

Revised and updated translation of
Geologie der Alpen, Second Edition

Geology *of the* Alps

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Chapter 05

Figure 5.1 Glarus Thrust and Martin’s Hole in the Tschingelhoren.

Figure 5.2 Glarus Thrust and Martin’s Hole in the Tschingelhoren.

◀ Figure 5.3 Glarus Thrust at the Lochsite locality.

▼ Figure 5.4 The Penninic klippen in the Mythen (canton Schwyz, Central Switzerland).

Figure 5.5 The Penninic klippen in the Mythen (canton Schwyz, Central Switzerland).

▶ Figure 5.1-1 Simplified geological-tectonic map of the Western Alps with traces of cross-sections (green lines–numbers are figure numbers).

◀ Figure 5.1-2 Geological cross-section through the Western Alps along the seismic lines of ECORS/CROP (redrawn after Schmid & Kissling 2000).

▲ Figure 5.1-3 Geological cross-section through the Jura Mountains along the seismic lines of ECORS.

▲ Figure 5.1-4 Geological cross-section through the Chaînes subalpines of Haute Savoie (France).

Figure 5.1-5 Geological cross-section through the Chaînes subalpines of Chartreuse (France).

◀ Figure 5.1-6 Geological cross-section through the Chaînes subalpines of Vercors (France).

Figure 5.1-7 Geological cross-section through the Chaînes subalpines near Digne (France).

Figure 5.1-8 Geological cross-section through the external Penninic nappes and the internal Belledonne massif (France).

▲ Figure 5.1-9 Geological cross-section through the Penninic nappe system along the seismic line ECORS/CROP).

▲ Figure 5.1-10 Geological cross-section through the southern Western Alps.

▶ Figure 5.2-1 Simplified geological-tectonic map of the Central Alps with traces of cross-sections (green lines – numbers are figure numbers). Double arrows denote major fold axes.

Figure 5.2-2 Geological cross-section through the eastern Central Alps along the seismic lines of the Eastern Traverse of NRP20 (after Pfiffner & Hitz, 1997).

▲ Figure 5.2-3 Geological cross-section through the central Jura Mountains.

▶ Figure 5.2-4 Geological cross-section through the Folded Jura along the Grenchenberg railroad tunnel (redrawn after Buxtorf, 1916). The photograph displays a view of the folds in the gorge of Moutier (Canton Jura, Switzerland) looking west-southwest. The syncline is a kink fold with straight limbs whereas the anticline is more open and contains several gentle kinks. The cliffs are made of Late Jurassic limestones.

▲ Figure 5.2-5 Geological cross-section through the western Molasse Basin along the seismic lines of the Western Traverse of NRP20.

▲ Figure 5.2-6 Geological cross-section through the eastern Molasse Basin along the seismic lines of the Eastern Traverse of NRP20.

► Figure 5.2-7 Geological cross-section through the Helvetic nappe system along the transect of Sanetschpass. The internal structure is characterized by an interplay of isoclinal folds and thrust faults. The photograph gives a view of the frontal folds in the Cretaceous limestones of the Wildhorn nappe in the western flank of the Schluchhorn. Light coloured cliff is Schrattekalk Formation. Drusberg Marl form the core of the fold.

Figure 5.2-8 Geological cross-section through the Helvetic nappe system along the transect of Jungfrau. The photograph shows the situation at the front of the Helvetic nappes where Cretaceous limestones of the border chain of the Drusberg nappe overly Subalpine Flysch and Subalpine Molasse units.

Figure 5.2-9 Geological cross-section through the northern margin of the Aar massif in the region of Grindelwald-Wetterhörner (ct. Bern, Switzerland).

► Figure 5.2-10 Geological cross-section through the Helvetic nappe system along the transect of Pilatus-Goms. The photograph is taken a few kilometres east of the cross-section and shows the view across the Uri branch of Lake Lucerne (view is to the west). An internal thrust fault (highlighted in red) in the Drusberg nappe places a normal sequence of Early Cretaceous onto a syncline formed by Cretaceous strata. Bedding is indicated by dotted lines. Pa, Palfris Shale (detachment horizon); Kk, Kieselkalk Formation; Sr, Schrattekalk Formation.

◄ Figure 5.2-11 Geological cross-section through the Helvetic nappe system along the transect of Mythen-Lukmanierpass. The photograph shows the Windgällen fold located on the south-southeast flank of Windgälle (view is to the west-southwest). The recumbent anticline has Permian Windgällen Porphyry in its core (Pe); Middle Jurassic strata (MJ; brown) directly overly the Permian; the Late Jurassic Quinten Limestone (Qi; grey) highlights the fold hinge.

► Figure 5.2-12 Geological cross-section through the Helvetic nappe system along the transect of Säntis-Flims. The photograph is a view across Seez valley at Sargans (canton St. Gall, Switzerland).

looking northeast, showing the transition from imbricate thrusting to folding. The Gonzen anticline has a core of Middle Jurassic strata. Northwest of Gonzen, the Quinten Limestone is repeated by thrust faults following a detachment horizon in the Middle Jurassic. The Säntis thrust follows the Palfris Shale, shown here at the type locality Palfris. MJ, Middle Jurassic; Qi, Quinten Limestone; Pa, Palfris Shale; Kk; Kieselkalk Formation.

Figure 5.2-13 The Glarus Thrust in the Tschingelhoren (looking South), a center piece of the UNESCO World Natural Heritage site 'Tectonic Arena Sardona'. The Quinten Limestone beneath the Glarus Thrust is a sliver dragged along the base of the Helvetic nappes, which came to lie on top of the Sardona Flysch. This sliver consists itself of smaller slivers as indicated by the tongue of Sardona Flysch near the Martin's Hole.

Figure 5.2-14 Fold-and-thrust tectonics in the Helvetic nappe system. (A) Inverted limb of Morcles fold in the Dents de Morcles (western Switzerland). (B) Recumbent folds at the front of the Doldenhorn nappe (Gasterntal, Canton Bern, Switzerland). Late Jurassic and Early Cretaceous are folded more or less harmonically. Qi, Quinten Limestone; Ze, Cementstone Formation; Öh, Öhrli Limestone; Kk, Kieselkalk Formation. View is to the east-northeast. (C) Plunging fold in the flank of Graustock (west of Engelberg, central Switzerland). The recumbent fold with a core of (Early and) Middle Jurassic sediments was tilted in the course of the latest updoming of the Aar massif. EJ, Early Jurassic; MJ, Middle Jurassic; Qi, Quinten Limestone (Late Jurassic); Ax, Axen thrust. View is to the West. (D) Imbricate thrusting in the area of Vättis (Canton St Gall, Switzerland). Thrust fault (marked red) puts two normal sequences on top of each other. Qi, Quinten Limestone; Öh, Öhrli Limestone; Kk, Kieselkalk Formation; Sr, Schratenkalk Formation; Se, Seewen Limestone; Bü, Bürgen Formation; Gl, *Gobigerina* Marl. The Garschella Formation forms the thin dark band between Schratenkalk Formation and Seewen Limestone. View is to the north. Asterisk, location of Drachenberg Cave with bones of extinct cave bears assembled some 45 000–40 000 years ago (see Fig. 7.4). (E) Imbricate thrusting in the eastern flank of

Crap Mats (north-northwest of Reichenau, canton Graubünden, Switzerland). Tschep thrust (marked red) places Late Jurassic Quinten Limestone onto a manifold stack of Cretaceous limestones. The imbrication is outlined by the repetition of the Schrattenkalk–Garschella pair (light Schrattenkalk Formation and dark Garschella Formation above). The pairs are marked by a black filled circles. View is to the west. (F) Thrusting and folding in the western flank of Piz d'Artgas (north of Breil/Brigels, canton Graubünden, Switzerland). The inclined north-vergent anticline beneath the summit of Piz d'Artgas is well outlined by the brown Bürgen Formation (Eocene). The summit area above the thrust fault marked in red consists of an inverted sequence with crystalline basement (diorite) forming the peak and overlying Triassic Röti Dolostone. The Val Nauscha mélange (VN) in the footwall of the thrust fault consists of multiple repetitions and blocks of Cretaceous and Eocene strata. View is to the east. X, crystalline basement (Punteglias submassif of Aar massif); Rö, Röti Dolostone; Sr, Schrattenkalk Formation; Ga, Garschella Formation; Se, Seewen Limestone; Bü, Bürgen Formation; Gl, Globigerina Marl; VN, Val Nauscha mélange.

► Figure 5.2-15 Palaeogeographical map of the pre-Triassic basement (upper diagram) and the Mesozoic sediments of the Helvetic nappe system (lower diagram) in the Central Alps (redrawn and supplemented after Kempf & Pfiffner 2004). Ax, Di, Do, Dr, Ge, Gl, Mo, Wi: Axen, Diablerets, Doldenhorn, Drusberg, Gellhorn, Glarus, Morcles, Wildhorn nappes; Chs, Chaînes subalpines (allochthonous); Bc, Border chain (of the Drusberg nappe).

Figure 5.2-16 Stockwork tectonics in the area Walensee–Sichelchamm (canton St Gall, Switzerland). The Cretaceous limestones of the Säntis nappe are detached from their Jurassic substratum and folded as detachment folds above the Säntis thrust. The Jurassic limestones in the footwall of the Säntis thrust display a completely different style characterized by imbricate thrusting. The individual imbricates are detached along shales at the base of the Middle Jurassic.

▲ Figure 5.2-17 Geological cross-section through the Penninic Klippen nappe in the transect of Gantrisch (canton Bern, Switzerland). Imbricate thrusting prevails in the rear (south), whereas thrust faults at the front are associated with folds.

◀ Figure 5.2-18 Geological cross-section through the Penninic nappes along the seismic lines of the Western Transect of NRP20. Thin slivers of sediments mark contacts between crystalline basement nappes. The photograph shows a highly deformed augengneiss from the 'root' of the Monte Rosa nappe taken near Villadossola (Italy). Pencil gives scale.

◀ Figure 5.2-19 Geological cross-section through the Penninic nappes along the seismic lines of the Eastern Transect of NRP20. Cover rocks were detached from their crystalline substratum and form a nappestack of their own (Vals, Grava, Tomül, Schams). The crystalline basement was piled up to four major nappes (Simano, Adula, Tambo, Suretta).

▲ Figure 5.2-20 Geological cross-section through the Austroalpine nappes of Graubünden (eastern Switzerland).

Figure 5.2-21 The contact between the Austroalpine (Adriatic margin) and Penninic nappes (Piemont Ocean and Briançon Rise) in the area around Arosa (canton Graubünden, Switzerland). Amselfluh and Furggahorn are made of Permian and Mesozoic sediments of the upper Austroalpine Silvretta nappe. The sediments are repeated by a nappe-internal thrust fault. The upper Austroalpine Languard nappe consists of crystalline basement and pinches out towards the lake at the bottom of the photograph (Älplisee). The Lower Austroalpine Tschirpen nappe in the lower left consists of Mesozoic sediments and pinches out in the distance. The Arosa Zone is a mélange of ophiolitic rocks and oceanic sediments derived from the Piemont Ocean that underlies the Silvretta nappe, but is visible in the flank of the Furggahorn, and in turn overlies the Falknis nappe visible at the left margin of the photograph. The Mesozoic sediments making up the Falknis nappe were deposited on the Briançon Rise. View is from Parpaner Rothorn toward the east-northeast.

▲ Figure 5.2-22 Geological cross-section through the Southalpine nappe system along the seismic lines of the Southern Traverse of NRP20 (redrawn and modified after Schumacher, 1997).

▲ Figure 5.2-23 Geological cross-section through the Southalpine nappe system of Lombardy (Italy).

▶ Figure 5.3-1 Simplified geological–tectonic map of the Eastern Alps and Dolomites with locations of cross-sections (green lines–numbers are figure numbers).

▶ Figure 5.3-2 Geological cross-section through the Eastern Alps and Dolomites along the seismic lines of TRANSALP (Lüschen et al. 2004).

▲ Figure 5.3-3 Geological cross-section through the Molasse Basin of Bavaria and Austria.

▲ Figure 5.3-4 Geological cross-section through the Helvetic nappe system of Vorarlberg (western Austria).

▲ Figure 5.3-5 Geological cross-section through the western Tauern window (Austria–Italy).

▲ Figure 5.3-6 Geological cross-section through the Northern Calcareous Alps in Tyrol–Bavaria (Austria–Germany).

▲ Figure 5.3-7 Geological cross-section through the Northern Calcareous Alps of Styria, Upper Austria.

▲ Figure 5.3-8 Geological cross-section through the the Karawanks.

▲ Figure 5.3-9 Geological cross-section through the Dolomites (Italy).

Figure 5.4-1 Structure contour map of the top of the pre-Triassic basement in the foreland and the crystalline basement uplifts of the Central Alps and neighbouring areas.

Figure 5.4-2 Lithosphere-scale geological cross-sections through the Western and Central Alps along the seismic lines of ECORS/CROP and the Eastern Traverse of NRP20. Crustal structure is based on Waldhauser et al. (2002), Diel et al. (2009) and Wagner et al. (2012),

and mantle structure after Lippitsch et al. (2003) and Kissling (personal communication, 2013). The Conrad discontinuity between lower and upper crust is taken at a seismic velocity of 6.5 kilometres per second.

Figure 5.4-3 Two lithosphere-scale geological cross-section through the Eastern Alps, one along the seismic lines of TRANSALP, the other farther east. Crustal structure is based on Waldhauser et al. (2002), Diel et al. (2009) and Wagner et al. (2012), and mantle structure after Lippitsch et al. (2003) and Kissling (personal communication, 2013). The Conrad discontinuity between lower and upper crust is taken at a seismic velocity of 6.5 kilometres per second.

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► Figure 6.1 Simplified metamorphic map of the Alps – based on Oberhänsli et al. (2004). Regional Barrovian type metamorphism is of Cretaceous age in the Eastern Alps and of Cenozoic age in the Western and Central Alps. The Eastern Alps are characterized by a Cretaceous aged high-pressure metamorphic overprint dated at around 100 million years ago. In the Western Alps a high-pressure metamorphic overprint occurred between 45 and 35 million years ago.

Figure 6.2 High-pressure metamorphism in the Western Alps. P – T – t paths are from the Penninic Dora Maira basement and the Zermatt–Saas Fee Zone in Valtournache, and from the Austroalpine Dent Blanche nappe.

Figure 6.3 High-pressure metamorphism in the Central Alps. (A) P – T – t paths are from the Penninic Adula nappe and Tambo nappe. (B) Morphological expression of eclogite outcrops in the Adula nappe. View is to the south-southeast. Easterly dip of lithologic contacts and foliation of the Adula nappe are clearly visible in the distance. (C) Mafic boudins (green) within paragneisses (grey). Eclogites are preserved in the core of the boudins while the outer rims are amphibolitized. Outcrop is at Alp di Trescolmen in the central part of the Adula nappe.

Figure 6.4 High-pressure metamorphism in the Eastern Alps. P - T - t paths are from the Austroalpine Southern Ötztal nappe and the Penninic Eclogite Zone in the Tauern Window.

Figure 6.5 Regional metamorphism in the Leventina (Central Alps).

Figure 6.6 Contact metamorphism in the contact aureole of the Bregaglia Pluton (Central Alps). See text for discussion.

▲ Figure 6.7 Synoptic cross-section through the Northern Calcareous Alps in the Cretaceous showing synorogenic Gosau sediments – compiled from Ortner (2001).

Figure 6.8 Orogenic timetable of nappe formation, sedimentation, metamorphism and magmatism in the Eastern Alps.

Figure 6.9 Schematic block diagram of the Eastern Alps in the Late Cretaceous – inspired after Froitzheim et al. (1997). A west-vergent nappe stack is bordered in the north and south by strike-slip faults. Sedimentation prevails in the future Central and Western Alps.

Figure 6.10 Folded folds and thrust faults.(a) In the Middle Penninic Suretta nappe (Val Ferrera, canton Graubünden, Switzerland), a southeast-vergent fold beneath Piz Grisch folds an older, Avers Phase thrust fault, along which the Southpenninic Avers nappe came to lie on top of Triassic carbonates pertaining to the Suretta nappe. The southeast-vergent fold was initially a north-vergent Ferrera Phase fold which was back-folded by shearing of the Niemet–Beverin Phase.(b) A folded and overturned, steeply south-dipping thrust fault marks the contact between the Trun submassif of the Aar massif and the Mesozoic of the Cavistrau nappe. The thrust fault follows a gully to the summit of Piz Dado and continues at distance into the summit area of Piz Dadens. A thin layer of Triassic remained attached to the crystalline basement. The sediments of the Cavistrau nappe young towards the thrust fault (indicated by arrows). A penetrative (Calanda Phase) foliation cuts across and post-dates the (Cavistrau Phase) thrust fault.

Figure 6.11 Orogenic timetable of nappe formation, sedimentation, metamorphism and magmatism in the eastern Central Alps.

◀ Figure 6.12 Tectonic evolution of the Central Alps of eastern Switzerland depicted as a series of palinspastic cross-sections. Note that because of strike-slip motion along the Insubric Fault, some units of the Southalpine nappe system disappear with time and are replaced by others. Growth of the orogen is accomplished by successive incorporation of detached upper crustal blocks (e.g. Simano, Lucomagno, Gotthard, Aar). The sedimentary cover of these units was stripped off and moved to the north in an earlier stage. The core of the orogen made up of Penninic basement nappes was uplifted by retro-thrusting along the Insubric Fault and basal accretion of Simano, Lucamagno, Gotthard and Aar basement blocks. Uplift was aided by erosional removal of the Austroalpine nappe pile.

Figure 6.13 Kinematic evolution of the Helvetic nappes near the western end of the Aar massif.

Figure 6.14 Geological cross-section through the Axen nappe of central Switzerland – redrawn after Menkveld (1995). The plunging isoclinal anticlines are evidence of orogenic collapse above the updoming Aar massif.

Figure 6.15 Early phase of folding in the Jura Mountains indicated by angular unconformities.

Figure 6.16 Orogenic timetable of nappe formation, sedimentation, metamorphism and magmatism in the western Central Alps.

◀ Figure 6.17 Kinematic evolution of the Central Alps in western Switzerland. Bernhard nappe complex after Scheiber et al. (2013), Prealps of western Switzerland after Wissing & Pfiffner (2002). Growth of the orogen was accomplished by successive basal accretion of upper crustal blocks (e.g. Verampio, Gotthard, Aar). The sedimentary cover of the upper crustal units was stripped off in an earlier phase and piled up at the front of the orogen by frontal accretion. Out-of-sequence thrusting during frontal accretion was responsible for the Southpenninic, Piemonte derived Gurnigel nappe now being beneath the Middle Penninic, Briançon derived Klippen nappe. In the core of the orogen, the Penninic basement nappes (Monte Rosa, Bernhard nappe complex) were intensively squashed,

stacked and back-sheared. Combined with retro-thrusting along a steeply dipping south-vergent thrust fault and aided by erosional removal of the overlying Austroalpine nappes, these units were exhumed.

Figure 6.18 Orogenic timetable of nappe formation, sedimentation, metamorphism and magmatism in the Western Alps.

▲ Figure 6.19 Folded folds in the Penninic nappes of the Western Alps. Isoclinal folds of the first phase can be recognized from the symmetric pattern of the ages of strata with either young or old strata in the fold cores. These folds were refolded by a second west-vergent shearing.

◀ Figure 6.20 Palaeogeographical map of the Alps towards the end of the Oligocene (22 Ma).

◀ Figure 6.21 Palaeogeographical map of the Alps in the Middle Miocene (15 Ma).

◀ Figure 6.22 Map showing the late Neogene cooling history of the Alps. Zircon fission-track ages indicate the time when the rock sample cooled below about 230 °C. For Apatite this temperature corresponds to about 110 °C. Data in the Western and Central Alps are from Vernon et al. (2008) and data in the Eastern Alps from Luth & Willingshofer (2008).

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▲ Figure 7.1 Palaeogeographical map of the Alps towards the end of the Miocene (Messinian, 6 Ma).

▲ Figure 7.2 Geological cross-sections through valleys carved and overdeepened by fluvial erosion. The valleys are to the south of the Central Alps and the cross-sections based on seismic reflection lines.

◀ Figure 7.3 Palaeogeographical map of the Alps in the Pliocene (3 Ma).

▶ Figure 7.4 Timetable of Pleistocene glaciations and the evolution of the hominini and *Homo*. Note that our ancestors experienced glaciations.

▲ Figure 7.5 The extent of the Alpine ice sheet and glaciers during the Last Glacial Maximum (20 000 to 15 000 years ago). On the northern side of the Alps, glaciers spread way out onto the Alpine foreland, whereas the Po Basin to the South of the Alps remained almost completely ice free. Three ice domes in the interior of the Alps can be distinguished (marked with +).

Figure 7.6 Limit of glacial polishing related to the Last Glacial Maximum in the area of Finsteraarhorn–Grimselpass (canton Bern, Switzerland).

Figure 7.7 Geological cross-section through the glacially overdeepened Rhone Valley near Martigny (canton Valais, Switzerland).

► Figure 7.8 Recent uplift rates determined from precision leveling. The map was compiled from various

Figure 7.9 Geological cross-section through the western Central Alps showing a simple crustal structure along with hypocentres of earthquakes and uplift rates. Note the conspicuous steep gradient of the uplift rates on the northern flank of the Aar massif (near Zweisimmen) and above the Adriatic mantle wedge (north of Ivrea) suggesting that the core of the orogen is being expelled upward. Seismicity is restricted to the upper 12–15 km in the core of the orogen.

Figure 7.10 Holocene tectonic fault in the Aiguilles Rouges massif near Lac de Fully (canton Valais, Switzerland). The offset of the glacially scoured surface by the fault is clearly visible.

▲ Figure 7.11 The Flims rock avalanche, the largest one in the Alps: shown as a block diagram (constructed with AdS2) and in cross-sectional view.

Figure 7.12 Ruinaulta, a gorge that the Vorderrhein River cut through the rock mass displaced by the Flims rock avalanche. (A) Remains of a gravel terrace representing an ancestral river bed located roughly 50 m above the modern river bed. (B) Ancestral valley bottom filled with gravel and boulders located above the modern river bed.

Figure 7.13 Gravitational slope movements as seen in the field. (A) Sackung of Cari (Leventina valley, canton Ticino, Switzerland). Motion occurred on surfaces dipping into the mountain flank and being parallel to the foliation in the gneisses. (B) Steep faults in Val Bedretto (canton Ticino, Switzerland) forming ridges and uphill-facing scarps. Small ponds and lakes form behind the ridges. (C) Steep fault in Val Bedretto (canton Ticino, Switzerland) offsetting a moraine ridge it intersects at a right angle.

Figure 7.14 Two types of deep-seated gravitational instabilities. (a) Antithetic normal faults merging with a basal detachment result in ridges and uphill facing scarps. (b) Steep faults delimiting tilted blocks also result in ridges and uphill facing scarps.

Figure 7.15 Erosional processes on the southern flank of Val Bedretto (canton Ticino, Switzerland): mass movements, rock falls and debris flows.