem to break a stone in two with a hammer. But to deform it like dough?

They are not quite as soft as dough, of course, but the comparison is not too bad, only if it is hot enough. In any case, we have to say goodbye to the idea of hard and undeformable rocks.

Not all rocks are equally deformable, but in principle they are "softer" at higher temperatures and thus at greater depths than at the cool surface. Therefore, movements near the surface are more likely to lead to fracture than movements at depth. For example, in the case of quartz-rich rocks, which are typical of the Earth's crust, a temperature of about 300 °C is sufficient for ductile deformation. The rocks of the Earth's mantle, however, are still rock hard at temperatures above 600 °C. Salt is so easily deformable even at low temperatures that it begins to flow and rises as a salt dome simply because of the difference in density to the overlying rock. When this salt dome or, as another example, granite melt is rising, it effortlessly pushes the surrounding rocks aside. This means that these must also be elastic enough to give way. If we want to understand what happens on a fault, we have to distinguish brittle deformation with formation of fractures and ductile deformation.

1.2.1 Fractures

Brittle deformation is restricted to the uppermost, cool part of the Earth's crust. Another factor in fracture formation is the speed at which deformation takes place. Rapid deformation is more likely to cause fracturing than very slow deformation. Rapid deformation can be very dramatic, as impressively demonstrated by earthquakes (Box 1.1). Earthquakes are largely confined to the cool and therefore rigid part of the Earth. Before an earthquake, stress builds up by elastically bending the rocks, as far as this is possible with rocks. Elastic means that they would bend back again without consequence if the tension were to disappear, like rubber. As soon as the tension becomes too great, cracks form in a fraction of a second. Suddenly, the elastic deformation energy is converted into movement. In large earthquakes, displacements of several metres can occur in an instant. The shock waves triggered spread in all directions and can cause houses to collapse even far away from the epicentre.

Box 1.1 Earthquakes

When the stress forces on a fault exceed a critical value, the rock fractures. The cracks propagate from the earthquake focus (hypocentre) at a speed of 2–3.5 km/s along the fault plane until the stress is no longer sufficient to cause rupture. In strong earthquakes, segments of the faults can be affected that are hundreds of kilometres long; in weak earthquakes, only a small area fractures. There is a jerky displacement along the fault, which can amount to several metres in strong quakes. At the same time, energy is released in the form of seismic waves that run through the rock and cause the ground to shake (Fig. 1.12). In the process, stress is relieved along the fault segment, and the next quake is not to be expected here until stress is built up again by the movement of the tectonic plates. However, a strong earthquake causes the stress to increase on adjacent segments of the fault or even on other faults in the vicinity, leading to rupture there. In the weeks or months that follow, there can therefore be a whole series of violent aftershocks—their strength is typically a magnitude lower. Sometimes a strong earthquake is preceded by smaller foreshocks.

Seismographs are used to measure earthquake waves. They mainly consist of a weight suspended from a spring, which—uncoupled from ground motion—can oscillate freely. Its movements used to be transmitted directly to a pen that drew on continuous paper. Today, of course, this is done digitally and the data from entire station networks are evaluated almost in real time.

The seismic waves propagate in three wave trains. The fastest are the primary waves (P waves), which are compression waves (similar to sound waves). Slightly slower are the secondary waves (S-waves), which are shear waves (i.e., oscillation perpendicular to the direction of propagation). Since shear waves cannot propagate in liquids, S-waves do not make it through the Earth's core (cf. Sect. 1.8). Apart from that, P- and S-waves propagate from the focus in all directions through the entire Earth. The exact speed depends on the density of the rock, and interfaces with a contrast in density can reflect or refract the waves.

Finally, there are the somewhat slower surface waves that propagate along the Earth's surface. These oscillate either in a rolling motion, similar to ocean waves up and down (Rayleigh waves) or back and forth sideways like a snake (Love waves). Surface waves are often responsible for the most severe destruction. In sedimentary basins with

Fig. 1.12 The baroque church El Carmen in Antigua (Guatemala), destroyed by an earthquake in 1773. Until the earthquake, Antigua was one of the most important Spanish colonial cities (© Florian Neukirchen 2006)

horizontal layers, they can really build up due to reflections and interference and reach particularly strong amplitudes and accelerations. When water-saturated clay-rich sediments lie at the surface, a particularly devastating phenomenon can occur: The ground liquefies into mud. Entire high-rise buildings can tilt and fall over like dominoes.

The further away a seismograph is from the hypocentre (or the epicentre, the point on the Earth's surface that lies exactly above the focus), the greater the difference in the travel times of the P- and S-waves. From this it is easy to calculate the distance to the earthquake focus. The exact location and depth of the focus can be determined from the data of three stations. The amplitude gives the earthquake intensity. The direction of motion of the initial shock wave can even be used to determine the direction of movement along the fault (focal mechanism).

To indicate the intensity (magnitude) of an earthquake, various scales have been developed, which unfortunately cannot be easily converted. Best known is the Richter scale developed by Charles Richter: The maximum amplitude of a seismogram is transferred (by taking into account the distance to the hypocentre) to a logarithmic scale. For example, the ground motion in a magnitude 6.0 earthquake is ten times greater than (at the same distance) in an earthquake of magnitude 5.0; the energy released is even 32 times greater. However, the Richter scale has the disadvantage that the amplitude is only directly related to the energy released if (a) the seismograph is close to the epicentre and (b) if the earthquake was not very strong (<M 6.5). For stronger earthquakes, the Richter scale is actually quite useless because the amplitude hardly increases with increasing energy.

For this reason, the moment magnitude scale is mostly used today. The "seismic moment" (M_W) corresponds to the mechanical work done. It is calculated from the size of the fracture surface, the mean displacement and the shear modulus of the rock (a material constant for deformability). This results in a magnitude on a logarithmic scale, the value of which corresponds approximately to the Richter magnitude at <M 6.5 but deviates increasingly from this at stronger quakes. An earthquake near Valdivia (Chile) on 22 May 1960 with M_W 9.5 was the strongest earthquake ever measured (cf. Sect. 4.2.1). Such a strong quake would not be possible on the San Andreas Fault in California, for example, as it is not long enough—the magnitude is directly related to the size of the affected fault plane.

A completely different approach is offered by intensity scales such as the modified Mercalli Scale (MMS), which are not based on measurements but only on the quite subjective perception at a given location. Depending on the observed effects of an earthquake on people and buildings, numerical values between I and XII are given—from "not felt" to "damage is total".

Despite all the research, it is not yet possible to predict earthquakes exactly. Only probabilities for longer periods of time can be given. In the San Francisco region, for example, according to the US geological survey (USGS), there is currently a probability of 72% for an earthquake with M 6.7 within the next 30 years, 51% for one with M 7 and of 20% with M 7.5.

On large active faults, earthquakes often occur periodically, e.g., on some segments of the San Andreas Fault about every 100 years (on other segments the intervals are longer). As is well known, the "Big One" in California is long overdue. However, they do not work like a clock; there can also be a much longer period of calm, followed by several strong earthquakes in a short time.

Whether a rock breaks under a certain stress depends on its mechanical properties. These result from the properties of the minerals of which it is composed but also from how these minerals are arranged in the rock and whether small cracks are already present. Ambient pressure and any water contained in the rock pores also play a role. All these factors determine the shear strength of the rock. The rock can withstand a stress as long as the shear strength is greater than the stress acting on the rock. If the stress is too great, the rock will break.

In order to observe what happens when a rock breaks, researchers have clamped cylinders of almost perfectly homogeneous rock into a hydraulic press. At first, the rock is elastically compressed but so little that we can't even see it. As soon as the pressure of the press is too great, the rock breaks. This experiment allows us to determine the shear strength of a rock. We can also test the influence of water in the pores of the rock. A water-saturated claystone can only withstand a tiny fraction of the stress that a dry claystone can. This is because the water pressure in the pores acts against the rock and promotes the formation of cracks. For this reason, we humans have already accidentally triggered earthquakes when the water pressure in the rock is increased so much with construction of a water reservoir or during geothermal drilling, that the rock could no longer withstand the tension already present.

Whether dry or wet, fracturing begins with microscopic cracks distributed throughout the rock that expand and connect with others to form continuous fractures. Movement occurs along the fractures so that the top and bottom of the cylinder are pushed together while the sides move out to the left and right. The result is two fracture systems that cross like an X at an angle of about 60°, where the compression has acted along the vertical line between the two fracture systems (roughly like the normal faults in Fig. 1.21). It is amazing how often one finds fissures or faults in nature that intersect at an angle of about 60° (Fig. 1.13). Since faults often occur as a pair, we speak of conjugate faults.

In our first experiment, we have put a rock in the press whose mechanical properties were the same in all directions. If instead we take a schist or a gneiss in which the minerals are aligned in a certain direction, then the stone cylinder breaks along the existing schistosity or foliation. The directions of stress can then no longer be reconstructed as easily from the fault geometry as was the case in the homogeneous rock.

A fault is nothing other than such a fracture on a larger scale. The surfaces of a fault plain are often downright polished. Sometimes it feels smooth in the direction of movement, rough in the opposite direction because of small steps. Geologists speak of a slickenside (Fig. 1.14) and stroke it, as this allows them to find out the direction of movement. Sometimes fibrous minerals oriented in the direction of motion also grow on the plain. If there is a sudden, rapid displacement during a particularly large earthquake, the rock along the fault can even be melted. It then solidifies as a thin strip of black rock glass (pseudotachylite). Near the Earth's surface, the rock is ground into flour over time as it moves. The crushed material is called fault breccia or cataclasite and acts almost like a ball bearing in the fault. The easier an existing fault can be moved, the rarer and more insignificant are the earthquakes.

1.2.2 Ductile Deformation

Since hot rocks can be ductile, the mechanism of movement at depth is different from that near the surface (Fig. 1.15). Some geologists are concerned with rheology, i.e., the flow behaviour of rocks, and treat them in a similar way as particularly viscous liquids. We can best compare hot rocks to dough or plasticine—with the notable difference that the force acting on it must exceed a certain threshold for deformation to begin. The deformability of rocks even goes so far that entire mountain ranges can flow apart like a cream cake in the sun (Sect. 6.7.1). Whether in the collapse of an entire mountain range or in the rise of a salt dome, whether in the strongly deformed limestone layer of the Glarus Thrust or in the convections in the Earth's mantle, more or less the same thing happens on a small scale in all these processes. Ductile deformation in rocks is particularly visible when fossils contained in them or, for example, the pebbles in a

Fig. 1.13 Fissure network within a fold. The two fissure systems enclose an angle of about 60°. Makhtesh Ramon, Israel (© Florian Neukirchen 2008)

Fig. 1.15 Marble with clear ductile deformation, south of Obergurgl, Ötztal Alps, Austria (© Florian Neukirchen 2021)

Fig. 1.16 In this strongly deformed conglomerate, the shape of the pebbles is still recognisable on the right cut surface, but in the other spatial direction they have been extremely elongated. Sample from Bygdin, Norway (© Florian Neukirchen 2009)

conglomerate, have been stretched out or flattened (Fig. 1.16). Ductile deformation produces the typical foliation or schistosity in metamorphic rocks, i.e., the arrangement of tabular and bladed crystals in a certain direction.

The first assumption would be that ductile deformation takes place along the grain boundaries of the rock-forming minerals. In fine-grained rocks, this actually works so well at high temperature that one speaks of superplasticity. But even in this case, the mineral grains themselves must be able to be deformed, as their corners and edges get in each other's way during sliding and rotation. In a coarse-grained rock, grain boundary sliding is of little importance. Flaky and acicular minerals are an exception, as soon as they are optimally oriented in the rock, namely parallel to the direction of displacement. It helps that any shear movement in the rock slowly rotates these crystals into the optimal position (cf. Fig. 1.17), causing the foliation. As a rule, however, deformations within the crystals play the biggest role. So let's zoom in to the atomic scale.

Crystals cannot be broken or deformed in arbitrary directions, because they are anisotropic: Their physical properties depend on the direction. This is because their atoms are not chaotically distributed but arranged in a crystal lattice that looks very different when viewed from different directions. The atoms are in fixed positions in the crystal lattice. Since the lattice is virtually undeformable, it must react in one way or another to the slightest deformation. In salt, the binding energy between the ions (Na^+ and Cl^-) is comparatively low. Within a salt crystal, therefore, sliding is possible along the surfaces given by the crystal lattice. For a moment, the energy has to be applied to overcome the bonds on this plane but, the next moment, the lattice looks the same as before. While in the salt crystal there are three planes oriented perpendicular to each other on which such sliding is possible even with a small expenditure of energy, in mica,

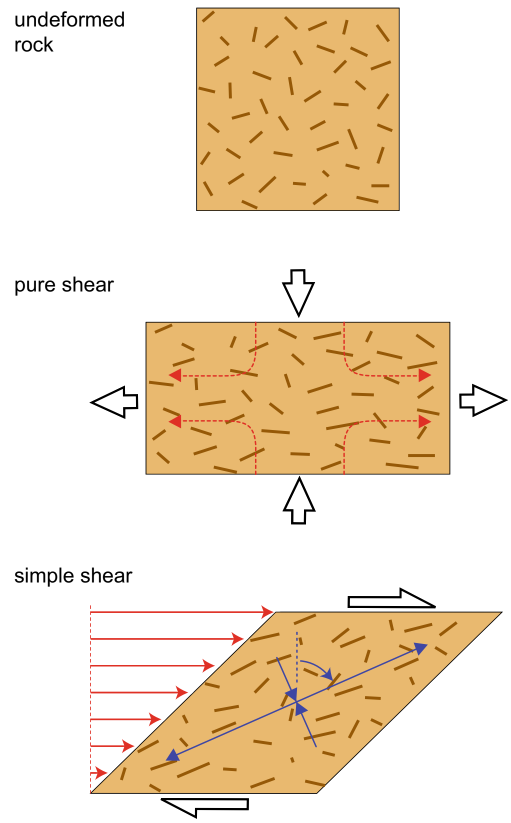

Fig. 1.17 Two types of shear: in pure shear, the rock is elongated and flattened, the main axes of strain are fixed (red: particle paths). In simple shear, the particles are displaced on parallel paths, and the main axis of strain rotates (blue). In both cases, there is an alignment of the minerals (brown)

for example, there is only one. These are the dark or light flake-shaped minerals in a granite, gneiss or mica schist. The binding energy between the individual layers within the flakes is relatively low, and they can easily be shifted against each other. Displacement at a different angle is not possible because the bonding within the layers is very strong.

For many minerals, the binding energy within the crystal lattice is too great for a complete shift along a lattice plane. However, no crystal is truly perfect; it contains defects such as vacancies (a site in the lattice is simply not occupied), dislocations (the lattice is bent because it is connected to the wrong point) and impurities. These defects can migrate through the crystal if the temperature is high enough. This is possible because the energy only has to be sufficient to overcome the bonds at a single point. This migration of defects also leads to a slow sliding along lattice planes, only this no longer happens simultaneously on the entire plane but slowly propagates site by site. The higher the temperature, the faster the defects can migrate through the crystal lattice and thus deform the crystal.

Another way to deform a crystal is to form twins. This term refers to parts of a crystal where the crystal lattice is systematically rotated or mirrored; for example, a crystal axis points diagonally to the left in one area of the crystal and diagonally to the right in the other. Not all minerals can form twins. In calcite and plagioclase, this happens easily under stress; under the microscope, the twins are visible as thin lamellae. These can migrate through the crystal and deform it (gliding twins). Calcite and plagioclase are important rock-forming minerals: Limestone consists almost entirely of calcite, while plagioclase (a feldspar) is a major component of many igneous and metamorphic rocks.

Some bladed or tabular minerals can deform by forming two kink folds between which the crystal axis is oblique (kink band). Here, too, the geometry is determined by the crystal lattice. The slanted part becomes larger over time as more parts of the crystal lattice fold over, causing the kink folds to creep towards the ends of the crystal.

If two grains of the same mineral border on each other, there is another possibility: The energetically more favourably oriented grain grows at the expense of its neighbour. Crystals whose crystal lattice is unfavourably oriented in the stress field can thus disappear, while favourably oriented crystals are preferred. If new minerals are formed by chemical reactions, they grow in the energetically most favourable orientation right from the beginning. Both the deformation of a rock and the transformation (metamorphism) to another rock (Sect. 2.7) thus lead to an arrangement of minerals that is adapted to the acting stress. In mica schist, all mica crystals are arranged in parallel. Such a rock is naturally easier to deform than one in which the minerals are arranged randomly, because the parallel mica flakes form countless slip planes. Not all minerals have to participate in the deformation. In a mica schist, relatively little happens to the hard garnet because the deformation of the mica is sufficient. At most, it rotates due to the shear movement.

The creep within the crystals is relatively slow. Deformation becomes much faster if water is present on the grain boundaries between the crystals, which can partly dissolve the crystals. The sides of the crystal that are most exposed to stress are energetically unfavourable and are preferentially dissolved. The dissolved ions diffuse through the water and are deposited on crystal surfaces on the energetically favourable sides. Pressure solution can, for example, deform quartz grains into thin discs, as can be seen in some rocks that have been affected by particularly high stress. Unfavourably oriented crystals can disappear quickly in this way. This process is also dependent on the temperature, as this has an influence on the solubility and the rate of diffusion. All these processes occur simultaneously during deformation. Depending on the prevailing conditions, one or the other is more important.

Basically, two types of shear can be distinguished (Fig. 1.17):

- With pure shear, the rock is stretched, comparable to a lump of dough that we pull apart with both hands. The position of the strain axes remains fixed.
- If our lump of dough lies between the tabletop and a board and we move the board, then we have simple shear: In the dough, the displacement increases more and more from the tabletop to the board. In this case, the axis of the strongest deformation rotates.

Mixed forms of pure and simple shear are the rule rather than the exception. Deformation can take place in a large body of rock or be concentrated in a narrow zone. It can also change direction on a small scale. For example, cleavages of shale within a fold are often arranged in a fan shape because there is a different direction of stress in the fold limbs than along the fold axis. If the deformation is distributed over a large body of rock, each individual mineral grain must react less strongly than is the case in a fault. However, since a rock adapts to the stresses by deformation, and strongly deformed rocks are easier to deform, the displacement is usually nevertheless concentrated in a narrow shear zone. In the case of strong deformation, additional frictional heat is produced which, in turn, facilitates movement.

A rock that has been extremely strained in a fault in ductile conditions is called mylonite. One example is the strongly sheared limestone of the Glarus Thrust. A mylonite is an extremely fine-grained rock with optimally aligned mineral grains. Often, minerals that normally do not have optimal shapes are deformed to a lenticular shape. In these rocks, all deformation processes occur simultaneously: sliding along grain boundaries, twinning, diffusion, creep of lattice defects and pressure solution. At low temperature, mylonites are often amazingly hard and resistant to erosion. They can look very different, depending on the rock from which they were formed. Sometimes they are light and finely striated, sometimes dark. The mylonite of the shear zone has a certain width; on the margins the strain rate drops relatively quickly.

1.2.3 More or Less Competent

The temperature above which a rock becomes ductile varies from rock to rock. Or, to put it another way, at a given temperature different rocks are more or less ductile or (as their resistance to deformation is called) competent. When alternating layers of different sedimentary rocks are subjected to stress, this is particularly noticeable. It is often possible to see how the layers of a firmer, competent rock have been laid down in folds while remaining quite rigid (Figs. 1.18 and 1.19), while the less competent rock has flowed to fill the gaps.

Fig. 1.18 An alternating layer of differently competent strata is folded under compression. These beautiful folds in flysch (alternating layers of sandstone and claystone) can be found in the Engadine window in Austria. The orange surface are lichens growing on the rock (© Florian Neukirchen 2002)

If the same sequence is stretched instead, the competent rock breaks up. The incompetent rock flows into the resulting gaps and is otherwise simply pulled apart like rubber. The result, when cut, looks like a string of sausages hanging together (Fig. 1.20). This kind of structure was given the name "boudinage" by creative geologists—boudins are French sausages.

1.3 Types of Faults

Without further explanation, we have distinguished pressure and stress, although both are of course related. Pressure (more precisely lithostatic pressure) is the force exerted by the surrounding rock. It increases with depth and acts equally from all directions, just as water pressure acts on a diver from all directions. It therefore does not cause deformation of the rock. Stress is an additional component that is directional and adds to the uniformly acting ambient pressure. Stress is physically defined as a force acting on a surface at a certain angle (a vector with the magnitude force per unit of area).

Pressure and stress acting on a point in the rock can be described by three perpendicular vectors, which we call the three principal stresses (Fig. 1.21). The rock is compressed particularly strongly in one direction and least in a direction perpendicular to it. The magnitude of the third vector is somewhere in between. If all vectors have the same magnitude, only the ambient pressure acts; there is no stress and therefore no deformation (or strain). The greater the difference between the largest and the smallest vector, the greater the stress that deforms a rock. Depending on the orientation and the vector amounts, this stress acts as compression or extension.

How different the amounts of the principal stresses are and how the vectors are orientated—whether the greatest vector is perpendicular to the Earth's surface, horizontal or has an oblique angle—depends on the circumstances. Think of colliding plates, rising magma or a mountain range pushing from a distance. Yes, even the geometry of more or less rigid rock layers, the mobility of pre-existing faults and even the shape of mountain slopes affect it on a smaller scale. We can speak of a stress field caused by all these factors and think of it as being similar to a magnetic field. The stress field can lead to the formation of faults (Fig. 1.21) when the stress overcomes the strength of the rocks. Depending on which of the three vectors is perpendicular to the Earth's surface, the result is a normal fault (Fig. 1.22), a flat-dipping thrust fault (or a reverse fault if the fault plane is inclined by more than 45°) or a strike-slip fault.

The force acting on a fault plane can be derived from the three principal stresses. The corresponding vector can, in turn, be divided into one that is perpendicular to the surface (normal stress) and one acting along the surface (shear stress).

Just as the conjugate fractures in the experiment in Sect. 1.2.1, a system of conjugate faults may form. But even if they do not appear as a pair, as soon as we have been able to determine the direction of movement along the fault, it is easy to read off how the three vectors are orientated. To do this, we only have to keep in mind the X that formed in the compressed rock cylinder in the experiment. The hydraulic press compressed the rock cylinder vertically, i.e., the greatest principle stress was vertical, exactly along the vertical mirror plane of the fracture systems. The smallest vector acted from the right and left respectively, and the pressure from these sides was so small that the sides of the cylinder could escape in this direction. We could also say that the rock was stretched in this direction (extension). The third vector points perpendicular out of the X. In the case of the cylinder in the experiment, this had about the same magnitude as the smallest vector.

Fig. 1.19 Folds in the flysch at the Šamar Pass in Durmitor, Montenegro (© Florian Neukirchen 2015)

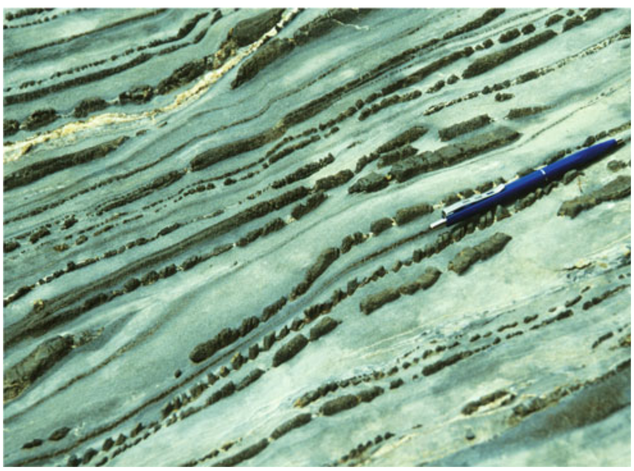

Fig. 1.20 Boudinage on a small scale. The heat of a granite rising nearby transformed an alternating bedding of limestone and claystone into marble and hornfels (contact metamorphism). The hornfels was more competent ("firm") and was torn into tiny boudins by slight elongation of the rocks. The less competent marble flowed into the gaps. Adamello, Italian Alps (© Florian Neukirchen 2002)

The geometry of a tectonic rift (cf. Sect. 6.2) is quite similar to the fractures in our experiment. A rift is formed when the Earth's crust is stretched. It is bounded on both sides by relatively steep normal faults along which the central block sinks. These conjugate faults also enclose an angle of about 60°. Extension of the Earth's crust means nothing other than that the smallest of the three principal stresses is horizontal and that it is so small that the blocks on either side can be displaced against the force acting in this direction. The greatest vector acts vertically downwards in this case, as in the hydraulic press. In a rift, there can also be blocks uplifted relative to the surroundings between two normal faults, referred to as a horst (Fig. 1.23).

It should be noted that even with extension there is no tensile stress. Even the direction in which extension takes place is under compression. The only difference is that the compressive force acting in this direction is rather small. Tensile stresses never actually occur in the Earth's crust—except on steep slopes, since a mountain is not compressed from both sides.

When two continents collide (Chaps. 7 and 8), constriction is horizontal, so we only have to rotate the image. This time the smallest vector is vertical. Corresponding to an X rotated by 90°, a rather flat thrust fault is created along which the upper block is pushed over the lower block. A series of such thrusts can lead to the formation of overthrust mountains like the Alps. A conjugate fault is sometimes also found and is then called backthrust.

The third possibility is that the medium-sized vector points downwards. This time the X lies flat on the Earth's surface and we are dealing with lateral displacement on a strike-slip fault (Chap. 5) like the San Andreas Fault in California. Depending on the direction of movement, we speak of a right-lateral (dextral) or a left-lateral (sinstral) displacement. Turkey would be an example of a pair of conjugate lateral displacements: Anatolia is wedged between Arabia and Eurasia and evades towards the west—like a melon seed that slips out between two fingers when we pinch it between them. One of these conjugate strike-slip

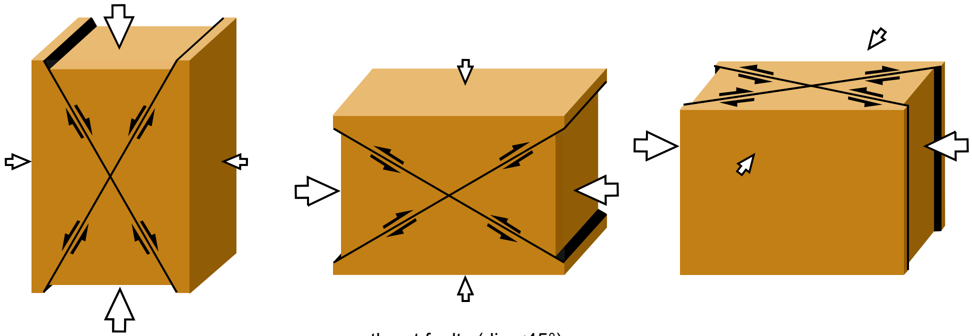

Fig. 1.21 Schematic representation of conjugate faults. The orientation depends on the orientation of the principal stress vectors, resulting in normal faults, thrust faults (if steep, reverse faults) and strike-slip faults. Only the orientation of the greatest and the smallest principal stress is shown in each case

Fig. 1.22 On this fault, the left block (which is situated above the slightly inclined fault) has shifted downwards relative to the right block. This fault type is called a normal fault. Bay near Marina di Campo, Elba, Italy (© Florian Neukirchen 2020)

faults is the right-lateral North Anatolian Fault which swings parallel to the Black Sea coast through northern Turkey. The other is the left-lateral East Anatolian Fault (Fig. 1.24).

Conjugate faults do not necessarily have to include the typical 60° angle. Much like a slate breaking along its schistosity, faults often follow pre-existing zones of weakness such as bedding joints, cleavages or fold axes. Older faults can also be reactivated. As these were usually formed in the past under a different stress field, movement often no longer occurs in the original direction. Normal or reverse faults are then displaced laterally at the same time. The movement can even take place in the opposite direction: A normal fault caused by extension can be reactivated as a reverse fault by compression.

Extension or compression along faults in the upper crust is accompanied by ductile flow in the lower crust: The rock is simply pulled apart or compressed like chewing gum. As a rule, faults bend into a horizontal shear zone at the corresponding depth of ductile deformation.

The Glarus Thrust (Sect. 1.1) was initially a rather flat shear zone with displacement by ductile deformation within the limestone mylonite. The overlying pile of sediments slid up a ramp and continued to move flat over the immobile part of the continental margin.

Fig. 1.23 The ancient rock fortress of Masada in Israel is a horst, an uplifted block at the edge of the Jordan Rift Valley (Sect. 5.1), with the Dead Sea in the background (© Florian Neukirchen 2008)

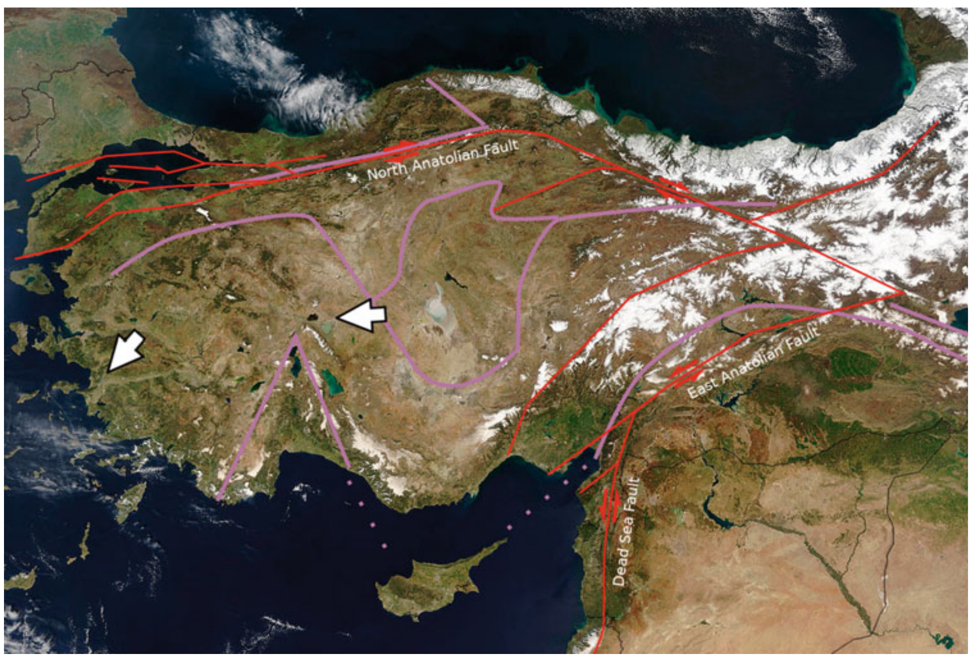

Fig. 1.24 A large part of Turkey is moving westwards. Displacement takes place mainly on two major strike-slip faults, the North Anatolian Fault and the East Anatolian Fault. The North Anatolian Fault, notorious for earthquakes, also threatens the metropolis of Istanbul. It fans out into several branches in the Sea of Marmara. Purple lines are the approximate location of the sutures explained in Sect. 7.7.4 (Satellite image © NASA)

1.4 Clefts

Box 1.2 Basalt Columns

A particularly fascinating phenomenon, also because of their aesthetics, are basalt columns (Figs. 1.25 and 1.26). Separated by regular joints, they are so perfectly formed that one inevitably thinks of ancient architecture or of giants or devils. There are corresponding myths about many occurrences.

Basalt columns are formed when lava that has already solidified cools down. The volume of the rock decreases in the process. In the coolest area (usually the surface), a network of cracks develops. Three fractures always develop at the same time, arranged like a Mercedes star, and continue to