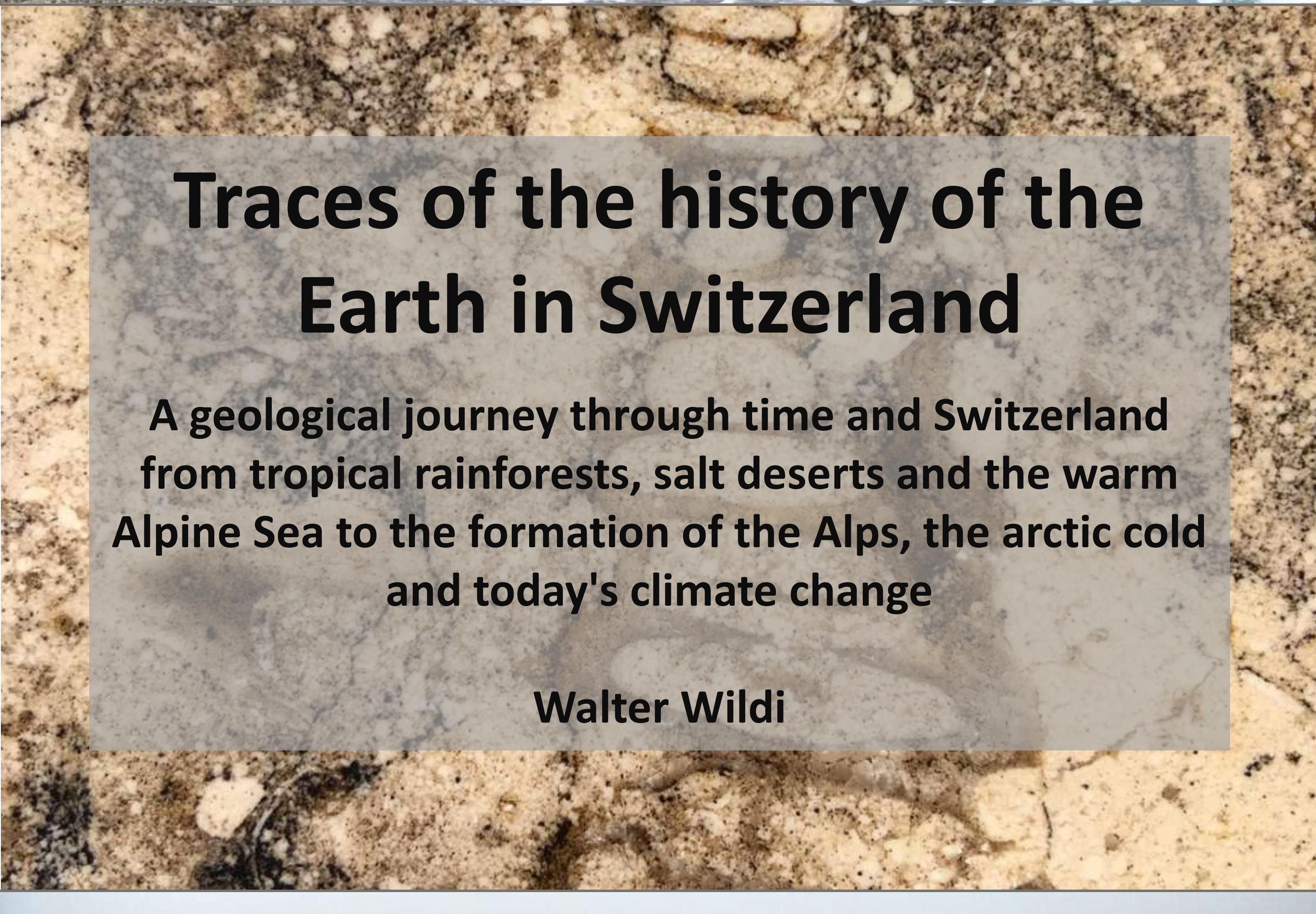

Traces of the history of the Earth in Switzerland

A geological journey through time and Switzerland from tropical rainforests, salt deserts and the warm Alpine Sea to the formation of the Alps, the arctic cold and today's climate change

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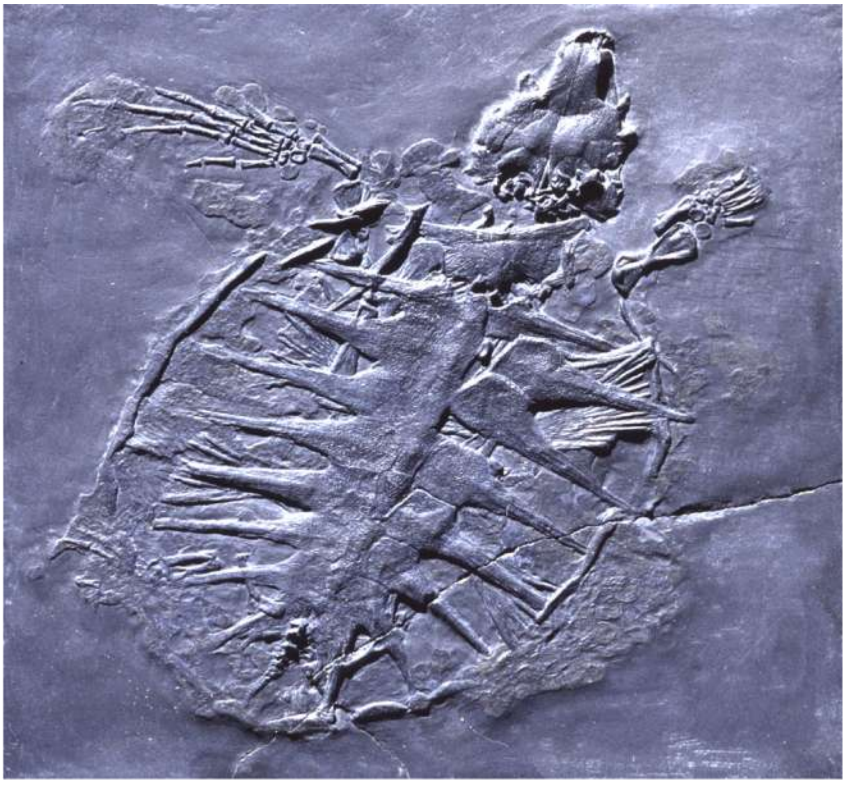

Fossil turtle, Glarner Dachschiefer (roof slates) from the former Engi mine (Lower Oligocene, Canton Glarus; Copyright: Dr. H. Furrer and Paläontologisches Museum Universität Zürich).

Cover:
- Triopetra beach (Crete)
- Nerinea limestone (Kimméridgian, tennis court, Dardagny, Genève)
- Mont Miné (Valais, photo: S. Girardclos)

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Foreword

Switzerland is a small spot on planet Earth. Its history is certainly older, but only the last 300 million years or so have been sufficiently documented by the geological record to tell the story that the country shares with the entire Earth.

At the beginning of this history, just over 300 million years ago, Switzerland was located slightly south of the equator, in a humid tropical forest. Then, as a result of continental drift, it slid into the hot sand and salt deserts of the subtropics. With the opening of the oceanic Alpine Sea and the Atlantic Ocean 200 million years ago, sea levels rose and a warm, shallow sea flooded Switzerland and large parts of Europe. This inundation lasted almost 150 million years until the folding of the Alps, caused by the collision of Africa and Europe. The sea subsided and a mountain range as high as the Andes scratched the sky. Rivers washed the eroded material onto huge alluvial fans in the warm and humid rainforest. 20 million years ago, another shallow sea inlet pushed eastwards from the Mediterranean along the northern edge of the Alps. Then, the sea on the northern side of the Alps disappeared for good.

Switzerland had now reached the present latitude of Central Europe. The climate gradually cooled down and turned into arctic conditions two and a half million years ago: at the same time as the ice caps on the northern continents, the alpine glaciers grew and sent their ice streams as far as the Swiss Plateau in the North and the southern alpine valleys. Ice ages and interglacial periods alternated in the rhythm of the fluctuations of the Earth's orbit around the sun and the inclination of the Earth's axis.

The last time the glaciers stood on the Swiss Plateau and in the southern alpine valleys was a good 20’000 years ago. Then the ice tongues melted back and reached their present position 11’700 years ago. Humans appeared 50'000 to 35'000 years ago, but the Swiss Plateau and the alpine valleys settled only from 15'000 years onwards.

Since the end of the last ice age, the climate has fluctuated with global temperature amplitudes of a few degrees Celsius. Following warm Middle Ages with almost ice-free alpine peaks, the last major glacial advance, during the so-called Little-Ice-Age, began in the Alps in the sixteenth century and ended around 1850. And, for the first time in Earth's history, warming is not exclusively of natural origin, but is also influenced by the release of greenhouse gases, deforestation, the drying up of agricultural landscapes, the retention of nutrients from continental erosion in dam lakes, and other consequences of human activity.

This is a summary of the recent Earth’s history based on geological evidence, rocks, fossils and geochemical signals. They bear witness of dynamic ecosystems and are an interplay of geological and biological processes which over millions of years, responded both to constant changes and catastrophic events, thus providing space and food for an increasingly diverse life. And let us be aware that the decrease in biological diversity currently observed on Earth represents a phenomenon, the magnitude and long-term consequences of which are not yet fully understood.

The present guide proposes a journey through the testimonies of the Earth's history in Switzerland. It points out geological sites and landscapes, museums, mines and other witnesses, where the geological history is illustrated, from the tropical rainforest, the salt deserts, the Alpine Sea, the folding of the Alps and the erosion of the mountain ranges, to the ice ages and the recent glacier retreat!

Table of content

Further leading literature

We would like to take this opportunity to point out books to interested readers that can serve as a further basis for this guide-book and the understanding of the geology of Switzerland.

Geology of the Alps:

Pfiffner, O.A. 2014: Geology of the Alps. Wiley, 400 p.

Marthaler, M. 2019: Moiry: From Europe to Africa. Editions LEP, Le Mont sur Lausanne.

Geological history of Switzerland:

Weissert, H. & Stössel, I. 2015: The ocean in the mountains. Vdf Zurich, 198 p. Third edition

Wildi, W. & Lambert, A. 2019: Earth's history and landscapes in the canton of Aargau. Aarg. Natf. Ges. Aarau, 183 p.

Acknowledgements

This short history of the Earth benefited from suggestions, corrections and/or additional documents from Eric Davaud (Bardonnex), Philippe Favre (La Forclaz), Christian Schlüchter (Lützelflüh-Goldbach), Heinz Furrer (Rümlang), André Lambert (Baden), Mario Sartori (Ayen), St. Girardclos (Geneva), Michel Wildi (El Salvador), Sandrine Vallin (Bern), Christophe Wildi (La Rippe), Michel Marthaler (Univ. de Lausanne), Marcos Buser (Zürich), Jean-Claude Lalou (Vaumarcus), Pierre-Yves Jeannin (ISSKA, La Chaux-de-Fonds) and ANG (Aargauische Naturforschende Gesellschaft). I would like to thank them warmly for their contribution.

A. The Film of the Earth's history of Switzerland

Every place on Earth has its barely comprehensible long geological history. The universe was formed 13.81 billion years ago, while the planetary system and Earth were formed 4.54 billion years ago. The geological history of Switzerland has a long record, but only the last 300 million years are sufficiently documented to make a complete film of the geological development. Switzerland is an alpine country, geographically and geologically. We would like to tell its history as if we had experienced it ourselves. But, it is going to be in a condensed form, as in a short film.

1. Carboniferous (359 - 299 million years)

320 million years ago, towards the end of the Carboniferous period, we sit down on a long hill of what is known as the Hercynian mountain range, situated a little south of the north-eastern Folded Jura, and look around us. We are in the middle of the tropical rainforest, under fern and equisetum trees (Fig. A 1). Large dragonflies swarm through the humid air. Year in, year out, temperatures are between 25 and 30°C. The days and seasons are the same here, at the equator.

Figure A 1: *Switzerland in the Carboniferous, a reconstruction by Oswald Heer (1865).*

Geological hiking tours:
1.Tropical forests of the Carboniferous

In the northern direction we discover a 10 to 15 km wide, East-West oriented depression, with boggy underground. The sandy-clayey sediments eroded on the hills and the plant remains introduced by rivers accumulate here.

Figure A 2: Time table of the geological trip to Switzerland.

Era	Period	Epoch		Mio Years
Cenozoic	Quaternary	Holocene		0.01
		Pleistocene		2.6
	Neogene	Pliocene		5
		Miocene	Upper	
			Middle	
			Lower	23
	Paleogene	Oligocene	Upper	
			Lower	34
		Eocene	Upper	
			Middle	
			Lower	56
		Paleocene		66
Mesozoic	Cretaceous	Upper Cretaceous		
		Lower Cretaceous		145
	Jurassic	Malm		
		Dogger		
		Liassic		201
	Triasssic	Upper Triassic		
		Middle Triassic		
		Lower Triassic		252
Paleozoic	Permian	Upper Permian		
		Lower Permian		299
	Carboniferous	Upper Carboniferous		
		Lower Carboniferous		359

Due to the still rudimentary microbial activity they hardly decompose and are later transformed to coal seams under the overload of further sediments. The depression is caused by a tectonic trench which is constantly sinking further, the so-called “Permo-Carboniferous Trough" of north-eastern Switzerland, as we call it today. The southern hemisphere of the Earth is covered with a massive ice cap south of latitude 55°. However, this leaves no traces in tropical Switzerland.

In the Alps, there are several former depressions of the Carboniferous and Permian periods. Beautiful fossil plants are known from the Glarus, Bernese and Valais Alps, where coal seams were mined locally.

2. Permian (299 – 252 million years)

Millions of years go by and the climate becomes dry. We have arrived in the Permian (299 million years ago). Thanks to continental drift, Switzerland has shifted away from the equator to the height of today's Sahara. The climate is hot and dry. If precipitations fall, it looks like a kind of monsoon rain. The vegetation is thin and largely confined to the river valleys. The red soil consists of alluvial sediments of clayey sand and gravel. A desolate landscape! The observer on his Hercynian hill notes that his observation point is gradually eroding and the resulting sandy debris are being washed away into the Permo-Carboniferous trough, where they fill up the delta of an inland lake. The shallow lake is home to primeval fish. They represent the oldest vertebrate fossils in Switzerland and were discovered in 1983 in the Nagra Weiach borehole at a depth of 1312 m. Switzerland remains far from the gentle rise in sea level and the formation of the thick salt deposits called “Zechstein” in northern Germany.

Figure A 3: *»Red desert" in the South of Morocco, similar to a landscape in the Permian of Switzerland.*

Worldwide, the Permian is characterized by intensive volcanism. This is also evidenced in Switzerland, for example by pebbles of volcanic origin in the sediments of the alpine Verrucano. In the South of the Canton Ticino, such a volcano occurs in the form of solidified volcanites and volcanic sediments, especially "ignimbrites", i.e. caked volcanic slag.

Geological hiking tours:
2. Red deserts of the Permian
3. Permian volcanites of Melide

3. Triassic (252 - 201 million years)

The transition from the Permian to the Triassic (252 million years ago) corresponds to a major crisis in biodiversity. Especially in the oceans, numerous animal species become extinct as a result of catastrophic volcanic eruptions. However, in Switzerland, this mass extinction is nowhere documented in the fossilised desert deposits. Only faint reliefs now protrude from the subtropical hot desert plain. Rivers disperse red and white sand on the wide alluvial plains and form the future red sandstones of the “Buntsandstein”.

At the beginning of the Middle Triassic, the landscape changes: the worldwide rise of the sea level leads to the flooding of large parts of Central Europe. The observer in northern Switzerland has to save himself on Noah's Ark and is now drifting on a sea a few metres deep in which calcareous mud with numerous shells is deposited (“Lower Muschelkalk”). However, this transgression is short-lived: when the sea level falls again, large lagoons and salt lakes remain, in which gypsum and rock salt are deposited. During a new rise of the

***Figure A 4**: Sebkha El Melah, Tunesia (photo: E. Davaud, Bardonnex).*

sea level, lasting only a few million years, the Upper Muschelkalk is deposited in a shallow sea covered with crinoids. At the limit from the Middle to the Upper Triassic, the sea withdraws again, leaving behind a desert landscape with sebkhas where salt and gypsum can form (Fig. A 4, 5a).

In the late Triassic, dinosaurs ran across the wide alluvial plains of fine, clayey mud; today they populate the dinosaur museum in Frick (Canton Aargau, Fig. A 5b). Red sands and the remains of Equisetum plants that line the river courses are deposited in winding riverbeds.

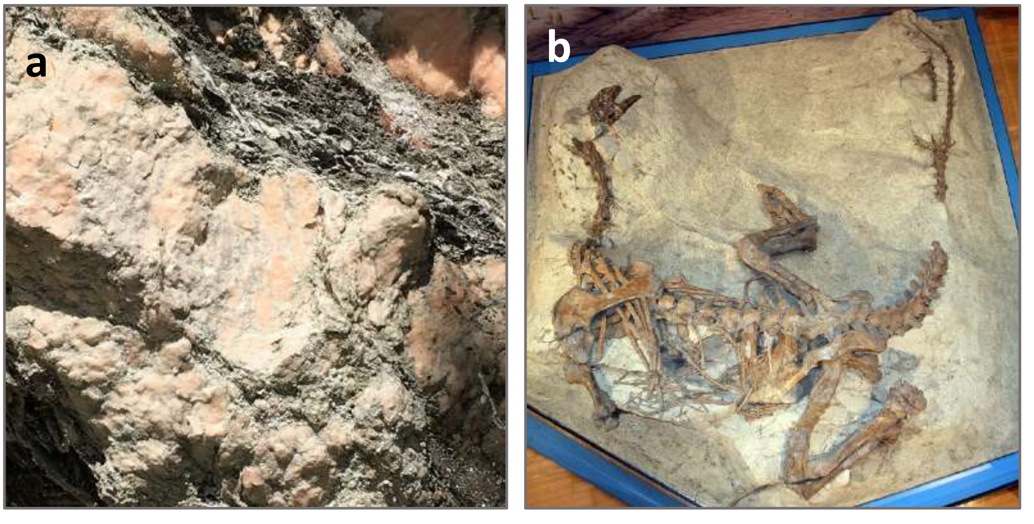


Figure A 5a: *Gypsum deposited in a sebkha; Tabular Jura at the limit Middle / Upper Triassic.* ***b:*** *Plateosaurus engelhardti, dinosaur museum of Frick (www.sauriermuseum-frick.ch).*

During the Triassic, the Tethys Sea invades the paleogeographical area of the Eastern and Southern Alps (Fig. B 7 b). This event signals the beginning of the opening of the Alpine Sea between Africa and Europe. The fish saurians discovered on Monte San Giorgio are world-famous (see Chapter C). The Upper Triassic is characterized by dolomite deposits of up to 2 km thickness, formed mainly by cyanobacteria (stromatolites).

4. Jurassic (201 - 145 million years)

201 million years ago, at the beginning of the period of the Earth's history known as the Jurassic, the global sea level begins to rise, dictating events on the Earth's surface for 1365 million years. This rise is due to intensive volcanic activity on the mid-ocean ridges, which

testifies relatively rapid (on a geological scale) shifts of the plates: between Europe and Africa, the Alpine Sea opens up as the two continents drift apart, combined with a lateral mutual counterclockwise shift (Fig. B 5). At the same time, from the Jurassic onwards, the North Atlantic opens first, and then the South Atlantic, in the Cretaceous from about 145 million years onwards.

This rise of the sea level makes that large parts of Europe, and also other continents turn into a shelf sea. Only old massifs from the Hercynian mountain formation, such as the French Massif Central or the Bohemian Massif, rise above sea level.

Figure A 6: *Mangroves on the Pacific Coast of El Salvador. At the beginning of the Liassic, similar conditions were found in the rising sea of northern Switzerland; although at that time the specific plants shown in Fig. A 6 did not exist yet (Photo: Michel Wildi).*

Even if very diverse conditions prevail in an area the size of Switzerland, or even Europe, some typical features of the development of this sea can be deduced from the geological record.

In the **Liassic** (Lower Jurassic, from 201 million years), the sea remains shallow from the European continental margin to Central Europe. The sedimentary rocks and fossils (”Insect marls") remain in some places comparable to a mangrove coast (Fig. A 6). The rapid rise of the sea level is manifested by the fact that already in the first rock layers above the Insect marls the first ammonites of the genus *Psiloceras* appear just somewhat later, together with the primitive oysters of the genus *Gryphaea* (Fig. A 7). In the Austroalpine and Southalpine region, however, the seafloor in some places subsides very quickly, and deeper sea basins are formed.

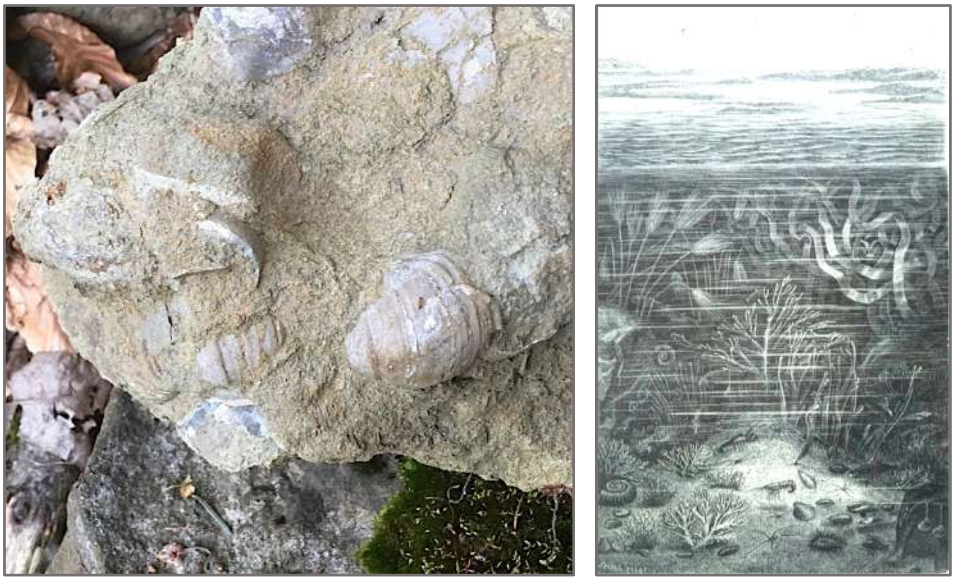


Figure A 7 a: *Gryphaea limestone in the Folded Jura of canton Aargau, the first sediments deposited in the open sea in the Jurassic sea (Wildi & Lambert 2019). b: marine transgression in the Liassic; reconstruction by Oswald Heer (1865).*

In Switzerland, only the region above and around the future Aarmassif remains dry ("Alemannic Land").

At the end of the Liassic, the sea in Central Europe and England suffers from a lack of oxygen. The *Posidonia*-slates deposited during this time are leafy, finely layered and rich in well-preserved fossils such as mussels, ammonites, bony fish and ichthyosaurs.

The **Dogger** (Middle Jurassic, 164 million years ago) begins in the shelf sea in the region of today's Jura Mountains in the North to the Helveticum in the South (Fig. B 7) with the deposition of black clay in water depths of several tens of meters (possibly more than 100 m?). In the Jura Mountains, this formation is called Opalinus-Clay after the ammonite *Leioceras opalinum*.

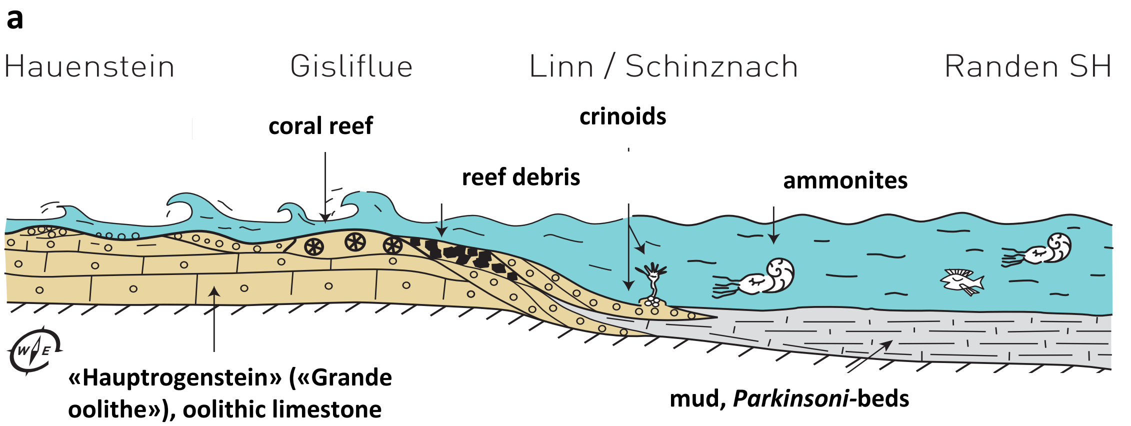
Then the landscape below the water surface changes radically: the Liguro-Piemontese deep-sea basin opens up between Europe and Africa (Fig. B 7). The continental margin in the South of the Alpine Sea, i.e. in the Eastern and Southern Alps, sinks and volcanic basalts pour out on the Ligurian deep-sea floor, which is presumably about 4000 m deep (the "ophiolites" of alpine geology). In this deep sea, the calcareous shells of the marine fauna are chemically unstable, so that only fossils with silica skeletons remain, such as the unicellular radiolarians. Mixed with fine red mud they form so-called radiolarites (Fig. A 8).

At the northern edge of the oceanic basin, steep slopes descend from the Briançonnais platform into the depths. On these steep slopes, breccias are deposited, consisting of the erosion debris of the platform (Fig. A 9). Today, these deposits are found in the Breccia nappe ("Nappe de la Brèche") of the Préalpes Romandes and in the Falknis Nappe in Graubünden.

Figure A 8: *Radiolarite: deep-sea sediments in the Tsate nappe (Wallis, Foto: M. Sartori).*

Figure A 9: *Breccia formed on the steep slopes between the Briançonnais platform and the deep Liguro-Piemontese basin;* ***a:*** *fine breccia with debris of metamorphic shales, yellow dolomite and grey limestone;* ***b:*** *facies with coarse grey limestone debris (Brèche du Chablais, Praz de Lys).*

In the shelf sea of today's Jura Mountains, a carbonate platform is building up from West to East. In the eastern Canton Aargau this can be traced in the field by means of the migrating boundary between the so-called “Hauptrogenstein” (shallow sea) and the Parkinsoni-beds (tens of metres deep sea, Fig. A 10).



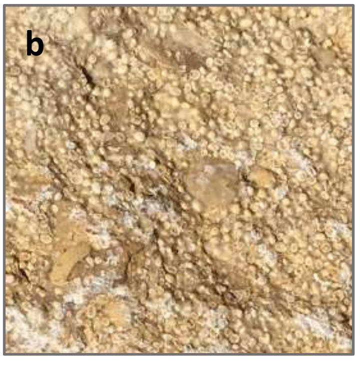


Figure A 10 a: *Platform of the "Hauptrogenstein" in the eastern Jura Mountains, advancing from West to East;* ***b:*** *"Hauptrogenstein" consisting of ooids (spheres of concentric calcareous layers, diameter: 1-1.5 mm) formed in the wave region of the shallow sea;* ***c:*** *Single coral from the coral reef at Gisliflue (diameter about 2 cm, Wildi and Lambert 2019, Figs. 47, 48).* ***d:*** *Aerial photos of oolite sand waves in the shallow sea of the Bahamas (https://de.wikipedia.org/wiki/Datei:Eleuthera.jpg).*

At the end of the Dogger, the sea level rises strongly, whereas the precipitation of lime decreases. In large areas of Europe, fine material from chemical rock weathering is being washed in from a distant continental area (probably from the East). Besides clay minerals, this material contains plenty of iron oxide. This precipitates to oolithic spheres form the historically important ore deposits in the Lorraine (France). In Switzerland, the most important iron deposits are found in the Tabular Jura of Herznach, where the ore was exploited from 1937 to 1967. The rocks are rich in well-preserved ammonites (Fig. A 11).

Figure A 11: *Ammonite accumulation in the Herznach mine (Photos: Geri Hirt, Linn; Wildi & Lambert 2019).*

***Figure A 12**: : Marl and limestone deposits in the eastern part of the Jura: Effinger strata in the Schümel quarry, Holderbank (Wildi and Lambert 2019); Perisphinctes, a common ammonite (https://en.wikipedia.org/wiki/Perisphinctes).*

Worldwide, **Malm** (Upper Jurassic, 164 - 145 million years) is a period of epicontinental seas with large carbonate platforms and the deposition of limestone and marl. Huge hydrocarbon deposits (oil and gas) are formed on the Arabian platform. Part of the North Sea's oil and gas reserves also date from this period.

In Switzerland, and especially in the Alps, the content of the information contained in these rocks varies considerably depending on the intensity of deformation and transformation during the Alpine folding process: in the Jura Mountains, the sediments and their fossils are very well preserved. In the Alps, on the other hand, the information content decreases from the tectonically highest to the lowest and most deformed nappes and their rocks.

In contrast to the calcareous and marly deposits in water depths of several tens of meters

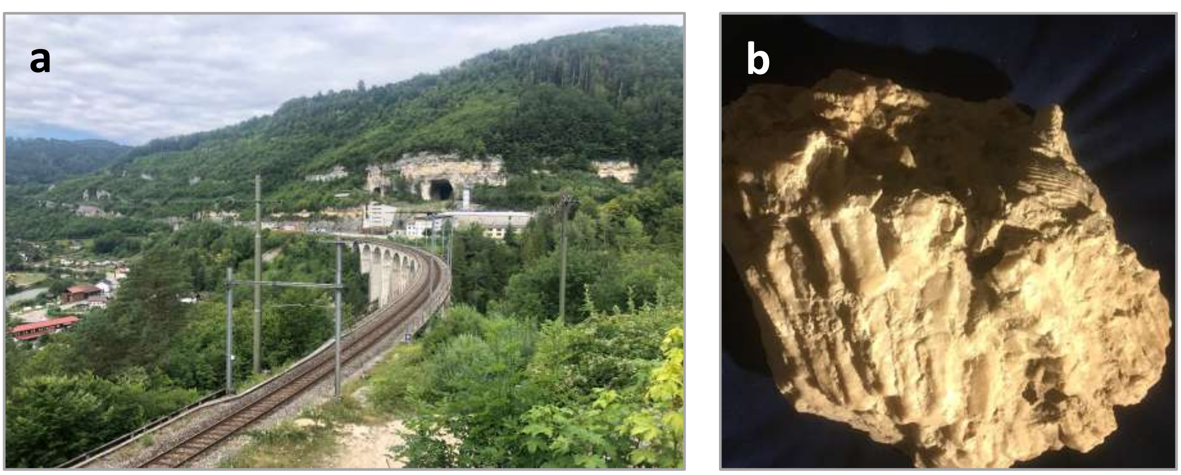


***Abbildung A 13 a:** Coral limestone, former underground quarries of the lime works in St. Ursanne (photo: Marcos Buser); **b:** coral from the area of the quarry entrance gate.*

in the eastern part of the Jura Mountains (e.g. the Effinger strata, Fig. A 12), the so-called “Raurakian platform” with coral reefs developed in the West. One of these reefs forms the cliffs above the railway station of St-Ursanne (Fig. A 13). It was mined by the “Usine de Chaux” as raw material.

The rocks in the Helvetic nappes corresponding to these layers are often strongly deformed and recrystallized. They allow fewer conclusions about the depositional environment, but coral limestones and deposits from the deeper shelf are also found here.

In the deep Liguro-Piemontese ocean of the Alpine Sea, basaltic lavas solidify into “pillow lavas”. Radiolarites from siliceous radiolarian skeletons and fine, often red deep-sea mud (Fig. A 14) and radiolarian skeletons are also found in the Eastern and Southern Alps.

***Figure A 14 a:** Oceanic pillow lavas, (Nappe du Tsaté, Evolène, photo M. Marthaler); radiolarites in the “Préalpes romandes” (“Nappe supérieure”, South of the Jaunpass).*

***Figure A 15:** Dinosaur footprints on limestone layers in Courtedoux (Jura), upper Malm.*

At the end of the Jurassic period, the Raurakian platform is located at sea level, with shallow lagoons, flat islands and muddy coastal plains, some of which are covered with vegetation. These deposits were formerly called "Purbeckien" (today: Goldberg-Formation). The rock horizon partly contained gypsum, which is now dissolved, and numerous indications of temporary continental conditions, such as black pebbles, plant roots and vertebrate bones.

The dinosaur footprints of Courtedoux (Jura, Fig. A 15) are found in a stratigraphically slightly lower position (Reuchenette-Formation). They also bear witness to this brief dry up of the landscape.

Geological hiking tours:
10. The Ligurian deep-sea basin at Lake Marmorera
11. The southern alpine deep sea in the Gorge of the Breggia
12. Iron ore and the ammonite necropolis of Herznach
13. Coral reefs in the Jura
14. Dinosaur footprints in the Jura

5. Cretaceous (145 - 66 million years)

In the geological period under consideration, the Cretaceous is the period during which the global sea level is at its highest, namely up to 250 m above the present level. During the Cretaceous, the South Atlantic opens up (Fig. B 5). Between Africa and South America, a new seafloor is formed with basaltic lava, which flows from the liquid asthenosphere to the Earth's surface in the centre of a mid-ocean ridge (Fig. B 3). The thermal expansion of this ridge explains to a large extent the global rise in sea level: the volume of the ocean basins has shrunk in a way that the sea "overflows" and transgresses the continental margins and even interiors.

However, the opening of the South Atlantic has another consequence that directly affects the Alpine Sea and Switzerland: the African continent rotates counterclockwise and narrows the Alpine Sea. In the Liguro-Piemontese basin, as the first sign of this constriction and the resulting formation of the Alps, a subduction zone (Fig. B 3) formed about 120 million years ago, where the still young oceanic crust of the Ligurian basin subducts below the southern continent (Adria and Africa).

The narrowing of the Liguro-Piemontese basin of the Alpine Sea leads to the formation of an island arc. This reaches the South of the Préalpes Romandes 100 million years ago. Rich vegetation grows on the island formed by this tectonic event. Plant remains are washed away to the seashore together with the erosion debris. Pebbles, sand, clay and organic remains are then washed into steep canyons and, due to turbidity currents (so-called “turbidites”), they are washed to the deep-sea fans at the foot of the island arch. These are the first “flysch” called sediments of the alpine orogens. Their outcrops are known as "Simmenflysch" at the Jaunpass and the Hunsrück mountain between Zweisimmen and Jaun. The deposition of flysch now continues, in parallel with the formation of the Alps, up to the Eocene/Oligocene limit, 34 million years ago (Fig. A 16, 17).

At the end of the Jurassic and especially at the beginning of the Cretaceous period, sediments with black shales, rich in organic matter and fine-grained pelagic limestones are deposited (Fig. A 18). The black shales indicate a lack of oxygen in the deep water,

Figure A 16 a: *Thin-bedded Helminthoides-flysch, Hunsrück (Préalpes Romandes, Jaunpass, Upper Cretaceous);* ***b)*** *Coarse-bedded Niesenflysch, tectonically inverted (Préalpes Romandes, Sepey, Upper Cretaceous);* ***c), d)*** *Flysch of the Gurnigel nappe (Upper Cretaceous, Les Fayaux quarry) and flute casts on a lower bed surface.*

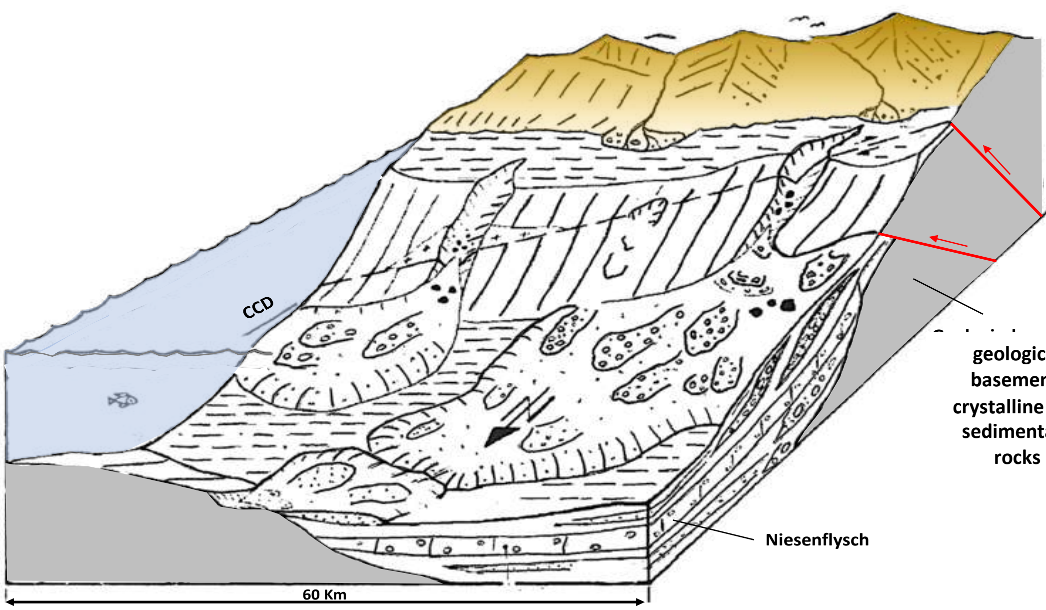


Figure A 17 : *Paleogeographic model of flysch sedimentation in alpine deep-sea trenches, an example of the Niesenflysch (Caron et al. 1989, modified). The detrital material deposited in the basin of the Niesenflysch is the result of the erosion of an island arc which was raised by the alpine subduction. CCD: sea depth below which calcite becomes unstable.*

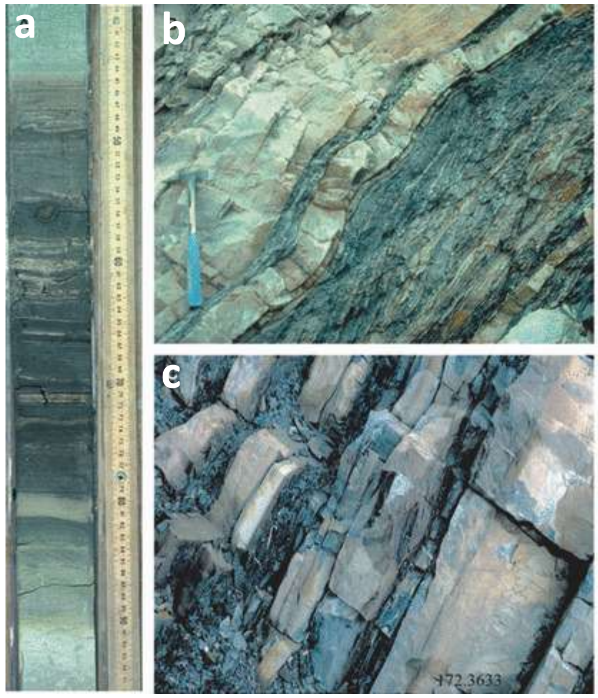


Figure A 18: *Examples of black shales in the literature:* ***a:*** *drill core from ODP hole 1049C in the North Atlantic.* ***b:*** *Exposure of light quartzites and black shales from Val Ferret (Valais).* ***c:*** *Black shales in alternating layers with micritic limestone from the Southern Alps (Kay 2009).*

which is due to the strong production of algae and other organisms in the warm surface water. This warming in turn is mainly due to the increased CO_2 content of the atmosphere caused by strong volcanism. Black shales can be found worldwide in deep-sea basins during the Lower Cretaceous. They are an important source rock for oil and natural gas.

During the Lower Cretaceous (stage of the Barremian), a wide, shallow sea platform is installed on the European continental margin, with massive, pure calcareous deposits and a rich fauna of oysters and gastropods, corals, etc. In the Helvetic region of Eastern and

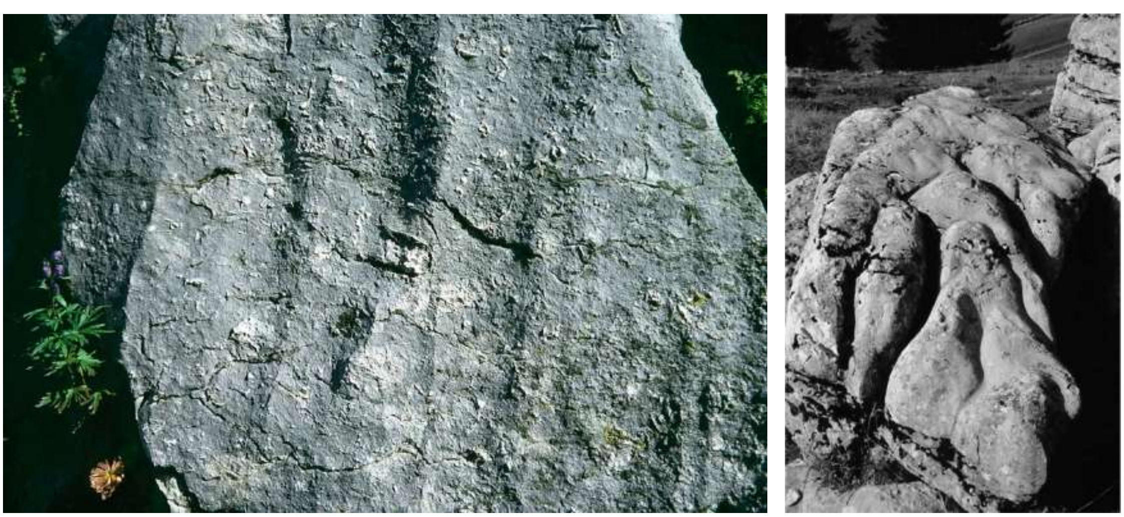


Figure A 19: *"Schrattenkalk" (Urgonian limestones or Vallorbe Formation) with numerous fossil remains, surface karstification.*

Central Switzerland, this formation is called "Schrattenkalk"; in Western Switzerland, it was called "Urgonien" (today: Vallorbe-Formation). Morphologically, the formation is characterized by its light-colored weathering and karst morphologies (Fig. A 19).

In the middle of the Cretaceous period (Aptian - Cenomanian), the sedimentation on the Helvetic marine platform is strongly reduced. Condensed sediments are deposited, the Garschella-Formation, consisting of glauconite and apatite containing sandstones, marls, limestones and phosphorite nodules (Fig. A 20). Due to the low sedimentation rate, numerous fossils, namely ammonites, can also be found. Strong ocean currents are mentioned as a reason for the formation of this condensed sedimentary sequence.

The highest global sea level is reached during the Upper Cretaceous. The Helvetic platform bears witness of this event by means of fine-grained limestone with planktonic

Figure A 20: *Garschella-Formation with limestone boulders and phosphorite nodules on Alp Garschella.*

foraminifera belonging to the *Globotruncana* group. Even more impressive are the Cretaceous formations on both sides of the Channel in the South of England and the North of France. Here, white rocks consisting of calcareous nannoplankton form impressive cliffs (Fig. A 21).

Figure A 21: *Upper Cretaceous atmosphere: Cretaceous chalk rock cliffs of Douvre (https://commons.wikimedia.org/wiki/File:White_cliffs_of_dover_09_2004.jpg); strongly enlarged planktonic foraminifers Globotruncana and nannoplankton und; a wide, open shelf sea as illustration..*

Sediments of the Cretaceous are missing in the central and eastern Jura Mountains, under large parts of the Swiss Plateau and up to the northeastern part of the Helvetic platform. The question arises: did these regions rise from the water during the Cretaceous period? Or were once Cretaceous sediments deposited and then eroded again before the formation of the Molasse?

The Cretaceous ends with an ecological catastrophe: the disappearance of dinosaurs, ammonites, globotruncanas and many other organisms from the Earth's surface in a very short time. The reasons given in the literature for this are a huge meteorite impact on the Yucatan peninsula and the enormous trap volcanism in the South of Mumbai (India), or at best a massive biological crisis.

Geological hiking tour:
15. Turbidites and flysch of the first Alpine folding

6. Palaeogene (66 - 23 million years)

The transition from the Cretaceous to the Palaeogene (formerly: Lower Tertiary) 66 million years ago is accompanied by the first decline in temperatures and sea level (Figs. B 8, B 13). The current Jura mountain area and Swiss Plateau are now above sea level and are still covered with subtropical vegetation at an average annual temperature of around 15°C. The weathering of the rocks produces weathering horizons with high iron and partly manganese content, called bolus (Fig. A 22). In the shallow sea of the Helvetic platform, there are small reefs formed by calcareous algae (*Lithotamnium*), nummulites, discocyclines and astérocyclines (all large foraminifers with calcareous skeletons). The narrow marine basin of flysch sedimentation at the front of the alpine subduction migrates northwards from the former deep Alpine Sea and reaches the Helvetic area in the late Palaeogene. These last flysch sediments contain material from the erosion of volcanoes that were located a little further south, in the Penninic realm. The spotted sandstones of this flysch are known as Tavayannaz-Sandstones. The famous fossil fish, turtles and birds of the former mine near Engi (Glaris) originate from a former mine for roof slates.

Figure A 22*: Nodules of iron ore in the bolus clay from the Eocene in the Folded Jura mountain chain, Thalheim (Coo 47.43253/8.10074).*

From the early **Oligocene (**34 million years ago), the sedimentation migrates into the alpine foreland, for example into the area from the North of the Aare Massif to the southern Swiss Plateau, were the so-called Lower Marine Molasse forms in a narrow East-West oriented sea arm. However, this estuary is rapidly filled up; at the same time, the global sea level is falling, and the thick alluvial fan deposits of the Lower Freshwater Molasse from Mt Pélerin to the Napf, the Rigi and the Speer are piled up at the edge of the Alps (Fig. A 23, 24).

In the area far from the Alpine front, along the present-day foot of the Jura Mountains and throughout the Geneva basin, one finds oneself on the flat alluvial plain, with fine clayey and sandy deposits. In the Geneva basin, this is the "Molasse Grise", partly with gypsum inlays, and the "Molasse Rouge" with its beautiful red-spotted sandstones, from which most of the buildings in the old town are built (Fig. A 25).

The Oligocene is characterized in the Alpine foreland by a humid Mediterranean climate, similar to the present climate in the southern part of Canton Ticino.

7. Neogene (23 - 2.6 million years)

In the Miocene, especially from the so-called Burdigalian (20.5 million years ago) onwards, the Alpine folding progresses further north. The alluvial fans of the Lower Freshwater Molasse are thrusted northwards. The sea rises again and floods the area from the Swiss Plateau to the Jura Mountains. This Upper Marine Molasse extends from the Vienna Basin over the Swiss Plateau to the Mediterranean (Fig. A 26, 27). After the retreat of the sea, alluvial fans are formed and extend from the northern edge of the Subalpine Molasse to the Swiss Plateau (Upper Freshwater Molasse). A river system from the East delivers mica sand up to the Tabular Jura (Fig. A 28).

Shortly before the end of the Miocene, about 7 million years ago, the

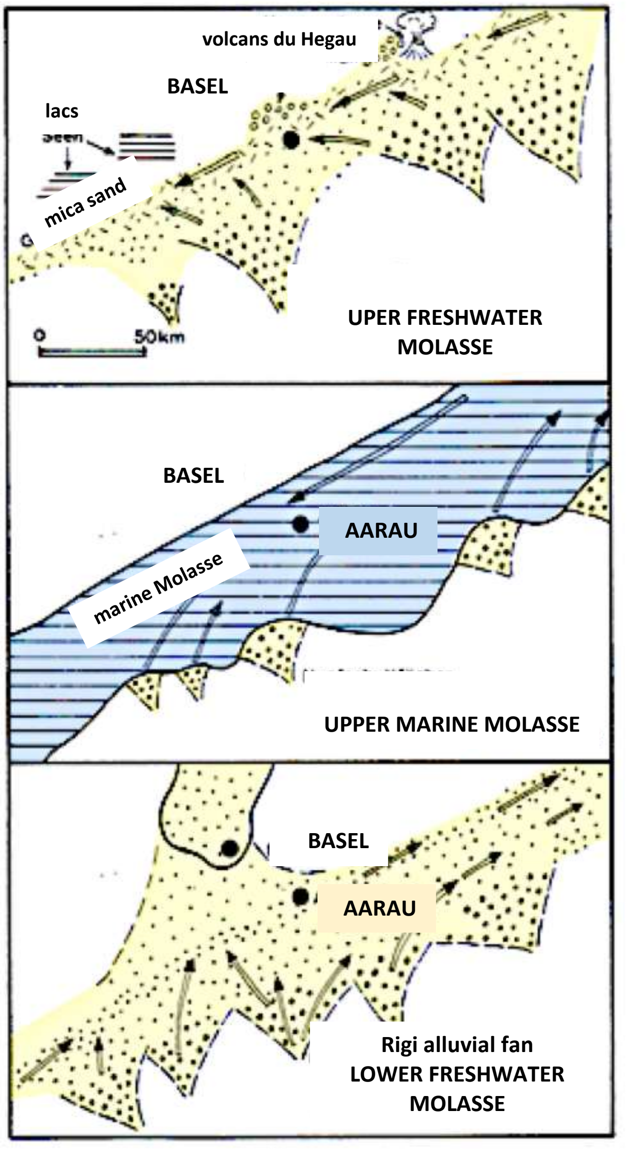


Figure A 23*: Figure A 23: paleogeography of the Molasse Basin from the Middle Oligocene (Lower Freshwater Molasse) to the Late Miocene (Upper Freshwater Molasse, after Trümpy 1980).*

Figure A 24 a: *The Rigi mountain is a tectonic slice of a fluvial fan of the Subalpine Molasse, consisting of a thick sequence of Lower Freshwater Molasse; conglomerate layers ("Nagelfluh") above Vitznau.*
b: *Erratic block of Nagelfluh (origin: Rigi or Rossberg) on the moraine of Reuss Glacier near Mägenwil.*

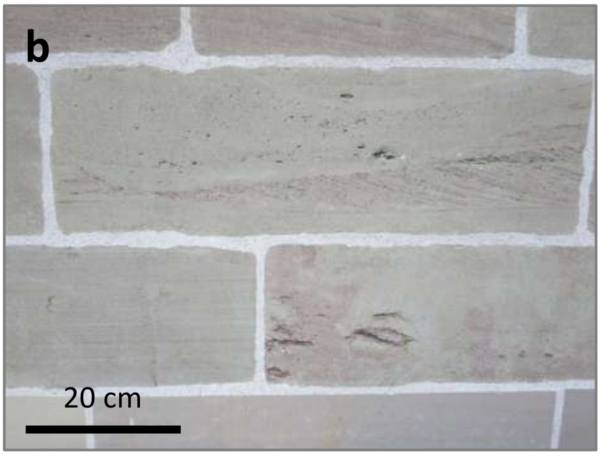
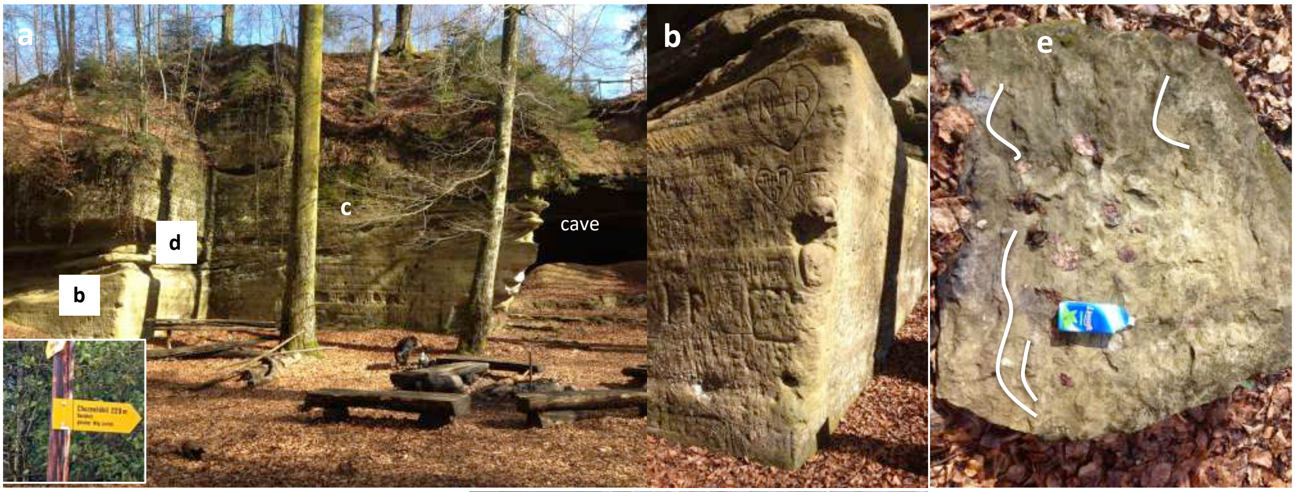
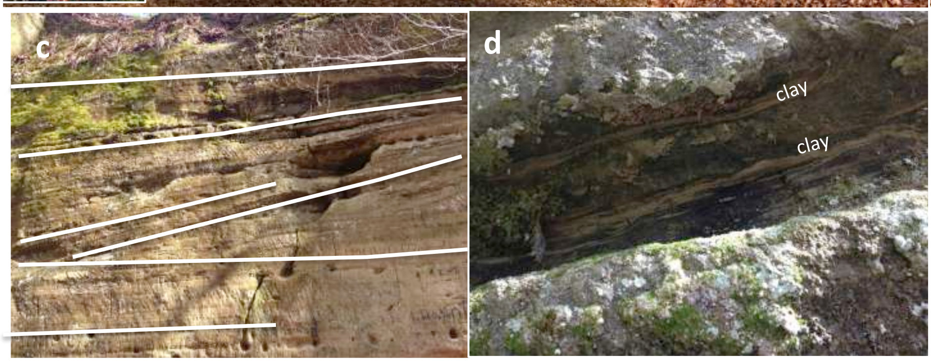


Figure A 25 a: *Sandstones of the Lower Freshwater Molasse in the Roulave Valley west of Geneva; flow channels. The oblique layering gives an idea of the width and depth of the river gullies.* ***b****: Molasse Rouge as a building material of the Cathedral St-Pierre in Geneva.*

sedimentation of the Alpine foreland is completed. This indicates that the morphology is already so pronounced that the rivers transport the eroded material from the Alps directly into the Mediterranean.

In the early Miocene the subtropics are back for a short time. The journey continues to a warm, temperate climate; the well-known site of fossil plants of Oehningen (Lake Constance) characterizes this period (Fig. A 28). Then, during the Pliocene, the temperature gradually drops until the cold Pleistocene.





a: *Quarry and picnic area, "Chuzenhöhle" ("Owl Caves").* ***b***: *In the quarry, area for the exploitation of Molasse sandstone in large benches.* ***c***: *Filling of a tidal channel in the Molasse Sea; oblique stratifications.* ***d***: *Detail of the oblique stratification with intercalations of clay layers marking current-free moments. Sandstones are more resistant to weathering and form a positive relief.* ***e***: *Current ripples on the underside of a Molasse block.*

Figure A 26: *"Chuzenhöhle" quarries in the Upper Marine Molasse near Zofingen.*

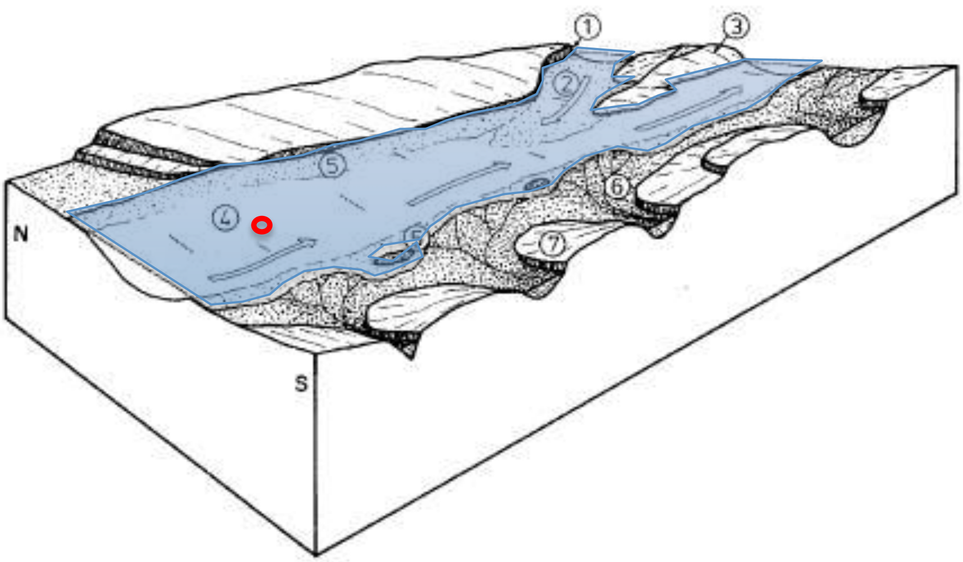


Figure A 27: *Shallow sea of the Upper Marine Molasse at the time of the Muschel-Sandstone (Burdigalian); Swiss Plateau east of the Rhine Valley. 1) steep coast (cliff), 2) coarse sand from a source area located in the East, 3) Albstein swell, 4) red circle: the approximate position of Zofingen 5) beach, 6) Alpine fluvial fan, 7) Alpine front; (W.H. Müller et al. 1984, Fig. 60, slightly modified).*

Figure A 28: *The landscape of Oehningen at the time of deposition of the Upper Freshwater Molasse (Oswald Heer, 1883).*

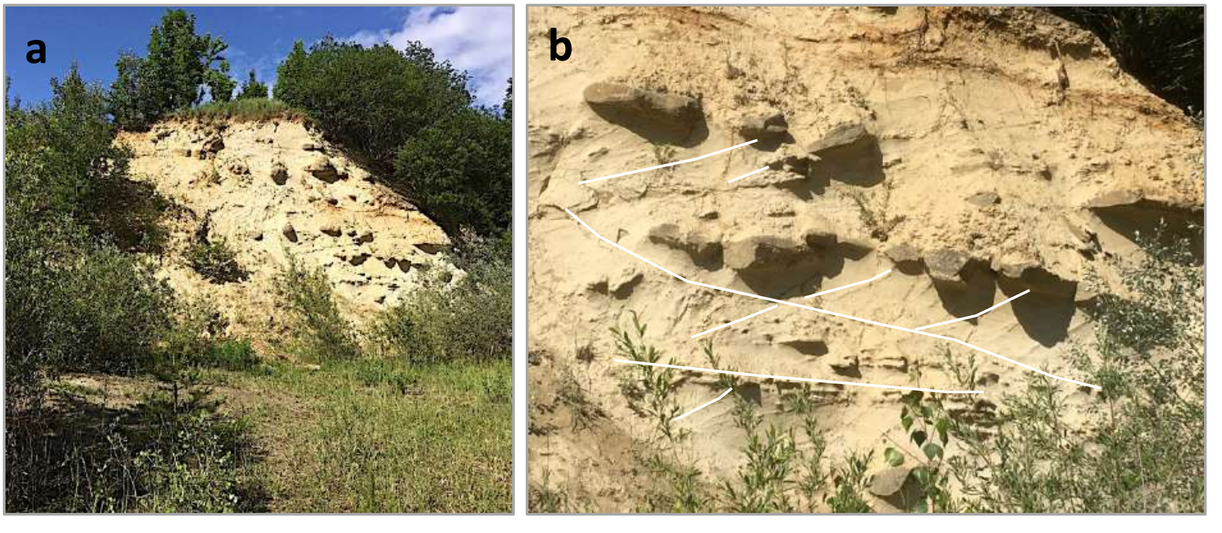


***Figure A 29**: **a:** Mica sandstone on the northern mining wall of the Schüracher pit, Iberg (Upper Miocene, Coo 47.46834/8.11514) The fine sands were used as aggregate in the Frick clay works.*
***b:** Detail with inclined layers from the meandering river channels at the time of deposition of the mica sands. The hard, protruding sections (so-called "Knauern") are cemented. White lines underline the stratification (Wildi & Lambert 2019).*

On the territory of Switzerland, the Palaeogene and Neogene of the Southern Alps are hardly comparable with the northern side of the Alps. While the erosion debris of the rising Alps are deposited in the northern Alpine foreland, whether in the estuary extending from the Mediterranean to the Vienna Basin, or on the huge alluvial fans of the rivers flowing from the Alps, the rivers on the southern side of the Alps wash the erosion material directly into the Po-basin in northern Italy. The thick clay deposits of the Oligocene Chiasso-Formations are overlain by coarse conglomerates, marls and sandstones of the Miocene "Gonfolites".

Towards the end of the Neogene, around 10 million years in the late Miocene, an almost unimaginable event occurs: the Strait of Gibraltar closes and the Mediterranean Sea finds itself isolated from the world oceans. The rivers flowing into the Mediterranean are not sufficient to compensate the evaporation of the seawater. Thus, the Mediterranean dries up and salt is deposited in deep basins ("salinity crisis of the Messinian"). During this period, the rivers flowing into the sea dig deep canyons. The deepest river valleys reach the southern Ticino from the Po Basin. Coarse river deposits (Pontegana-Conglomerate) are correlated with this event. When the Strait of Gibraltar reopens during **Pliocene** and the Mediterranean Sea rises again, clays with a rich marine fauna are deposited near Balerna (Chiasso). These are the most recent marine deposits in Switzerland.

Geological hiking tours:

16. Erosion of the early alpine mountain chain: Rigi fluvial fan (Subalpine Molasse)
17. The last alpine foreland sea: the Upper Marine Molasse
18. Witnesses of the folding of the Alps and alpine nappes
19. The Folded Jura Mountains: last expression of the alpine folding

8. Pleistocene - the ice age (2.6 million - 11'700 years)

Preface

Great cold periods occur in the Precambrian, about 750 million years ago, in the Palaeozoic between 460 and 440 (Ordovician) and 345 to 280 million years (Late Carboniferous and Early Permian) and in the Pleistocene (Quaternary), from 2.6 million years onwards. Particularly during the second half of the Pleistocene, several extreme cold periods, so-called ice ages, occurred, with large extensions of the ice masses at the poles, in the Alps and other mountain chains. These ice ages are interrupted by shorter, warm periods, the interglacial periods. Today, or rather for 11'700 years, we have been living in such an interglacial period, the Holocene.

The discovery of the ice ages, in the second half of the 19th century, was based on the observation of glacial deposits, especially erratic boulders, far from today's glaciers, whether in the Alpine foreland, in northern Europe, or in North America. On the continents, however, the reconstruction of an exact chronology of these glaciations proved to be difficult. A solution to decipher the global climate history was provided in the 1950s and 1960s by the work of two researchers, C. Emiliani and N. J. Shackleton, who linked the composition of oxygen isotopes in the shells of foraminiferous shells embedded in oceanic sediments with the fluctuations of ice masses on the continents and water temperatures in the oceans. Since then, it has been possible to link large and small fluctuations in ice masses worldwide; the isotope fluctuations in oceanic sediments are regarded as a reference for the global climate history of the last millions of years of the Earth's history. However, the correlation of the findings in the oceans with the moraine levels in the Alpine foreland remains difficult.

Ice ages

At the end of the paroxysm of the folding of the Alps and the Jura in the Pliocene, Switzerland is characterized by a relatively balanced relief on both sides of the Alps; the deepening of the valleys occurs during the Pleistocene, through the action of the glaciers. Today's landscapes are largely the result of the action of these glaciers during the Pleistocene.

However, our understanding of the history of the ice ages in the Alps and the Alpine foreland is still very patchy. In their pioneering work, Penck and Brückner (1901/1909) identified four major ice ages in eastern and northern Switzerland, based on the type of localities of the Bavarian Alpine foreland, which they called the Günz, Mindel, Riss- and Würmeis periods:

- They attributed the formation of the highest gravel beds in the glacier foreland, the Upper cover gravel *(“Höhere Deckenschotter”),* to the oldest glaciation, the Günz Ice Age. Today, these gravels are found on the summits of the Swiss Plateau and Jura (Albis, Üetliberg, Irchel, among others).

- They correlated the Mindeleiszeit with the formation of the Lower cover gravel *("Tiefere Deckenschotter*"). These gravels would have been deposited in already slightly deepened valleys.

- According to Penck and Brückner, the following "Riss" ice age corresponds to the largest extension of the glaciers in the Alpine foreland. They attributed the formation of the High-Terrace gravel in the glacier foreland to it. During this ice age, the united Rhone, Aare, Reuss, Limmat and Rhine glaciers would have advanced as far as Möhlin, close to the city of Basel, excavating the deep valleys in the Alps and the Alpine foreland.

- The authors' Würm ice age concludes this story.

The Holocene, i.e. today's warm period, would correspond to the last interglacial period to date.

Two older ice ages later join the cold ages mentioned above, namely the Danube ice age (Eberl 1930) and the Biber ice age (Schaefer 1957).

The history of the Pleistocene ice ages of the Alps and the Alpine foreland suggested by Penck and Brückner is largely based on morphological criteria, such as the relationship between moraines as witnesses of glacial sands and gravel terraces as witnesses of alluvial plains in front of the glaciers. This approach has since been confirmed in many points. On the other hand, our knowledge in other areas of glaciology has been enriched and multiplied since the beginning of the twentieth century. During this period, thousands of boreholes have been drilled, which provide information about the three-dimensional structure of the glacial sedimentary bodies in the former glacial valleys. Palaeontology and palynology (especially pollen in fine-grained sediments) allow the reconstruction of the local climate history. Thanks to the C-14 method, based on the decay of the radioactive C-14 isotope formed in the ionosphere, sediments and the organic remains contained in them can be dated to the last 50'000 years or so. Thermoluminescence and the measurement of the duration of solar exposure of surface rocks allow dating for several 100'000 years. The climate history of the Holocene benefits from dendrochronology, i.e. the growth history of trees. Finally, the history of variations in the Earth's magnetic field preserved in sediments provides valuable temporal clues.

By combining all this information, a more refined picture of the course of ice ages and interglacial periods is obtained. However, even this picture still suffers greatly from the insufficient number and limited precision of dating. Furthermore, the knowledge gained from one locality is often not easily transferable to another region.

In Fig. A 30 we show a possible structure of the ice ages and interglacial periods in northern Switzerland and a correlation with the conditions in the Bavarian Alpine foreland, in northern Germany (edge of the Scandinavian ice masses during the Pleistocene ice ages) and with the oceanic reference curve, based on the fluctuations of the changes in the global ice masses expressed by the oxygen isotopes O-18 again. But even this correlation is still uncertain in many points and will certainly be specified in the coming years.

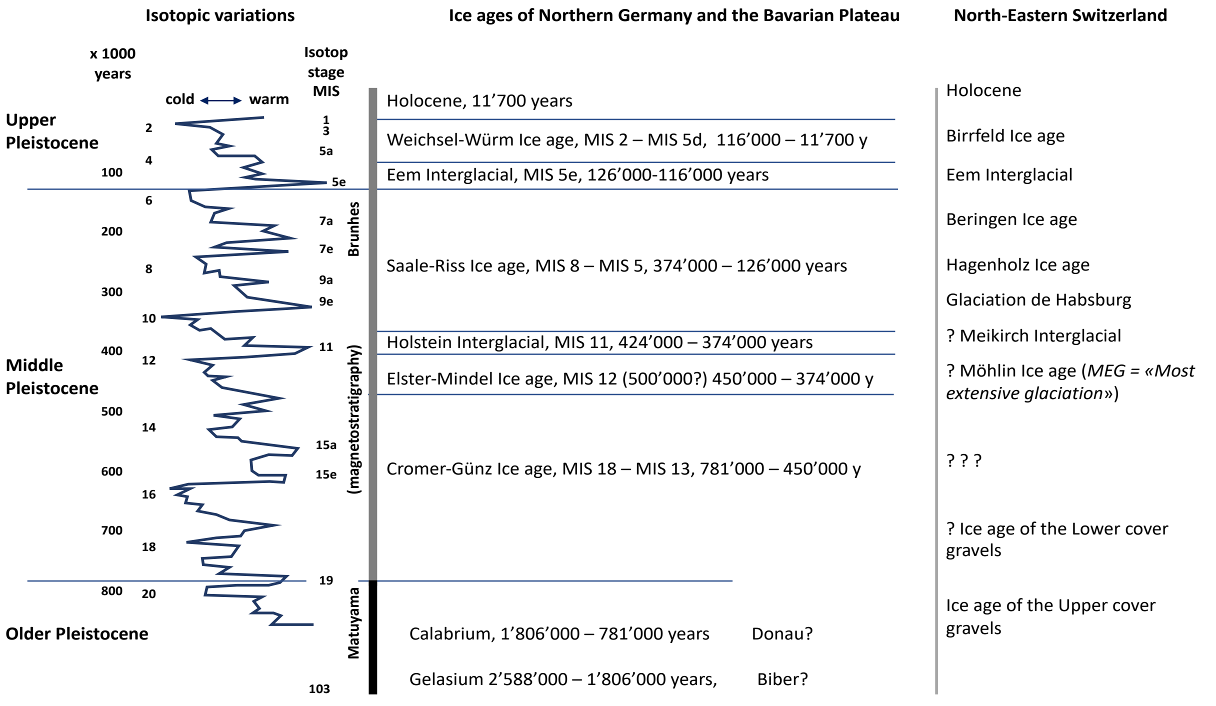


Figure A 30: *Quaternary chronology: an attempt to correlate marine isotope stratigraphy and ice age stratigraphy in northern Germany, the Bavarian Alpine foreland and north-eastern Switzerland. (Northern Germany - Bavarian Alpine Foreland: http://www.dandebat.dk/eng-klima5.htm, Stratigraphic Table of Germany 2016, Northern Switzerland: Preusser et al. 2011, fig. 19, Schmincke et al. 2008, fig.20.20).*

As mentioned above, the Upper cover gravels occupy the highest hilltops in north-eastern Switzerland, from the Albis over the Üetliberg in the Swiss Plateau, to the Mandacher heights and the Studenland in the Tabular Jura (Fig. 31), the Egg near Oberweningen, and the Irchel between the Töss and Rhine valleys. Research work over the last three decades has made it possible to get a better understanding of this complex geological formation (Graf 1993, 2019, Bollinger et al. 1996), and provides an overview of its current knowledge. Higher cover gravels are formed mainly by glacial moraine, fluvio-glacial gravel and warm age clays. The presence of small mammals on the Irchel mountain indicates it is 1.8 to 2.5 million years old. This age is confirmed by palaeomagnetic data. Thus, the formation is dated as Old Pleistocene.

The Lover cover gravels of the lower Aare valley, the Reuss and Limmat valleys show the progress of the glacial erosion (Fig. 32). These gravels are not dated but are counted as belonging to the late Old Pleistocene or the earliest Middle Pleistocene.

In Western Switzerland, at Ecoteau (Palézieux), at an altitude of 800 m, there are two formations (Lower and Upper Ecoteaux-Formation; Fig. A 33) of lake sediments, which are separated by a level of glacial ground moraine. The Lower Ecoteaux-Formation also lies on a ground moraine. The lake sediments having pollen indicates the climate there is cool ("boreal", Scandinavian). The sediments show an inverse magnetization and are therefore

Figure A 31: *Upper cover gravel ("Höhere Deckenschotter"), river sediments cemented into a conglomerate, on the Schneisingen Mountain, "Studenland" (Coo 47.52313/8.35153).*

Figure A 32 a*: Mysteriously folded sedimentary package in the Lower cover gravel ("Tiefere Deckenschotter") of the Bruggerberg (glacial deformation? Coo 47.49733/8.22138).* ***b****: Towers of cemented "Tiefere Deckenschotter" gravel in the locality "Tüfels-Chäller" (Baregg near Baden, Coo 47.46318/8.30142), photos: A. Lambert, Baden (Wildi & Lambert 2019).*

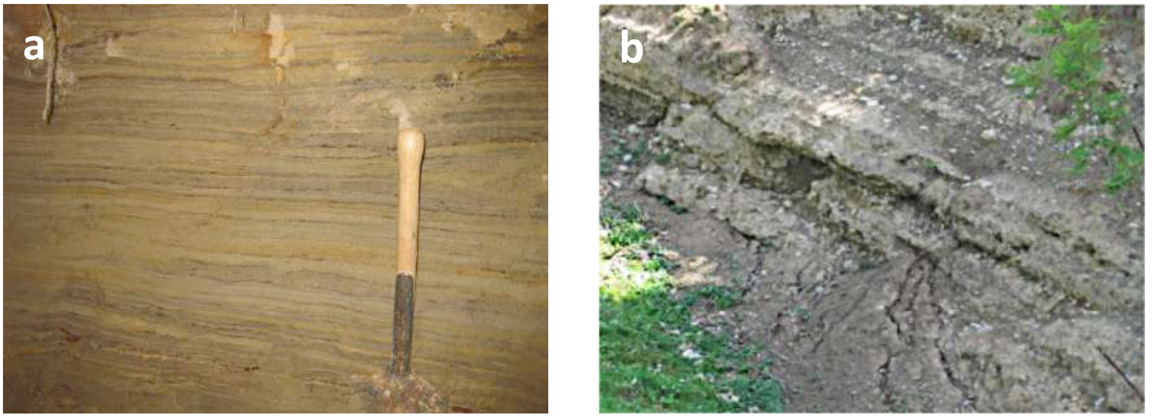


***Figure A 33 a**: Fine lake sediments rich in plant remains, Upper Ecoteaux-Formation.*
***b:** Delta deposits above Ecoteaux (Pugin et al. 1993).*

older than 781'000 or 801'000 years, according to the authors; they belong to the Old Pleistocene. This may have been the first basin of the later Lake Geneva. The Upper Ecoteaux-Formation is rich in organic remains and was formed in a warm, almost Mediterranean climate. In the pollen spectrum, winged nuts (Pterocarya), ash, elm, alder, hazelnut, hornbeam, lime, oak and yew stand out. They could stem from the Holstein interglacial (the "Pterocarya interglacial"), 424'000 - 374'000 years ago.

During the Möhlin Ice Age of the Middle Pleistocene (“Riss Ice Age” of Penck & Brückner), the Rhone, Aare, Reuss and Rhine-Linth glaciers merge (Preusser et al. 2009). This united ice stream advances as far as Möhlin in the Rhine valley close to the city of Basel (Fig. A 34, 35). Here is the outermost moraine ring of all ice ages. At the time of maximum advance, the ice in the Folded Jura chain in Canton Aargau reaches a height of more than 800 m above sea level. It flows over the passes of Salhöchi, Bänkerjoch and Staffelegg. On the Swiss Plateau, even the Lindenberg (878 m altitude) is covered by ice.

The different ice ages of the Middle Pleistocene (Fig. A 30, 35) are difficult to distinguish in the landscape. The gravel terraces at the valley margins are called High Terrace Gravel; often there are also small deltas (kames) at the glacier margin. The moraine walls, which denote longer periods of stagnant glaciers, are weathered and rounded by erosion. In the Rhine and Aare valleys, such lines of glacier stagnation can be found near the towns and villages of Laufenburg, Koblenz, Wislikofen, Ruckfeld, Siggenthal and Schinznach.

Figure A 34: *Moraine and terrace landscape of Möhlin in the Rhine Vallex upstream Basel. View from Schönegg over the village of Wallbach and the Rhine valley towards the North. The gentle morphology on the left side corresponds to the terminal moraine wall of the Möhlin ice age of the Middle Pleistocene (Wildi & Lambert 2019, Fig. 82).*

On the heights of the Swiss Plateau and the Jura Mountains, the Middle Pleistocene ice ages have left a layer of ground moraine (till) with boulders (Fig. A 36). Important morphologies are valleys washed out by the meltwater, as well as rounded “Molasse humps”, the rock drumlins (e.g. Staufberg and Schlossberg near Lenzburg).

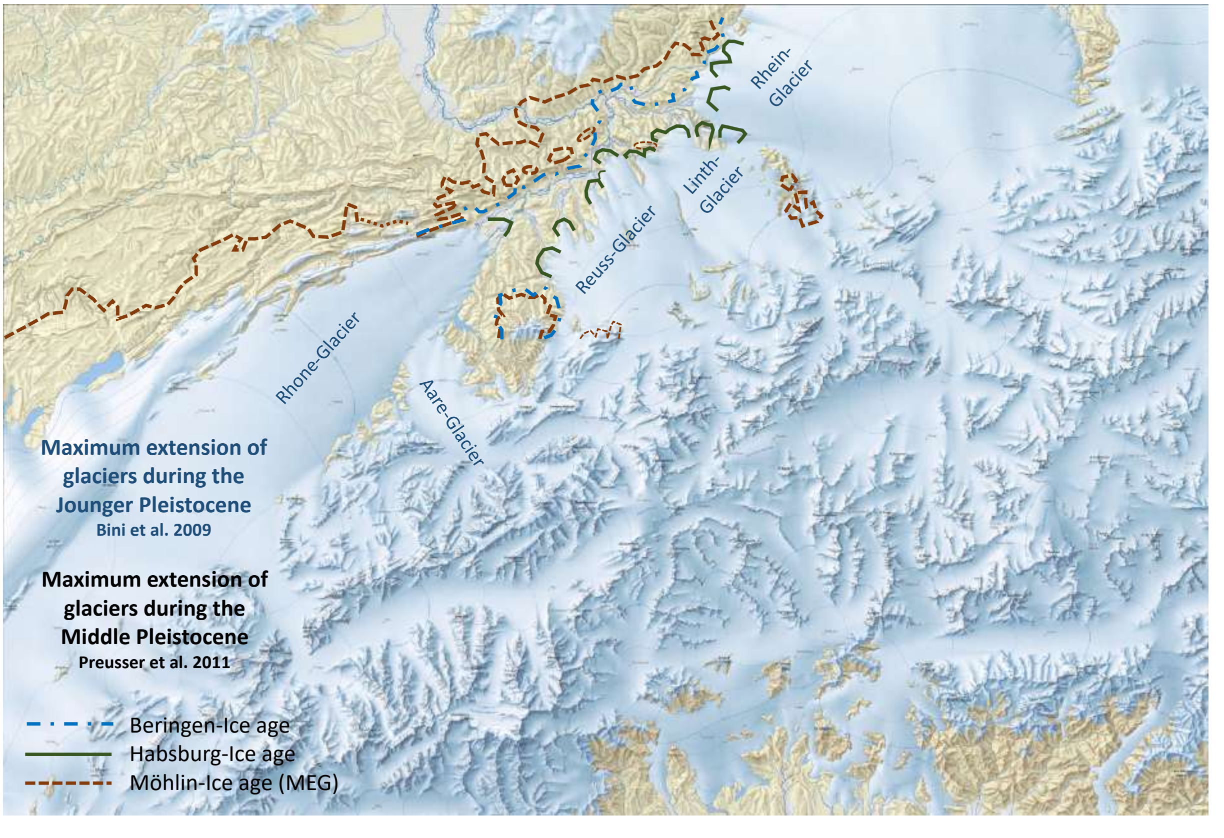


Figure A 35*: Maximum extent of alpine glaciers during the Middle and Late Pleistocene. Middle Pleistocene: Preusser et al. 2009, Penck & Brückner 1901/1909); Upper Pleistocene: Bini et al. 2009 (copyright swisstopo). The map does not distinguish between the different cold phases of the last ice age.*

Figure A 36: *Erratic block of the Rhone Glacier ("Honeystone") from the Middle Pleistocene on top of a Molasse hill near Roggliswil (Kt. Luzern, Coo 47.20606, 7.88272).*

The time between the Middle Pleistocene and the Late Pleistocene corresponds to the Eemian interglacial period. This is documented at several sites by sediments mostly rich in organic material, witnessing a warm climate. The Eemian warm period was somewhat warmer than the Holocene.

The last ice age up till now, the Würm- or Birrfeld ice age (Preusser et al. 2011), is better known as its predecessors. Its sequence of events can be described in the northern hemisphere as follows:

- 122'000 years BP*, the glaciers at the poles and in the mountains grow strongly.
- After a long period of glacier fluctuations, the first maximum expansion of the glaciers is reached around 70'000 BP. It lasts until 60'000 or 55'000 BP.
- The history continues with glacier fluctuations, but smaller ice volumes than during the first glacier maximum.
- 35'000-30'000 BP the second period of maximum ice extent begins. It lasts until 23'000 or 22'000 BP and the last advance is dated around 20'000 BP. The so-called LGM (last glacier maximum) does not bear the same date everywhere but can be dated between 27'000 and 21'000 BP (Seguinot et al. 2018).
- Then the glaciers melt, interrupted by short cold periods. The two most important pauses in this glacier retreat are around 16'800 and 12'700BP. They correspond to so-called "Heinrich events": during these events, temperatures around the world drop sharply. The cause of this climate shock has been identified as the outflow of huge water masses from glacial lakes in the Great Lakes region of North America.

* BP: before present, refers to the age determined by radioactive carbon-14 ("radiocarbon"). The reference year is 1950, after which the concentration of carbon-14 has been falsified by nuclear weapon tests and nuclear power plants.

- The end of the last ice age in the Alpine region is officially 11’700 years ago. This date is considered as the beginning of the post-glacial period known as the Holocene. Looking beyond Central Europe, it is revealed that the Scandinavian and North American glaciers have been resisting for thousands of years.

In Switzerland, during the Würm or Birrfeld Ice Age, the glaciers advance in several phases into the northern Swiss Plateau. The Rhine Glacier reaches Neuhausen and Eglisau, while the Linth Limmat Glacier reaches Bülach in the Glattal and Killwangen in the Limmattal. The foothills of the Reuss Glacier extend in the Mittelland valleys to Mellingen, Othmarsingen, Seon, Gontenschwil and Staffelbach. The Rhone Glacier reaches Solothurn in the Aare Valley (Fig. A 35) and the gates of the city of Lyon in the Rhone Valley. The melting of the ice flows after the last glacier maximum (LGM) takes place with several stops, leaving a moraine crest at each stop line. In the Reuss valley, these moraine chains from the retreat period are particularly characteristic morphologies (Fig. A 36, 37): upstream the terminal moraine of Mellingen, two stages are found at Stetten and two others at Bremgarten. In contrast to the moraines of the Middle Pleistocene, those of the last ice age are very distinctly preserved in the Late Pleistocene. This also applies to the moraine walls formed on the sides of the glaciers.

The Rhone Glacier remains during its last maximum expansion phase within the Geneva Basin. According to Seguinot et al. (2018), this maximum is dated 27’000 years BP (Fig. A 38). Then, Rhone and Arve glaciers melt back and leave behind an extensive glacial lake, Lake Geneva.

Figure A 37: *Drumlin landscape from the border area of the Reuss and Limmat glaciers of the last ice age in Schwand (Menzingen, Canton Zug, Wildi 2017).*

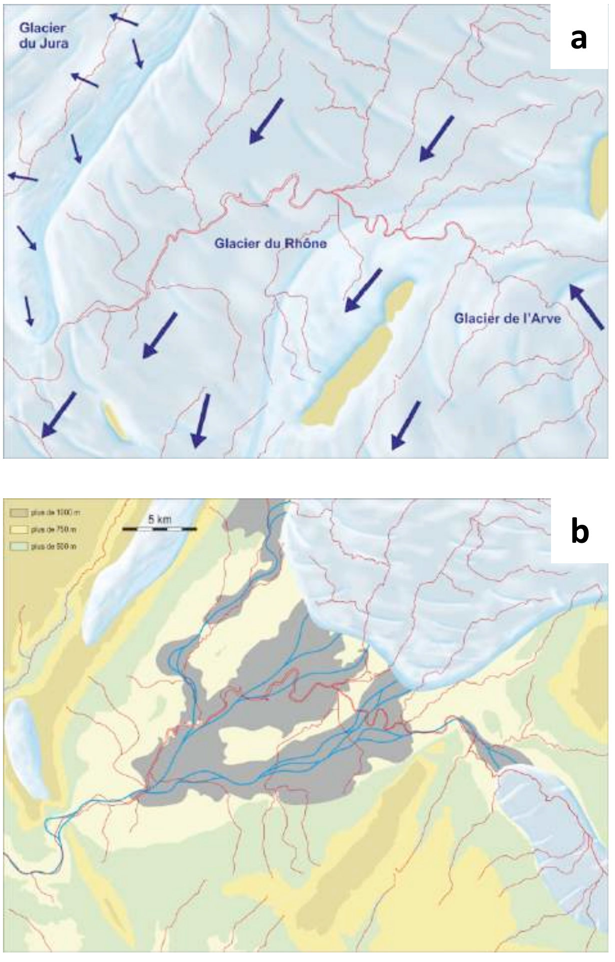


Figure A 38: Major phases of Rhone and Arve glaciers during the last ice age in the Geneva Basin.

a) First maximum extent of the Rhone and Arve Glacier 60'000 to 70'000 years ago (see also Figure A 35).

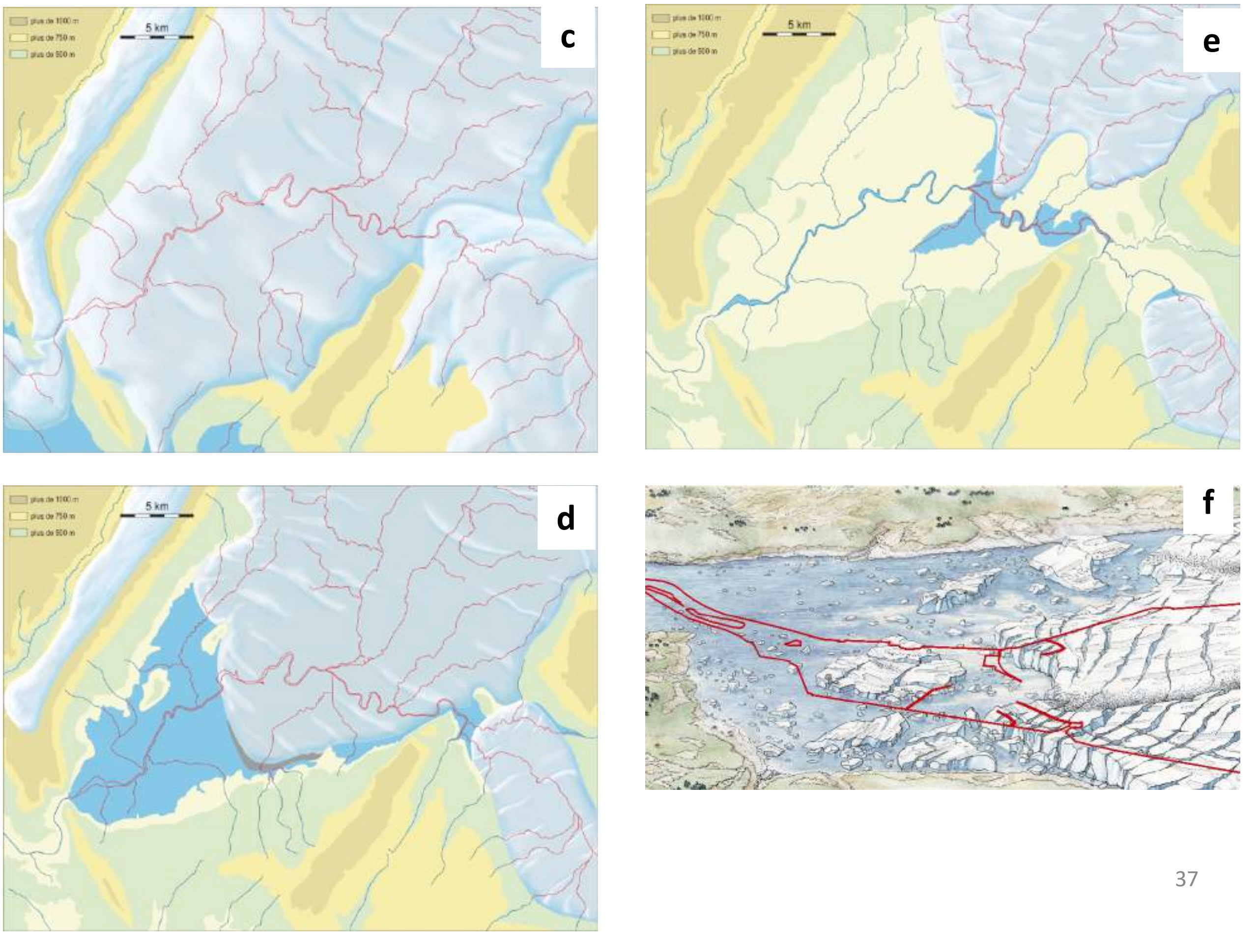
b) Situation 35'000-38'000 years ago: melting of Rhone Glacier. In the external Geneva Basin, the river plain of the "Alluvion Ancienne" extends (in grey, dated by 14C).

c) Situation about 27'000 years ago: Last maximum extent of glaciers in the Geneva Basin.

d) Approx. 25'000 years: Stadium of Laconnex and glacial lake until the breakthrough of the Jura at Fort de l'Ecluse, lake level at 470 m)

e & f) 22'500 years: Stadium of Geneva (dated by C14), lake level at 405 m.

(Red lines: present lake level, river network; after Wildi et al. 2017, modified)



The landscapes of Switzerland are strongly influenced by the Würm or Birrfeld Ice Age (Fig. A 39). The most important morphological witnesses are moraines, drumlins, erratic blocks, ponds in former dead ice holes and, in the main valleys, a system of gravel terraces, the so-called Low Terrace Gravel. Outside the glaciated areas, on the summits of the Swiss Plateau and in the Jura Mountains, the landscape also bears the marks of the ice age: under the influence of permafrost, the slopes, which had remained quiet since the Middle Pleistocene, begin to move in many places. The valleys occupied by the glaciers are deeply excavated and over-deepened by them. As the glaciers retreat, a glacial lake remains in each of these valleys. This lake is often filled first with moraine material, then partly with fine lake sediments. All lakes on the edge of the Alps, whether in the South or North of the Alps, are such former glacial lakes. At that time, many slopes in alpine valleys get unstable and landslides occur in many places.

Geological hiking tours:
20. “Deckenschotter”: the gravel terraces of the early ice ages
21. Ecoteaux: traces of the first Lake Geneva 800,000 years ago
22. Glacier morphologies in the Swiss Plateau
23. Climate change, glaciers and landscapes

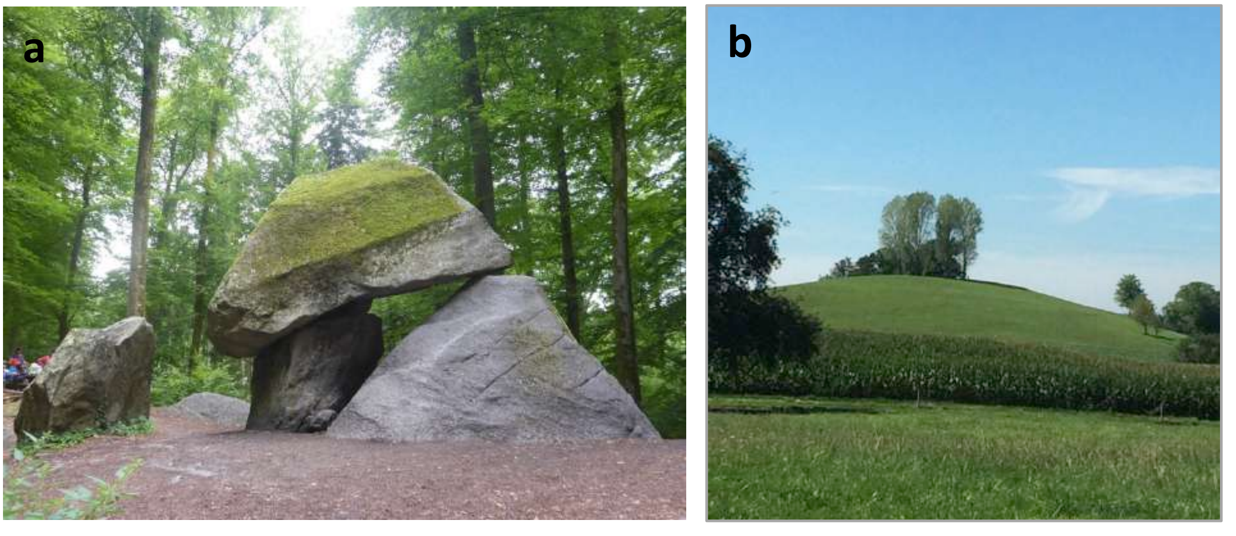


Figure A 39 a: *Erratiques blocs on the moraines of the last maximum extension of the Reuss Glacier (LGM): Erdmannlistein (granite block) in the Wohlener Forest (Wildi & Lambert 2019).* ***b:*** *Drumlin of the Würm- or Birrfeldeiszeit; moraine crest of Mellingen (Boll, Fislisbach, Coo 47.43211/8.28243).*

9. "Late Glacial": climate change and melting of alpine glaciers from the Pleistocene to the Holocene

The transition from the last maximum (LGM) of the Würm or Birrfeld Ice Age to the Holocene takes about 8’000 years, from 20’000 BP to 11’700 BP. During this period, the Earth's atmosphere warms by about 10°C, the glaciers melt back and the level of the oceans rises by 135m. These are remarkable figures. However, they do not show that these changes that took place are irregular, and are also interrupted by massive counter-movements. To illustrate this, Fig. A 40 shows the temperature trend in Greenland: the temperature rises only slightly at first, and then is interrupted by shortfalls. From about 14'500 BP on, a real temperature jump occurs, which leads to the warm periods called Bölling and Alleröd. During this time, current temperatures are reached for a short time. From 12'700 to 11'600 BP, there is an abrupt regression into a cold period, only slightly less severe than the last ice age: the so-called Younger Dryas, named after a small flower (Dryas octopetala) which can be found today in the forefield of the glaciers.

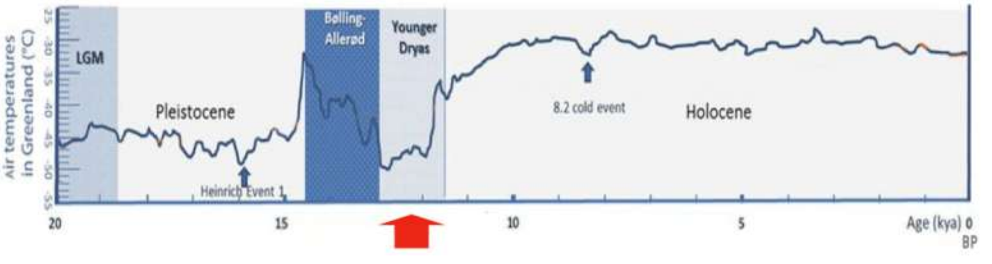


Figure A 40: *Development of temperatures in southern Greenland from the last maximum (LGM) of the Würm or Birrfeld Ice Age to the present day. (https://en.wikipedia.org/wiki/Younger_Dryas#/media/File:Evolution_of_temperature_in_the_Post-Glacial_period_according_to_Greenland_ice_cores_(Younger_Dryas).jpg).*

The drop in temperature that initiates the Dryas happens in the northern hemisphere in less than ten years, perhaps even less. The ice retreat stops, glaciers even advance again slightly and then stagnate. The vegetation is adapting quickly to the situation: where pine forests once grew, as in Scandinavia, cold steppe returns with steppe grass. Loess sand covers large areas and permafrost spreads.

The hypotheses which try to explain the eruption of this cold period range from volcanism to the impact of a large meteorite. The most credible hypothesis is that the Gulf Stream in the North Atlantic is held back by the outflow of huge masses of cold water from Lake Agassi and thus no longer influences the climate of the North Atlantic. Lake Agassi corresponds to the glacial lake which remained in the Great Lakes region before the front of the melting Laurentian ice sheet. 12'700 years ago, when the last ice bar in Hudson Bay melts away, it erupts abruptly and spills into the North Atlantic.

In the southern hemisphere, the Dryas period is characterized by smaller temperature deviations than in the northern hemisphere. This is probably a further indication that the

Dryas was initiated by an event triggered in the northern hemisphere. In Switzerland, the Younger Dryas has left impressive moraines in many alpine valleys, such as those described at the hamlet of Luette in Val d'Hérens (Valais, Fig. A 41, Wildi et al. 2015).

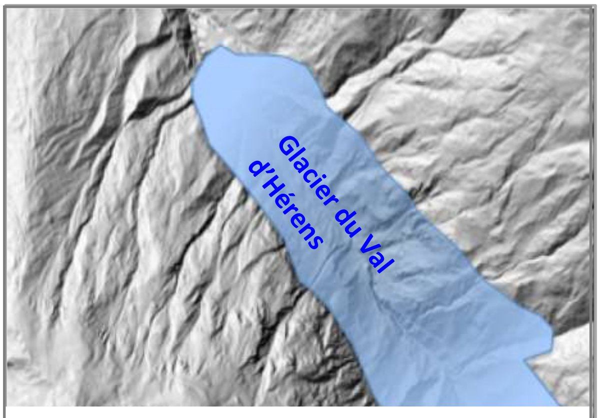


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Figure A 41: *Dryas moraine of the Luette glacial stadium in Val d'Hérens (Valais) and reconstruction of the glacial lake after the renewed melting of the glacier at the end of the Dryas cold period.*

10. Holocene, the post-glacial period (since 11'700 years)

The post-glacial period (Holocene) began 11'700 years ago. The temperature profile of this period appears quite regular in comparison to the Late Glacial described above, but in human terms, it is still quite unstable. The warmest period of the Holocene, which can easily be reconstructed from pollen in lake sediments, occurs between 8'000 and 5'000 BP; this is known as the "Holocene climate optimum". Temperatures then show a decreasing trend but in a wavy line of slightly warmer and slightly cooler periods. After a last warm period during the Roman period and the High Middle Ages, the climate gradually cools down from the 13th century onwards. From the early 16th century onwards there is a strong increase in glaciers. This corresponds to the beginning of the coldest post-glacial period to date, the so-called "Little Ice Age". Around the year 1660, the Alpine glaciers reach their first maximum, in which the alpine glacier tongues often advance by about 1.5 to 2 km. Such glacier levels are well documented in Switzerland from the Engadine (e.g. Morteratsch Glacier) to the Bernese Oberland (Grindelwald Glacier) and the Valais (Rhône Glacier) and the neighbouring "Mer de Glace" in the Mont Blanc massif (France).

Literature mentions strong volcanism, reforestation in Europe, reduced solar activity, changes in the earth's orbit around the sun, and many others as the causes of Little Ice Age. Of these hypotheses, that of weaker solar activity is best documented.

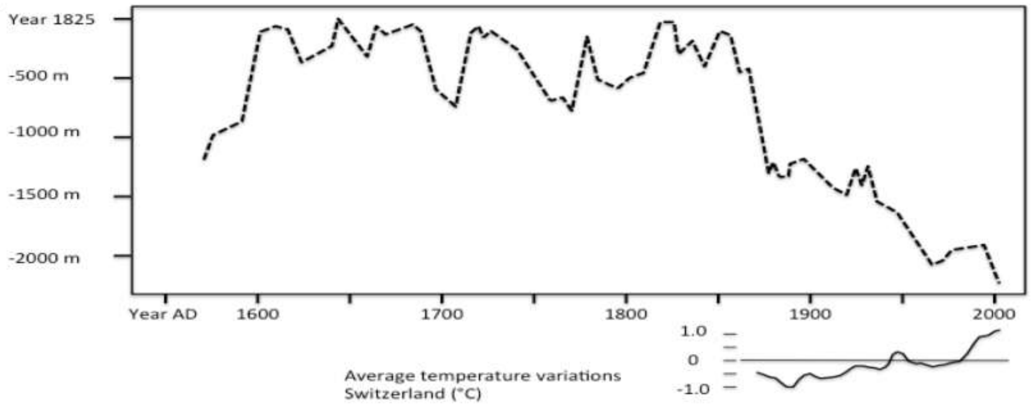


Figure A 42: *Fluctuations of the glacier tongue of the "Mer de Glace" (Chamonix, Mont Blanc) between 1550 and 2001 (Nussbaumer et al. 2007, interpolation). The reference point for 1825 corresponds to an erratic block (boulder). Lower curve: Temperature development in Switzerland (meteoswiss.admin); reference period: 1961-1990.*

Since the end of the Little Ice Age in 1852, the glacier tongues are melting back in a stair-like movement: periods of rapid ice retreat alternate with periods of stagnation. After a period of stagnation from around 1960 to 1990, the glaciers have been melting rapidly ever since (Fig. A 42, 43). However, they have not yet reached their withdrawn position of the High Middle Ages. At that time the timberline in the Alps was about 200 m higher than today.

Presentation by Bühlmann 1835, Graphische Sammlung ETHZ

Mont Mine-Glacier in 1900, Dumoulin et al. (2010).

Ferpecle-Glacier and Dent Blanche in 1910, Dumoulin et al. (2010)

Mont Miné-Glacier 1931, © Collection Gesellschaft für ökologische Forschung, München

Mont Miné-Glacier 1990, photo E. Reynard

Mont Miné-Glacier 2003, © Collection Gesellschaft für ökologische Forschung, München

Glaciers de Ferpècle et du Mont Miné, 2012, photo P. Masset

Figure A 43: *History of the glaciers of Mont Miné and Ferpècle (Val d'Hérens, Valais) from the Little Ice Age to 2012 (Wildi et al. 2016).*

11. Human colonization

In Switzerland, the traces of the first human presence which were not destroyed by the glaciers date back to the so-called "Moustérien", the middle Palaeolithic period 50'000 to 35'000 years ago. The sites are mainly found in Alpine karst caves, whether in the East (e.g. Wildkirchli in the canton of Appenzell Innerrhoden) or in the West of Switzerland (Tanay Caves, Vouvry in Valais, 35’000 years ago).

The actual colonization began in the late glacial period (Late Palaeolithic, Magdalenian). The finds at Lake Monruz (Neuchâtel), around 13'000 BC and the finds at Veyrier (Etrembière, Geneva) around 13'000 - 11'000 BC date from this period (Fig. A 44)..

Abbildung A 44: *" Abris sous bloc" und "Abris sous roche" on the northern slope of Mount Salève (Etrembière, Geneva) dated as Magdalenian (http://www.la-memoire-de-veyrier.ch/420281743).*

12. "Landslide and human lives»

The title "landslide and human life" corresponds to a popular book by the geologist Albert Heim. At least 6% of Switzerland's surface is located in areas with unstable subsoil. Major landslides occurred mainly at the end of the last ice age (landslide of Sierre, Valais; landslide of Flims, Grisons) and also during the Holocene.

Prehistoric landslides in Switzerland (https://de.wikipedia.org/wiki/Bergsturz, modified):

- Landslide of Sierre (Valais): about 13'000 years ago, 50 million m^3.
- Flims landslide (Grisons): approx. 12 to 15 km^3, about 10,000 years ago.
- Davos (Grisons): over 0.3 km^3 fell from the Totalp in the Parsenn area, forming the Wolfgang Pass and Lake Davos. Dating: younger than 8000 years.

Figure A 45: *The Elm landslide of 1881, a lithograph by J.J. Hofer (Swiss National Museum, LM-44697) sold for the benefit of the victims.*

List of historical landslides in Switzerland :

- 30 September 1512: Buzza di Biasca landslide in the Valle di Blenio north of Biasca (Ticino). The rock masses dammed up a lake; the dam broke in 1515 and devastated the valley of Ticino up to Lake Maggiore.

- 1714 and 1749: landslides of Derborence (Valais), damming of Lac de Derborence.

- 2 September 1806 landslide of Goldau (Schwyz): an entire village of 40 million m³ of rock was buried here. 457 people died.

- 11 September 1881 Elm (Glarus): ten million cubic metres. The Elm landslide was caused by years of reckless mining of slate. 115 people died.

- April and May 1991 Randa (Valais): 30 million m³.

B. The "System Earth" and its history

1. The geological timescale

The measurement of geological time is not based on a pendulum or the agitation of a clockwork movement, but rather on the succession of events that, throughout the history of the Earth, have recorded the passage of time and left their imprint. The basic methods were developed during the 19th and early 20th centuries and are part of the science known as "stratigraphy" (Decrouez et al. 1997). At the basis of stratigraphy is the observation of the superposition of sedimentary layers and their contents. Each sedimentary layer represents a time interval; a sequence of layers represents a geological period.

Stratigraphic methods based on the study of the sequence of layers are called **lithostratigraphy**. The basic unit of lithostratigraphy is the rock formation.

Sir Charles Lyell (1797-1875), in his famous three-volume “Principles of Geology”, linked the chronological sequence of sedimentary layers to the evolution of fauna and flora. He showed how groups of organisms evolved throughout geological history, that is, how species change by mutation over time and eventually disappear again. The basic unit of this **biostratigraphy** is the biozone, based on the appearance, presence and extinction of species.

Thanks to biostratigraphy, the history of the Earth since the appearance of organisms and their preservation in rocks has been subdivided into long periods, named after typical sites, "stratotypes". In this **chronostratigraphy**, we distinguish the great eras (Paleozoic, Mesozoic, Cenozoic), which are subdivided into periods (e.g. Triassic, Jurassic, Cretaceous), which in turn are subdivided into epochs (e.g. Lias, Dogger Malm) and then stages (Malm: Oxfordian, Kimmeridgian). Chronostratigraphy (Fig. B 1) is used in geology as a reference scale for geological history.

Geochronology developed during the 20th century. Its purpose is to date geological objects (minerals, rock layers, etc.) in calendar years. The most commonly used method is based on measuring the concentration of radioactive isotopes that are trapped in a mineral, plant residue, etc., and that have undergone radioactive decay since their confinement, according to the decay period (half-life) of the isotope (determination of radiometric age). The most commonly used isotopes are as follows:

^{238}U -> ^{206}Pb; half-life = 4.25 x 10^9 years (from zircon, sphene, etc.)

^{40}K -> ^{40}Ar half-life = 1.3 x 10^9 years (from mica, hornblende)

^{87}Rb -> ^{87}Sr half-life = 6.1 x 10^{10} years (from mica, glauconite, total rock)

^{14}C -> ^{14}N half-life = 5630 years (organic residues: wood, plants, leather, fabrics)

Radiometric dating has the advantage of providing us with numerical estimates of the ages we believe we understand. However, radiometric ages are always subject to errors, whether due to the poor preservation of dated objects, the accuracy of measuring instruments, or the care taken in laboratory analysis.

In the case of the **radiocarbon** (^{14}C) method, another difficulty arises from the fact that this isotope is formed in varying quantities in the ionosphere. The radiocarbon makes it possible to date objects up to an age of about 50’000 years.

The use of **thermoluminescence** as a dating method is based on the fact that the crystal lattices of mineral grains in sediments are disturbed by the radioactivity of radioisotopes trapped within the minerals. The longer a mineral grain is protected from light and sunlight, the more disturbances in the lattice. If a mineral that has been stored underground (buried) for a long time is then mined and heated to 300-500°C, the electrons in its disturbed lattice return to their original position. During this process, they emit light that is proportional to the time the mineral has been underground.

Exposure age dating is based on the formation and accumulation of cosmogenic nuclides on the Earth's surface. Incident cosmic rays produce, for example, ^{3}He, ^{10}Be, ^{l4}C, ^{21}Ne, ^{26}Al and ^{36}Cl. The longer a rock surface is exposed (exposure time), the more these isotopes accumulate. The maximum dating age is about 5'000'000 years.

Another group of dating methods is based on event sequences (**event stratigraphy**). These include thin sedimentary layers (waves) in glacial lakes, or annual growth rings on tree trunks (dendrochronology).

Figure B 1: *Geological time scale for the last 300 million years of the Earth's history.*

Era	Period	Epoch		Mio Years
Cenozoic	Quaternary	Holocene		0.01
		Pleistocene		2.6
	Neogene	Pliocene		5
		Miocene	Upper	
			Middle	
			Lower	23
	Paleogene	Oligocene	Upper	
			Lower	34
		Eocene	Upper	
			Middle	
			Lower	56
		Paleocene		66
Mesozoic	Cretaceous	Upper Cretaceous		
		Lower Cretaceous		145
	Jurassic	Malm		
		Dogger		
		Liassic		201
	Triasssic	Upper Triassic		
		Middle Triassic		
		Lower Triassic		252
Paleozoic	Permian	Upper Permian		
		Lower Permian		299
	Carboniferous	Upper Carboniferous		
		Lower Carboniferous		359

2. Plate tectonics

The theory of plate tectonics dates back to the early 20th century. It is probably reasonable to link its birth to the formulation of Alfred Wegener's theory of continental drift from 1911 and its detailed justification in 1915 in "The Origin of Continents and Oceans" (Vieweg, Braunschweig). Wegener had noticed the complementary contours of the coasts of Africa and South America on both sides of the Atlantic. When he also became aware of the similarity of the Paleozoic fauna and flora of the two continents, he formulated the idea of a large primordial continent from which the different continents would have separated after the Paleozoic.

Figure B 2: *Commemorative plate in honour of Alfred Wegener at his workplace in Marburg (Wikipedia).*

The geological and geophysical basis for plate tectonics was finally compiled between 1960 and 1970 (see the excellent summary in the reference Fig. B 3).

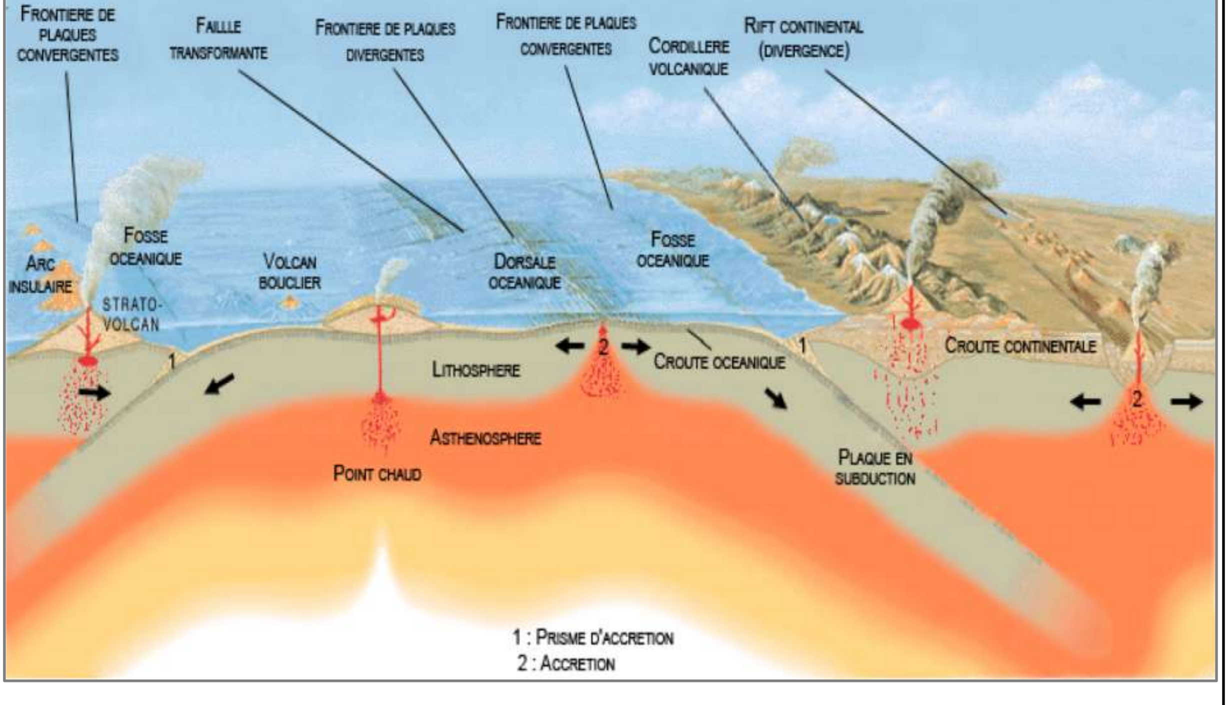


***Figure B 3**: Schematic diagram of plate tectonics (see the excellent compilation: https://fr.wikipedia.org/wiki/Tectonique_des_plaques, https://en.wikipedia.org/wiki/Plate_tectonics).*

The basic elements of plate tectonics are as follows (Fig. B 3) :

- The Earth's plates are moving away from each other on both sides of the mid-ocean ridges. These ridges are volcanic centres where liquid basaltic magma rises and cools to form oceanic crust on the ocean floor.

- New crust created on an oceanic ridge by continental drift is compensated elsewhere by subduction of old oceanic crust that sinks deep beneath another Earth plate in a subduction zone. These subductions can occur under continents (Pacific crust is subducted under the Andes), or under an other oceanic crust (subduction in the Mariana Trench, Java subduction zone). They are also earthquake epicentres.

- Subduction zones are often marked by volcanoes, where the Earth's crust has melted at depth and water and gases are ejected at the surface.

- When two continents meet, the process is called collisions rather than subduction. The formation of the Alps began with the subduction of the oceanic crust of the Alpine Sea and ended with the collision between Africa and Europe.

Plate tectonics has probably existed since the time of the formation of the solid Earth, i.e. the lithosphere, more than four billion years ago. Many authors have contributed in recent decades to the reconstruction of the position of continents and oceans for the period from 541 million years ago to the present, i.e. for the Phanerozoic, for which life on Earth is documented (Fig. B 5).

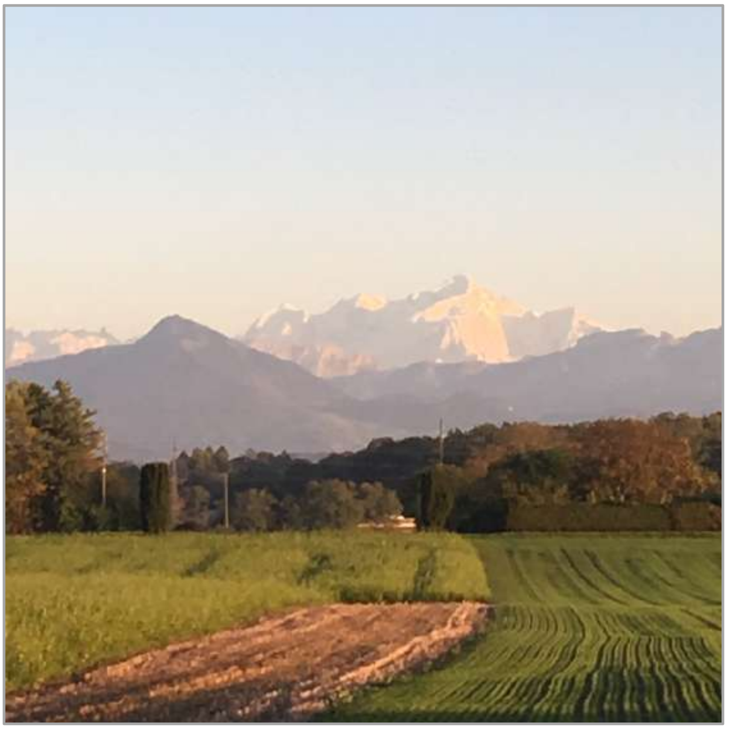


Figure B 4: *The Alps were formed by the collision of Africa and Europe. The uplift up to 4808 m (Mont Blanc) is the consequence of isostasy, i.e. the reaction to the accumulation of several superimposed layers of rocks of lower density than the viscous upper mantle on which they "float".*

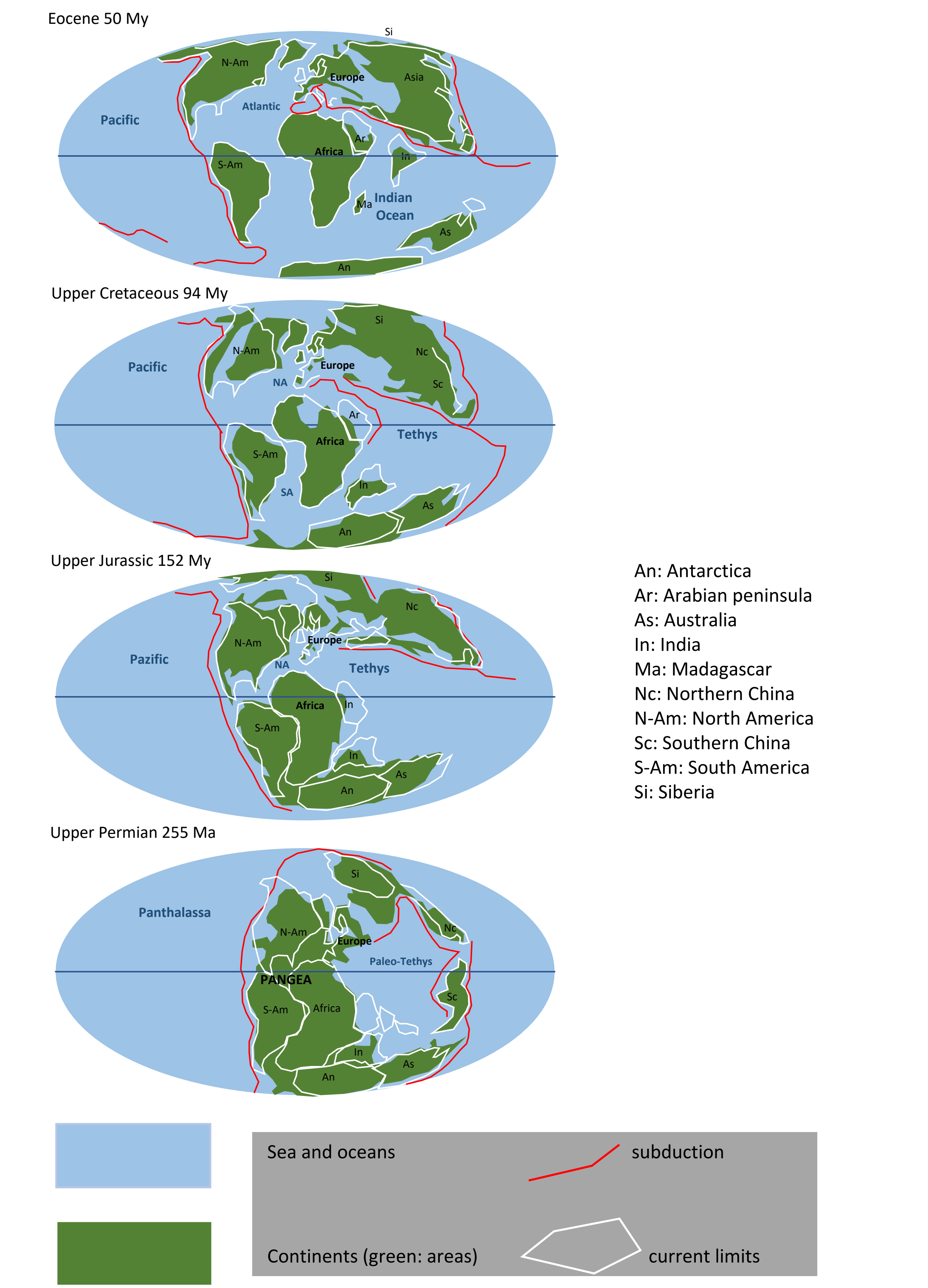


Figure B 5: *Reconstruction of the position of the continental plates from Permian (255 million years) to the Eocene (50 million years). Simplified according to www.scotese.com.*

3. From alpine nappes to paleogeography

The "nappe theory" was born at the turn of the 19th to 20th century. Geologists had observed that in the Alps - and other mountain ranges - layers of ancient rocks often surmounted younger layers with clear contact. They could only explain this phenomenon by the fact that the older layers had been tectonically pushed into this position during the formation of the mountains. Geological mapping has shown that these movements affected rock formations with a lateral extent of several kilometres and a thickness of hundreds of meters, i.e. real "nappes". The geological picture of the Alps that has since been developed proves that the entire Alpine chain is characterized by this architecture: during the collision between Europe and Africa, the sedimentary layers and thick crystalline rock units (gneiss, granite, etc.) of the upper Earth's crust were detached from their substrate by plate tectonic forces and pushed either northwards over the European foreland or southwards over the Adriatic (i.e. African) foreland.

The geological profile in Figure B 6 shows this nappe structure in a cross-section of the Valais Alps. If the sediments and crystalline rocks of the Earth's crust in this profile are to be brought back to their original geographical position before the folding of the Alps, one has to move the nappes towards their homeland further south. The result is a "paleogeographic map", as shown in Figure B 7. However, in this map, the lack of correlation between the sequence of the paleogeographic spaces from North to South and that of the overlapping nappes (e.g. the Middle Penninic nappes in the Prealps) is due to the fact that these nappes were partially separated from their roots at the beginning of the collision between Africa and Europe and slid far to the North under the effect of gravity. Subsequently, they were again caught up by other tectonic units.

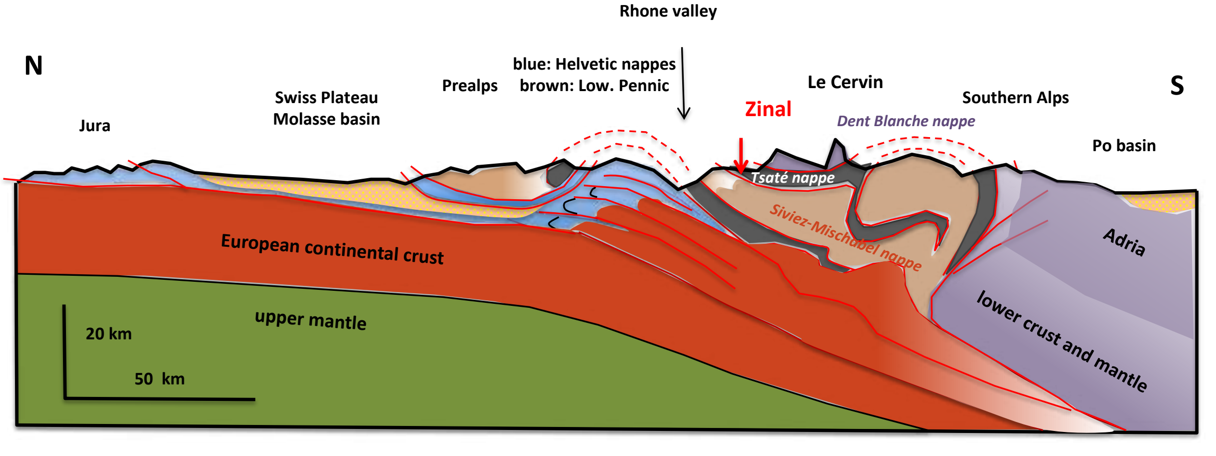


Figure B 6: *Simplified geological section through the Valais Alps and western Switzerland showing the most important geological units (source: Wildi 2017 b and http://cirquedebarrosa.free.fr/formpyr1.htm). Red lines: overthrusts.*

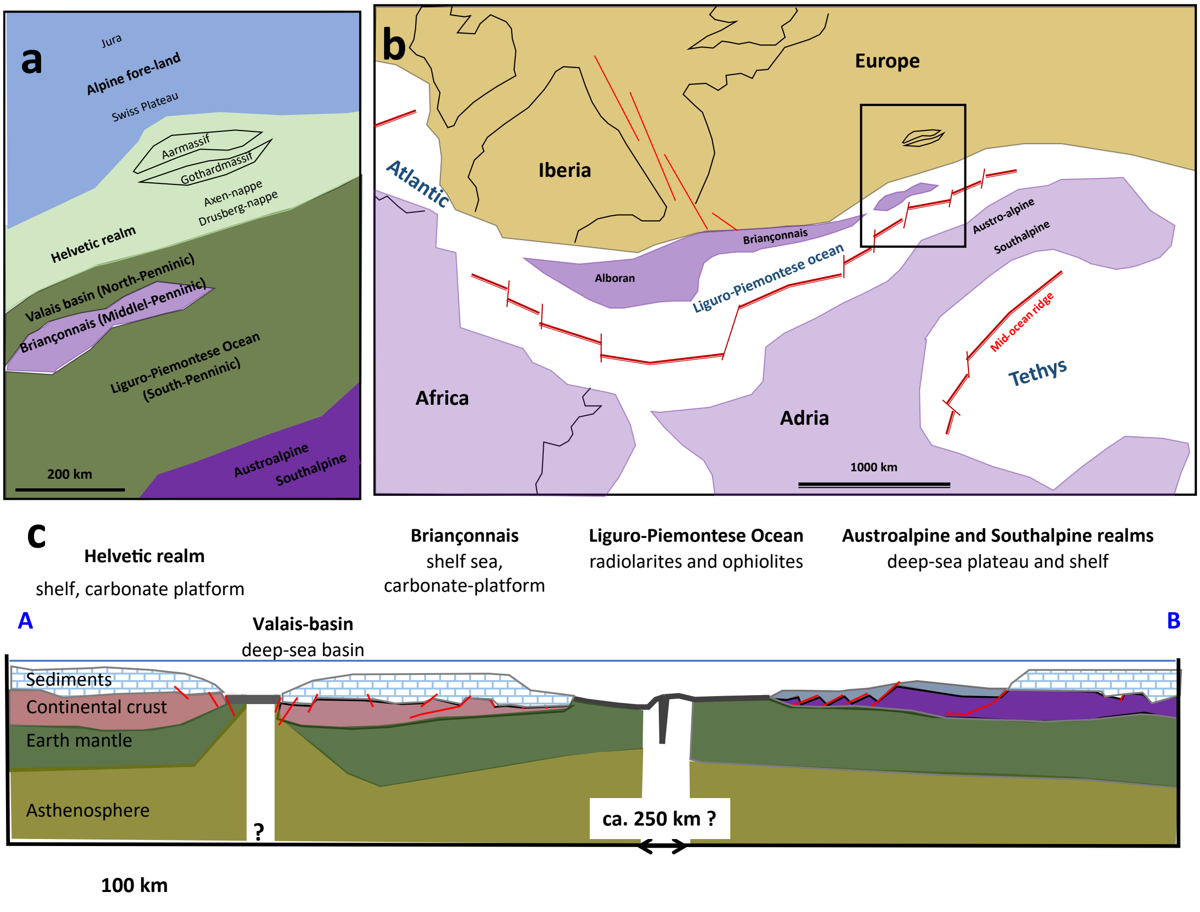


Figure B 7 a: *Paleogeographic map of the European continental margin from the Jura Mountain area through the Alpine Sea to the Southern Alps. The map shows the situation in the Upper Jurassic, 150 million years ago. The Alpine nappes are returned back to their original geographical position.*
b: *Paleogeography of Europe, the Iberian Peninsula, Africa and the Adriatic Sea at the same time as in figure a. The black frame corresponds to the area shown in figure a.*
c: *Paleogeographic section from the Helvetic realm to the Southalpine.*

p.s: the term 'Penninic' is used to refer to the tectonic nappes originating from the Valais Basin, the Briançon area and the Ligurian-Piemontese ocean. For lack of rigor, we also speak of the North-Penninic Domain, the Middle-Penninic and the South-Penninic.

4. Sea level variations

From space, an observer would have noticed over geological time not only the movement of the plates but also the great fluctuations in sea level and the associated flooding of the continental margins to a greater or lesser extent. The highest water levels are found in the Palaeozoic (Fig. B 8), from the Ordovician to the Devonian. During the 300 million years period considered here, sea levels were lowest at the end of the Permian. During the Triassic period, there was a brief rise and then a sharp fall. During the Liassic period (from 200 million years ago), the sea level started to rise and finally, during the Cretaceous period (100 million years ago), it reached a maximum of about 250 m above the present level. It then slowly declined again.

The high sea level indicates strong volcanic activity along the ocean ridges due to rapid continental drift (Fig. B 3). In this case, the volume of the ridges increases due to warming of the crust and upper Earth mantle, so that the ocean basin volume diminishes and sea water floods the continents.

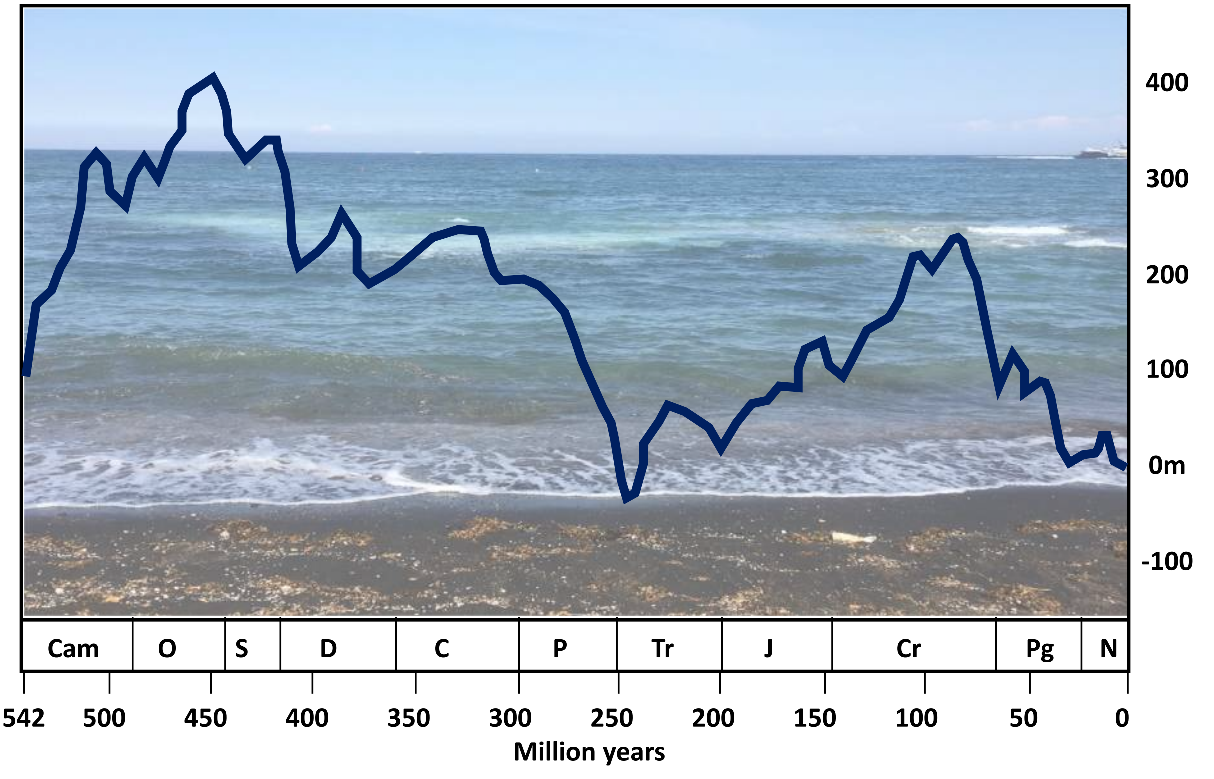


Figure B 8 : *Global sea-level fluctuations since the beginning of the Cambrian (542 million years ago; Hallam, A., Phil. Trans. Royal Soc. B 325, 437-455, 1989; see also https://commons.wikimedia.org/wiki/File:Phanerozoic_Sea_Level.png). N: Neogene, Pg: Paleogene, Cr: Cretaceous, J: Jurassic, Tr: Triassic, P: Permian, C: Carboniferous, D: Devonian, S: Silurian, O: Ordovician, Cam: Cambrian.*

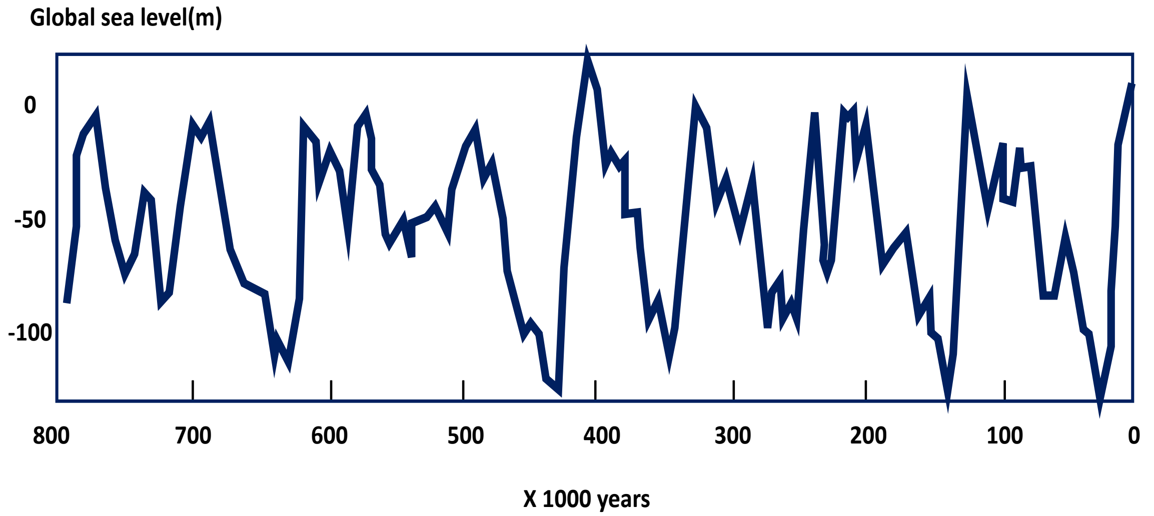
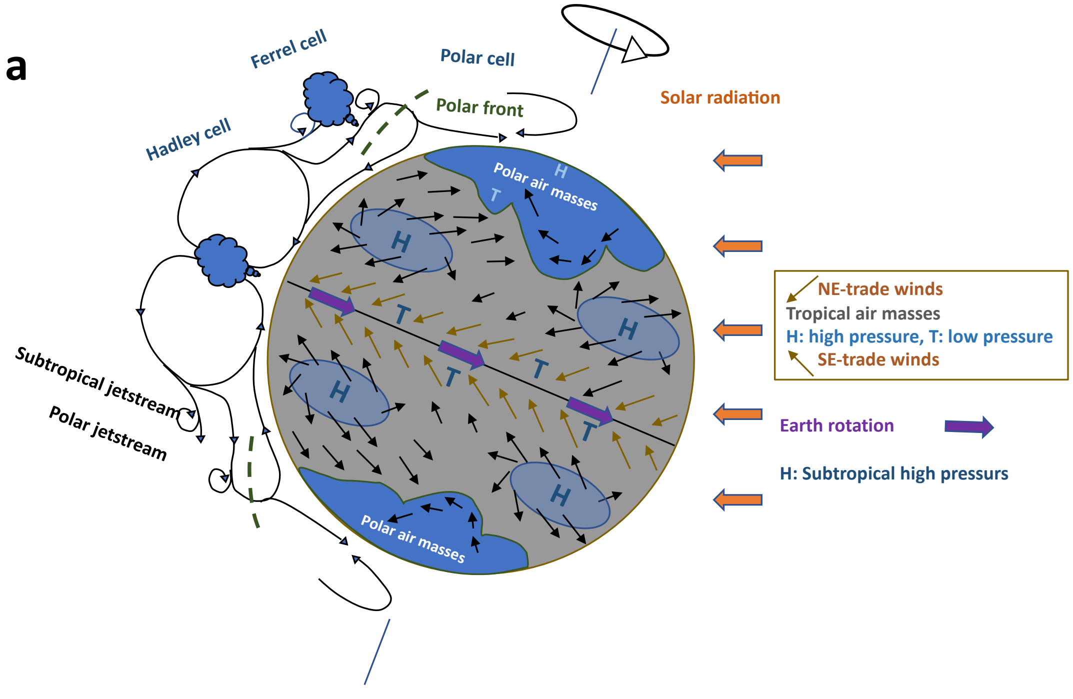


Figure B 9: *Sea-level fluctuations over the last 800'000 years of the Earth's history, including glacial periods (low sea-levels) and interglacial periods (high-sea levels; Spratt & Lisiecki, 2016, Fig. 4).*

5. The climate and its history

Climate

The word "climate" describes the sum of several parameters that describe the state of the atmosphere, the hydrosphere and the biosphere in general. Fig. B 10 a illustrates the interaction between solar radiation and the Earth's rotation, which are responsible for atmospheric circulation and precipitation. Fig. B 10 b illustrates the radiation balance of the sun.



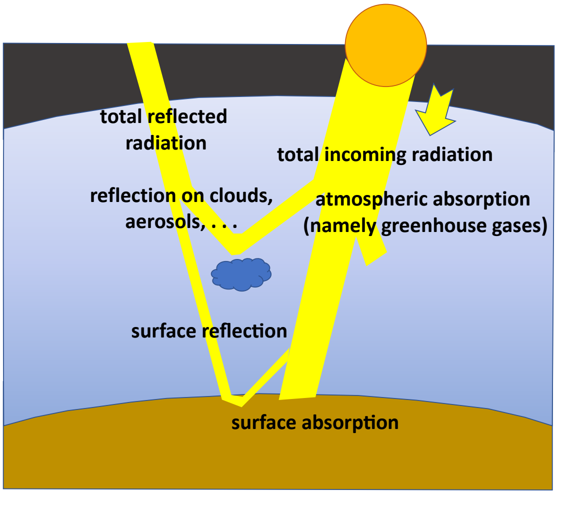


***Figure B 10 a**: Schematic representation of the interaction between solar radiation and the Earth's rotation, which together determine atmospheric circulation and precipitation. Situation in summer, when the northern hemisphere is turned towards the sun.*
***b:** Radiation balance .*

Climate history

The history of climate is of particular interest today, at a time when climate change is evident.

Since the creation of the Earth, its history has been characterized by a changing climate. The most frequent regime in this history is that of a warm climate, with average global temperatures of several degrees Celsius higher than today's own (Fig. B 13). The other, rarer climate regime is that of cold periods. Great cold periods occurred in the Precambrian, about 750 million years ago, in the Palaeozoic between 460 and 440 million years ago (Ordovician) and 345 - 280 (Late Carboniferous and Early Permian), then in the Pleistocene, at the beginning of the Quaternary, from about 2.6 million years ago. Especially during the second half of the Pleistocene, several periods of extreme cold with large extensions of ice occurred at the poles, in the Alps and other mountain ranges (glaciations). These cold periods were interrupted by shorter warm periods, called interglacial periods. Today, or rather since 11'700 years, we are living in an interglacial period, the Holocene. Between hot and cold periods, the temperature differences in the polar regions have always been greater than those in the tropics.

The discovery of the ice ages in the second half of the 19th century was based on the observation of glacial deposits, including erratic boulders, far from present-day glaciers, whether in the Alpine foreland, Northern Europe or North America.

On the continents, however, dating the glaciers associated with these events and their fluctuations have proved difficult. A solution was found in the 1950s to 1960s thanks to the work of two researchers, C. Emiliani and N.J. Shackleton, who studied the composition of oxygen isotopes in foraminifera (marine protozoan) shells and correlated the fluctuations with those of continental ice masses.

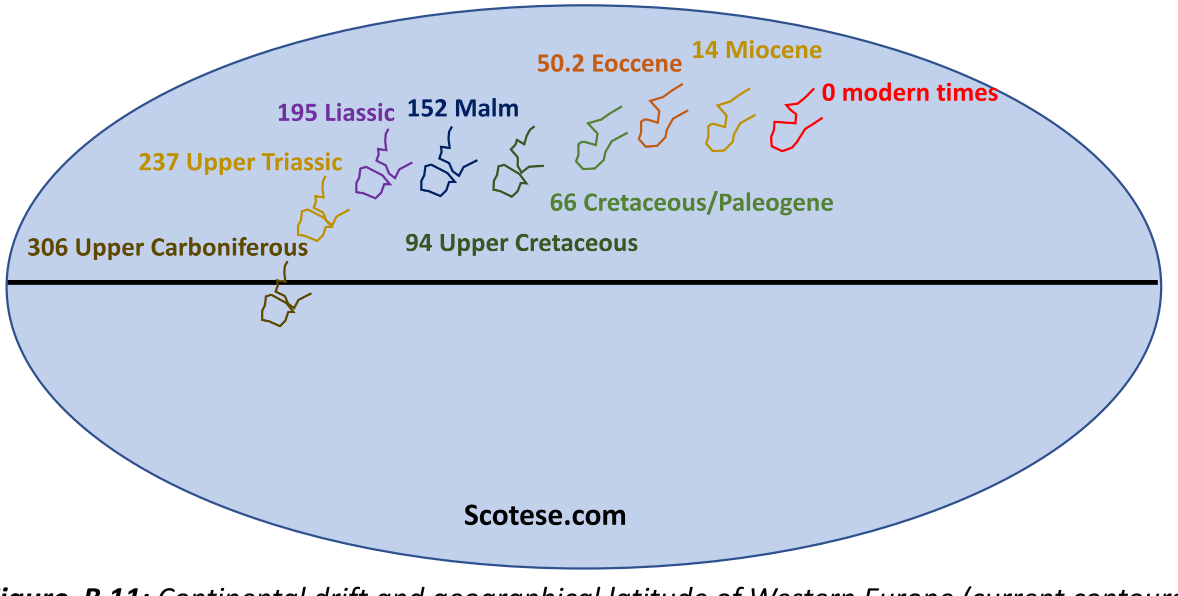
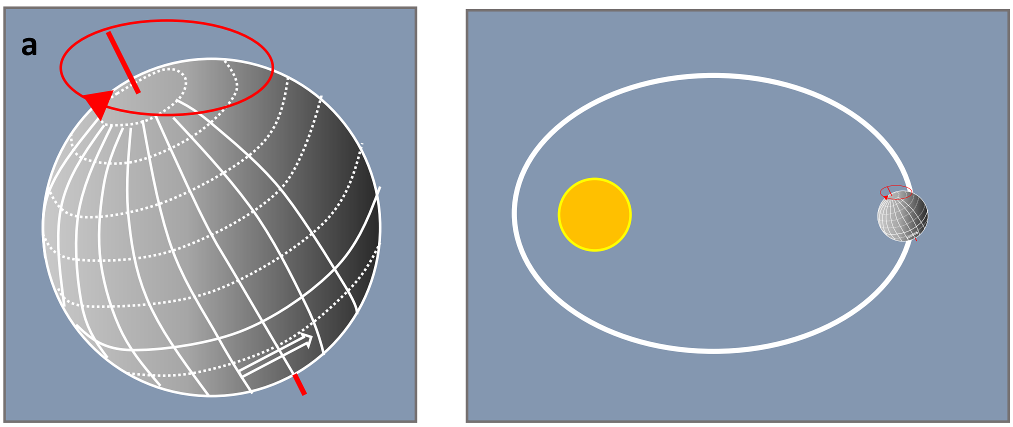


Figure B 11: *Continental drift and geographical latitude of Western Europe (current contours of Spain and France) over the last 306 million years (Upper Carboniferous to modern times); extracted from paleogeographic reconstructions from www.scotese.com.*

In the 1920s, the Serbian mathematician and astronomer Milutin Milankovic studied the cycles of the glacial and interglacial periods and compared them to the cyclic changes in the Earth's orbit around the Sun, as well as variations in the tilt of the Earth's axis relative to the orbit. He found that the superimposition of the effects of the evolution of the Earth's orbit and climate cycles during the Pleistocene (the last 2.6 million years of the Earth's history) was largely identical. Since this discovery, these cycles are therefore considered to be the explanation for the ice ages.



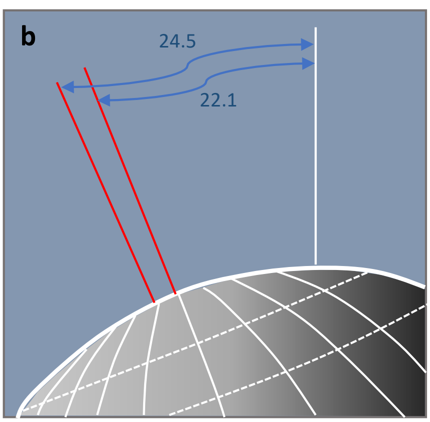
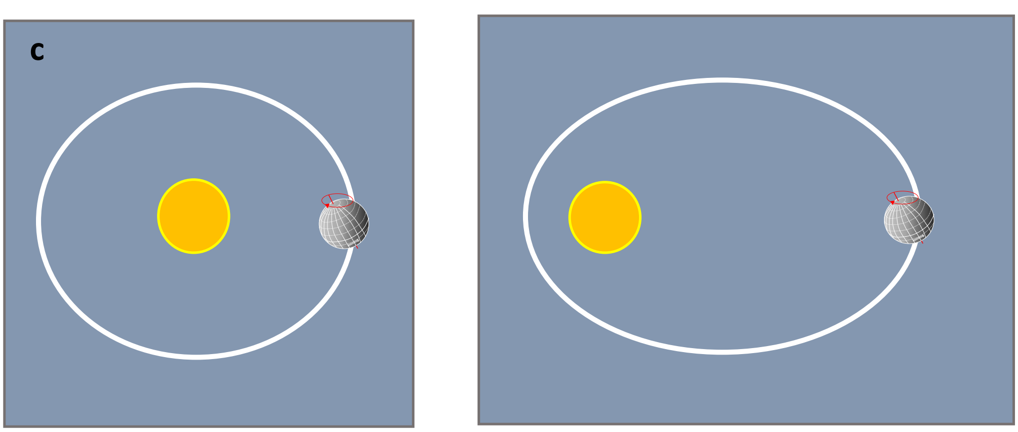


***Figure B 12**: Milankovitch cycle parameters:*

a) Precession (19'000-24'000 year cycle)

b) Inclination of the Earth's axis (41'000 years)

c) Eccentricity (100'000 years).



The three parameters of the Milankovic cycles are the following (Fig. B 12):

• Precession, which describes the orientation of the Earth's axis relative to the sun during the year on the elliptical orbit. It should be noted that the question of the orientation of the southern and northern hemispheres with respect to the sun in summer and winter, respectively, leads to very different climatic effects due to the unevenness of the surfaces of the continents and oceans. Precession has a cycle of 19'000 to 24'000 years.
• The inclination of the Earth's axis with respect to the orbit with a periodicity of 41'000 years
• The eccentricity of the Earth's elliptical orbit around the sun with a periodicity of about 100'000 years

An ice age can occur when all three cycles affect the continents in the direction of minimal solar radiation.

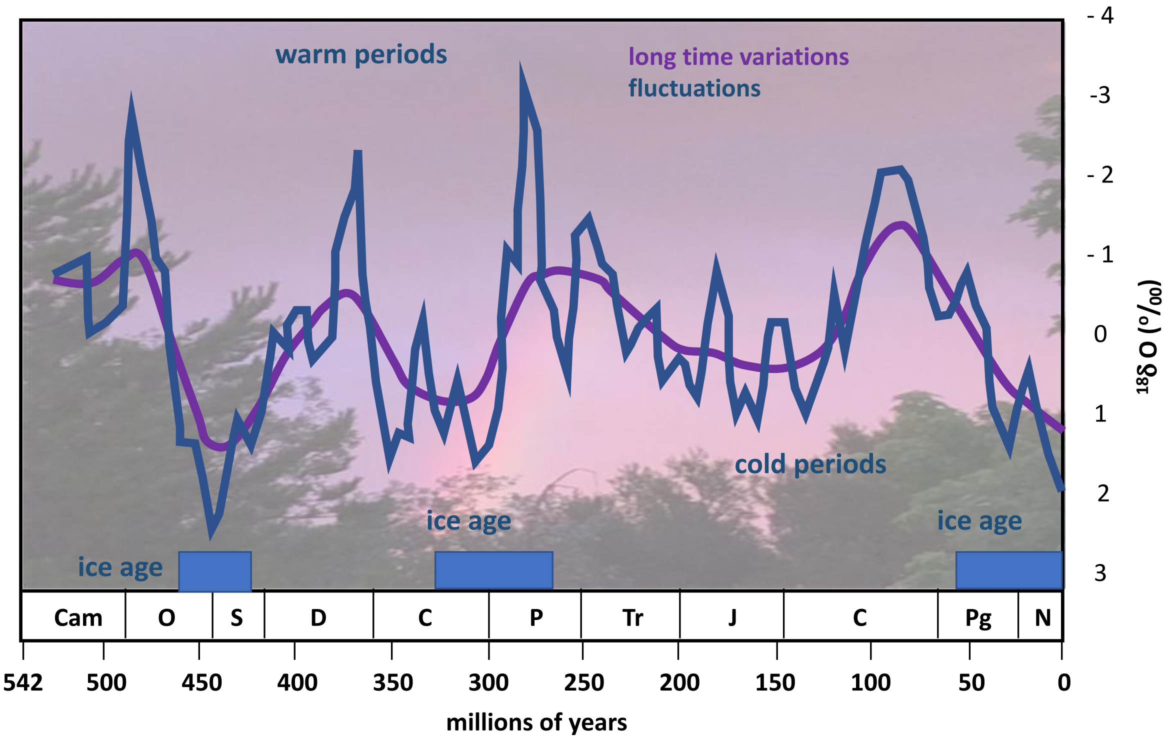


Figure B 13*: Fluctuations in mean annual temperatures during the Earth's history since Cambrian (542 million years ago), expressed by fluctuations by the oxygen isotope O-18 in marine sediments.*
(https://fr.wikipedia.org/wiki/Histoire_du_climat_avant_1850#/media/Fichier:Phanerozoic_Climate_Change.png)

Before the Pleistocene, the "Milankovic cycles" also existed, but the general temperature level of the Earth's atmosphere was too high to allow for ice ages.

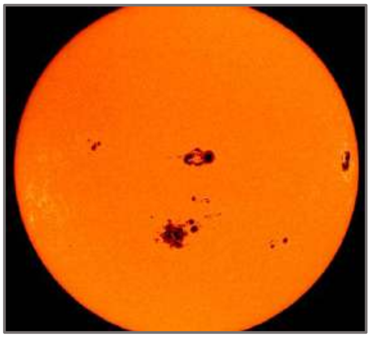
Today, the Earth's climatic history is reconstructed mainly through fluctuations in the oxygen isotopes O-18 in marine sediments and in the fossil shells of these sediments (Fig. B 13). Positive values indicate ice ages, while negative values indicate warm periods.

This method makes it possible to correlate major and minor fluctuations in glaciers around the world; this history of the ocean water composition is used as a reference today. However, the exact correlation of the results obtained in the oceans with moraine levels on the continents, including in the Alpine foreland, remains difficult.

O-18 oxygen is less abundant in the atmosphere than the lighter isotope O-16, and because of its greater mass, it is more abundant in seawater than in rainwater, snow and especially glacier ice. During a cold period, much of the "light" water is bound to glacier ice, which increases O-18 values in seawater (adapted from https://en.wikipedia.org/wiki/List_of_periods_ and_ events_in_climate _history#/media/File:Phanerozoic_Climate_Change.png).

Some climate changes cannot be explained by the Milankovic cycles. Even the climatic fluctuations of the post-glacial era, the Holocene, which has now lasted 11'700 years, cannot be explained by the cyclical variations of the Earth's orbit and the fluctuations of the Earth's axis.

After the end of the last ice age, temperatures increased worldwide and reached a maximum 8'000 to 5'000 years ago (called the "Holocene climatic optimum"). Since then, temperatures have fallen again around the world, and are interspersed with short-lived fluctuations. They are mainly correlated with fluctuations in the intensity of the Sun, expressed by sunspots, i.e. the flares observed on the surface of the Sun. The classic example is the correlation between the "Maunder Minimum" (Fig. B 14) and the Little Ice Age, which began in the 16th century and lasted until about 1850. Since the end of this Little Ice Age, the Earth's climate has been warming, not continuously, but step by step.



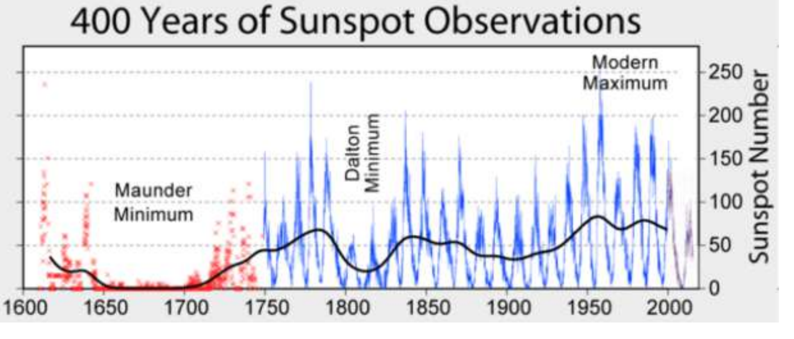


Figure B 14 a: *Sunspots are indicators of the intensity of solar radiation (https://www.weather.gov/fsd/sunspots).* ***b:*** *Number of sunspots since the year 1600. The depression of the 17th century is called the "Maunder Minimum". It is correlated with the first maximum of the Little Ice Age (https://en.wikipedia.org/wiki/Solar_cycle).*

6. Evolution and biodiversity

A classic, but not necessarily an accurate method for describing the evolution of biodiversity over the Earth's history is to count the kinds of fossil organisms mentioned in the paleontological literature. Fig. B 15 shows the result of such a reconstruction of the development of biodiversity.

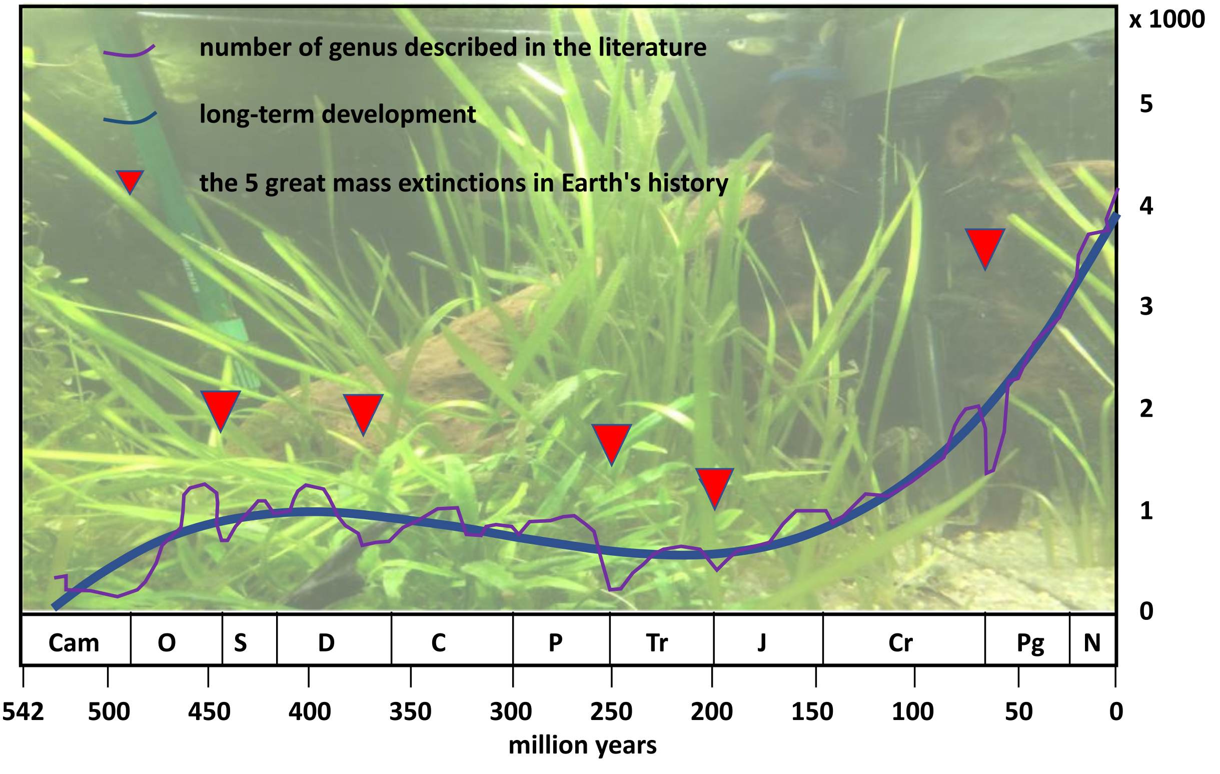


Figure B 15 : *Evolution of biodiversity (number of genera x 1000) since the beginning of the Cambrian 542 million years ago (simplified according to https://en.wikipedia.org/wiki/Phanerozoic#/media/File:Phanerozoic_Biodiversity.svg).*

Although the first unicellular organisms appeared as early as the Precambrian, about 4.1 billion years ago, the development of complex organisms is only documented from the Cambrian, 542 million years ago. Fig. B 15 shows that biodiversity gradually increased over time, interrupted by five major crises (mass extinctions). The largest of these occur at the end of the Permian and the end of the Cretaceous. Meteorite impacts and/or volcanism are considered to be the causes of these mass extinctions.

The oldest fossiliferous sediments in Switzerland date from the **Carboniferous** period. However, for the Carboniferous and **Permian** periods, only terrestrial organisms are known in Switzerland. Shortly before the Carboniferous period, plants began to conquer the continents. During the Carboniferous period, from about 360 million years ago, they form true forests with scale trees, horsetails (*Equisetum*), *Lycopodiophyta*, ferns, etc. (Fig. B 16).

Figure B 16 : *Plants of the fern group from the late Palaeozoic to the present day (Conservatoire et Jardins botaniques de Genève..*

These forests constitute an ideal ecosystem for dragonflies and amphibians. The largest coal deposits in Europe are formed in the Carboniferous, thanks to the preservation (fossilization) of dead vegetation. This evolution of vegetation can be followed in Switzerland as far back as the **Triassic** period, with its fossil plant sites, especially horsetail. With rare exceptions, it is only in the Middle Triassic (Muschelkalk) that marine fauna, such as crinoids, ceratites ("Triassic ammonites", Fg. B 17 b), bivalves and gastropods are known.

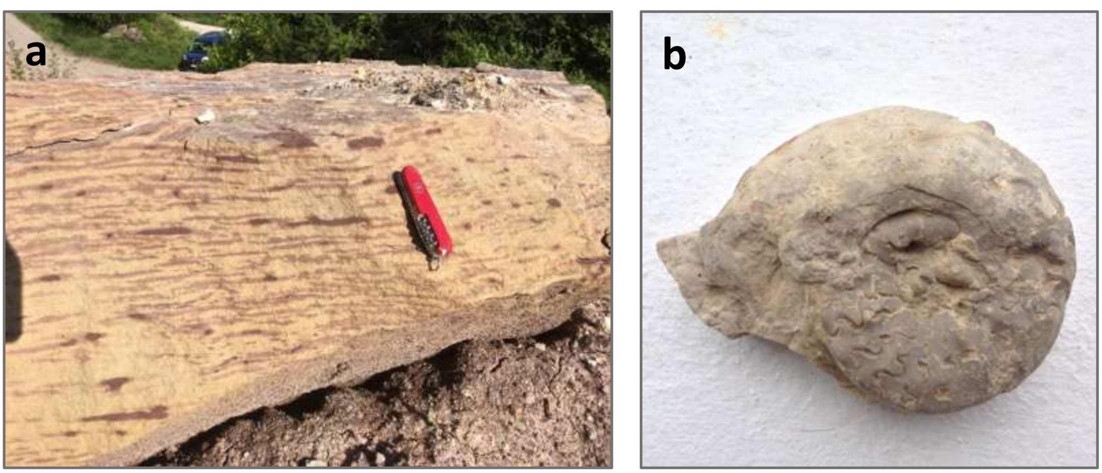


Figure B 17 a*: Typical red-stained fracture surface of a red sandstone block. The well-preserved plant remains are mainly Equisetes (horsetail); (Röt, Gansingen, Coo 651 600/266 750).*
b: *Ceratite of the marly layer at the limit between the Plattenkalk and the Trochitenkalk (Entrochal Limestone) near Mettau (Aargau). The diameter of the fossil is about 10 cm.*

During the **Jurassic** period, the composition of the fauna in sedimentary rocks is highly dependent on the depth of the sea. Special attention must be paid to ammonites that developed in the open sea, and whose rapidly changing morphology allows fine dating of the rocks. In the **Middle Jurassic** (Dogger), the Liguro-Piemontese basin of the Alpine Sea deepened, so that only unicellular organisms with siliceous skeletons (SiO_2), in particular radiolarians, were fossilized. Today they can form true "radiolarites" (Fig. B 18). On the other hand, calcite and aragonite skeletons are dissolved.

Figure B 18 :
Radiolarites: these sediments were deposited in the Liguro-Piemontese Basin of the Alpine Sea at a depth of about 2.5 - 4 km. (Tsaté Tablecloth, Tracuit, Coo 616'295, 107'850 and 618'460, 108'120). Photo: M. Sartori.

Fossil fauna on marine platforms is extremely rich. In addition to the ammonites and belemnites that swim in the open sea, there are many bivalves, gastropods and brachiopods fixed on the ground. In the region of the Jura Mountains and on the Swiss Plateau, coral reefs developed in the Middle and **Upper Jurassic** (Dogger and Malm, (Fig. B 19).

Figure B 19 : a: *Coral and* ***b:*** *Coral colony in the reef limestone at the top of the Gisliflue (Aargau). Age: Middle Dogger (Wildi & Lambert 2019).*

Microscopically small planktonic faunas, the *Calpionella*, are found in fine limestone rocks that are deposited in the deepest areas of the Southalpine area. They are excellent stratigraphic markers. Other microfossils of plant origin, called nannoplankton, also gained importance from the Middle Jurassic onwards. Their internal skeleton is in the form of rosettes of calcite, found mainly in limestone and marl.

During the **Cretaceous** period, ammonites continue to evolve and partly "degenerate", for example by rolling up their chamber at the beginning only, and remaining stretched towards the end of the fossil's life.

On the Helvetic platform and in the Jura Mountains, thick-shelled oysters and massive, asymmetrical, cup-shaped sessile bivalves, the inoceramids, are found. After the death of these organisms, the shells can decompose into calcareous prisms that are easily carried to deep waters. Unicellular, coin-sized foraminifera with a calcareous skeleton, the orbitolines, are also found on ancient marine platforms.

In the **Upper Cretaceous**, morphologically differentiated planktonic foraminifera, the *Globotruncana*, developed. They allow a temporal (stratigraphic) subdivision and a very fine dating in sediments from the open sea, similar to that of ammonites during the Jurassic period.

It is impossible to talk about fossils and biodiversity during the Mesozoic without mentioning the "curiosity" of this period, the **dinosaurs**. The best-represented group in Switzerland are the ichthyosaurs, the "fish dinosaurs", which were studied in detail at Monte San Giorgio (Ticino). In the Middle Triassic period, ichthyosaurs populate the Tethys

Figure B 20 : *Footprint of a dinosaur in finely bedded limestone at Courtedoux (Jura); diameter: about 50 cm.*

inlet, which invades the Southalpine and Austroalpine areas from the East. This site also illustrates the great biodiversity in the seas of this period of the Earth's history, notably with numerous well-preserved ceramics ("Triassic ammonites"). Skeletons and parts of skeletons of terrestrial dinosaurs have been discovered in Upper Triassic clay deposits in the Tabular Jura of Canton Aargau in the quarry of the Frick Tile Works. The land dinosaurs obviously liked the shallow areas of the sea and the lagoons. Traces of dinosaurs are therefore known from Triassic dolomites in the Alps as well as from Upper Jurassic limestones (Malm), e.g. at Courtedoux (Jura, Fig. B 20) and other sites in the Jura and the Alps.

The faunal change at the **Cretaceous/Paleogene (former Tertiary) boundary** (66 million years ago) is radical: ammonites disappear as well as dinosaurs; the planktonic *Globotruncana* are replaced by small *Globorotalia*. It is generally assumed that about 75% of plant and animal species were affected by the mass extinction of the Late Cretaceous.

During the **Paleogene** period, small planktonic *Globorotalia* were found in the deep areas of the Alpine Sea. In contrast, in the shallow sea of the Helvetic Domain, small reefs formed by *Lithothamnium* (red algae), large foraminifera of the discocycline, asterocycline and nummulite groups settled during the Eocene. Shortly after the limit from the **Eocene** to the **Oligocene**, the last deep-water areas of the Alpine Sea are closed and a shallow arm of the sea, characterized by high tides, extends from the Mediterranean along the Alpine front to the Vienna Basin. This marine arm of the Lower Marine Molasse receives erosion material from the rising Alps. Soon, however, the estuary silts up, and the Lower Freshwater Molasse covers the Marine Molasse with its huge spreading cones.

In the **Middle Miocene** (Burdigalian, 20 million years ago), history repeats itself: a new transgression leads to the invasion of the Swiss Plateau and the Jura. The Upper Marine Molasse is deposited in a sea strongly influenced by the tides. In the Upper Miocene, the deposition of Molasse ends in the Alpine foreland with the formation of the Upper Freshwater Molasse.

The fauna and flora reflect the changing environment of the Molasse deposit under mainly warm climatic conditions: shallow seas, alluvial plains with rivers and lakes and alluvial cones along the Alpine foreland describe a changing landscape. The Upper Marine Molasse is particularly rich in bivalves of all kinds, gastropods, sea urchins and other fossils (Fig. B 21). In the freshwater Molasse, plant remains and coal seams are often found, followed by land snails, mammal teeth, etc. (Fig. B 21). Fossil plants in the Freshwater Molasse include some tropical species, such as date palms, laurels, magnolias, camphor and tulip trees. Together with species from a temperate climate, the evergreen plants reflect an extraordinarily rich vegetation, comparable to the current vegetation of the south-eastern United States or parts of southern China.

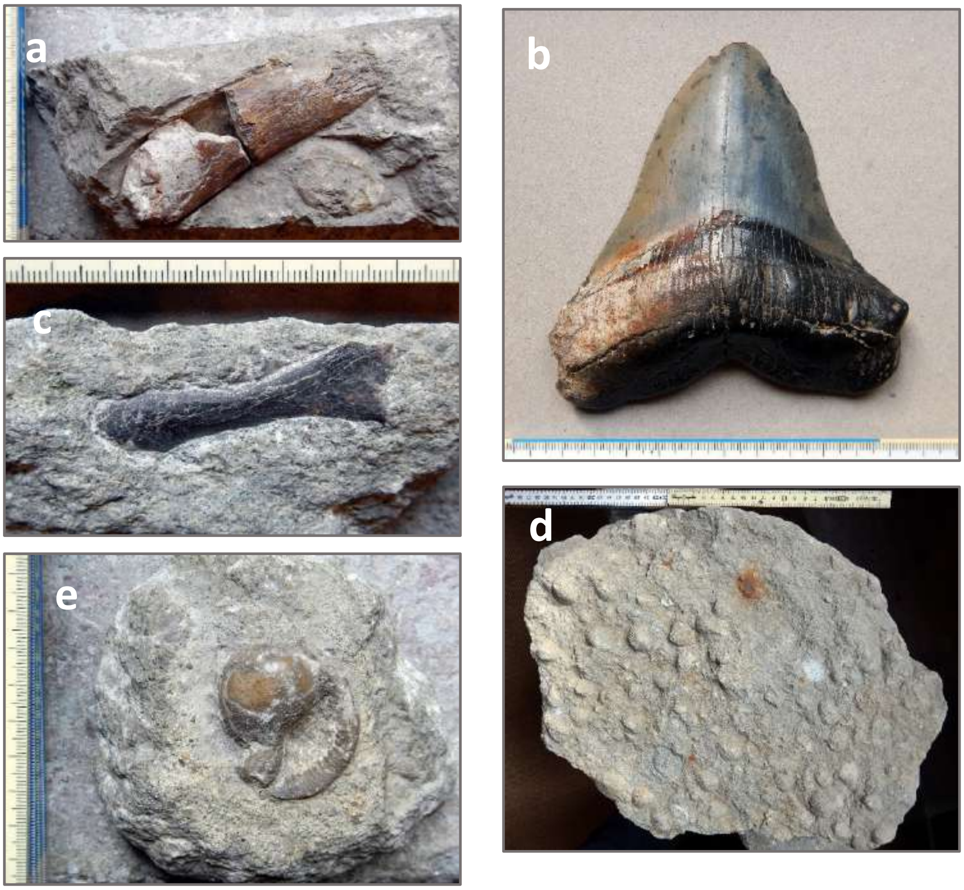


Figure B 21: *Fossils of the Würenlos Upper Marine Molasse (Emma Kunz Centre Exhibition, determination and photos: H. Furrer):* ***a:*** *Vertebral fragment of a mermaid,* ***b:*** *A perfectly preserved tooth of a great shark,* ***c****: Mammalian bone,* ***d:*** *Cardium,* ***e:*** *Phalium (gastropod),* ***f:*** *Chlamys.*

Fauna and Flora of the Oeningen Upper Freshwater Molasses

Oeningen is located north of the western end of Lake Constance (Land Baden-Württemberg, Germany), near the small town of Stein am Rhein. Here, in the 18th and 19th centuries, Freshwater Molasse from the Upper Miocene (13 million years ago) provided extremely rich flora and fauna in two quarries.

At a lower site, freshwater limestone was found, which probably formed in a crater lake ("maar") of the Hegau volcanoes. The highest site consists of marl with traces of an old floodplain forest (Ungricht & Biolzi, undated).

The site was studied in the 18th century by Johann Jakob Scheuchzer (1672-1733), in the 19th century by Oswald Heer (1809-1883), and in the 20th century by René Hantke.

The sites have yielded numerous fossils from a lake area and its shores, as well as plants and animals from the surrounding alluvial terrain. Ungricht and Pika-Biolzi cite the following plants by name: “A wine plant (*Porana oeningensis*), reed (*Phragmites oeningensis*), other marsh and shoreline plants such as horsetail (*Equisetum* sp.), cattail (Typha sp.), *Potamogeton* sp. and *Isoetes* sp., as well as the rich leaves and cones of the genus *Glyptostrobu*s, resembling a cypress, and especially the angiosperms *Acer* (maple), *Cinnamomum* (cinnamon), *Diospyros* (ebony), *Fagus* (beech), *Ficus* (fig), *Juglans* (walnut), *Liquidambar* (amber), *Quercus* (oak), *Persea* (avocado), *Platanus* (plane tree), *Salix* (willow), *Sapinus, Ulmus* (elm), *Zelkova* (Zelkove) and the now-extinct vegetable genus *Podogonium*.”

The list is followed by insects and other small animals, as well as many vertebrates: "Fish: eel (Anguilla sp.), pike (*Esox lepidotus*), carp (Cyprinus sp.), tench (*Tinca leptosoma*), asp (*Aspius* sp.), whitefish (Leuciscus oeningensis), perch (*Perca* sp.), *Prolebiasperpusillus*, *gudgeon*, bullhead (*Cottus* sp.), *Cobitis* sp.; amphibians: toad (*Palaephrynos* sp.), giant frog (*Latonia seyfriedi*), giant salamander (*Andrias scheuchzeri);* reptiles: marsh turtle (*Emys* sp.), alligator turtle (Chelydropsismurchisoni), viper (*Coluber* sp.), footless lizard (*Ophisaurus* sp.); mammals: fox (*Ganecynus palustris*), whistling hare (*Prolagus* sp.)". The giant salamander Andrias Scheuchzeri has become particularly famous.

Of this fauna and flora, the authors concluded that there was a "subtropical rainy climate with Atlantic influence (mild winters and not too hot summers)" for the period of the Upper Freshwater Molasse.

Figure B 22: *The Oeningen landscape at the time of the Upper Freshwater Molasse (Heer 1883).*

No deposits from the last part of the **Miocene and Pliocene** are known north of the Alps. **South of the Alps**, in southern Ticino, an interesting history has taken place. At the end of the Miocene, during the Messinian (7.2 to 5.3 million years ago), the level of the Mediterranean dropped dramatically and salt was deposited in the former deep-sea basin. This "salinity crisis" was caused by the closure of the Strait of Gibraltar, which connects the Mediterranean to the North Atlantic. The drop in sea level has even affected southern Ticino: from the Adriatic Sea, the Po River has cut a deep valley towards the Po Plain. The same applies to the lateral tributaries flowing into the Po from the Alpine valleys. Then, at the beginning of the Pliocene, when the Atlantic Ocean returned to the Mediterranean basin, the sea level rose rapidly to reach the Chiasso region. This is where the Balerna clays were deposited, with a rich marine fauna of macro- and microfossils.

The fauna and flora of the Neogene are very close to modern communities.

The **Pleistocene ice ages** brought a new type of flora and fauna from 2.6 million years ago. The flora close to the glacier was particularly adapted to the dry and cold conditions of the tundra, with the growth of fine grass, small leafy plants such as saxifrage, silver root, etc., and the presence of a large variety of plants. Trees and shrubs remained low-growing and limited to pioneer species such as birch, Swiss Scots pine, alder and heather. Large mammals include woolly mammoth, woolly rhino, cave bear, wolf, cave hyena, bison, etc. In the loess sand are the small tower snails characteristic of the genus *Pupilla*.

During **interglacial periods**, the cold vegetation retreated northwards and to higher altitudes. The plant remains in the sediments, and especially the pollen, are evidence of the colonization of the landscape at low altitudes by conifers, and later by deciduous trees that developed into forests as they are found today. During the interglacial period of Holstein (around 400'000 years ago), plant remains were found which indicate even warmer vegetation, which can be compared to a Mediterranean climate: Vine nut (*Pterocarya*), ash, elm, alder, hazelnut, hornbeam, linden, oak, yew. During the last interglacial period, known as the "Eemian", a mixed forest of oaks with a high proportion of hornbeam developed on the Swiss Plateau.

C. Hiking tours through the geology and the Earth history of Switzerland: information on excursions and visits

Introduction

In this chapter, the reader will find suggestions for field trips and museum visits that illustrate the history of the Earth in Switzerland. Most of the suggestions can be found on websites, which lead the hiker to interesting geological objects and invite him to visit them "on his initiative". In addition, guided geological excursions are now offered throughout Switzerland. Many interesting suggestions can also be found at www.erlebnis-geologie.ch.

Unfortunately, websites are unstable; they appear one day and can disappear again. For this reason, the information in this brochure is only up to date on the day of the last visit. We will try to update the addresses accordingly. We are also happy to receive new suggestions from our readers.

The field and museum visits offered here can be made individually and at your own risk (!). They require some preparation and precautions, e.g. with regard to clothing, field equipment, food, etc. Thanks to 3G and 4G, documents can be consulted almost anywhere in the field. But only almost! Paper printing of records (especially cartographic records) is therefore recommended! The conditions for field visits can also change over time: road conditions, access conditions, etc. The visitor is solely responsible in this respect for and during his or her visit!

The cartographic documents (geological and topographical maps, aerial photographs, etc.) can be consulted and partially downloaded and/or printed on www.swisstopo.ch. Geological data can be found at https://www.swisstopo.admin.ch/fr/cartes-donnees-en-ligne/cartes-geodonnees-en-ligne/donnees-geologiques-en-ligne.html. Swisstopo also sells classic geological maps and their explanatory notes. All these documents provide a better understanding of the geology and landscape.

Field observations contain a great deal of information and facilitate the understanding of the Earth's history. However, many results also come from instrumental research in the laboratory. Fossils also constitute a special chapter: fossil deposits are rare; valuable fossils belong to the cantons and are stored, scientifically processed and exhibited in museums. They can also be enjoyed by visitors. **Visitors are therefore advised to refrain from "collecting" fossils in the field.**

Proposals for excusions and visits

1. Tropical forests of the Carboniferous

In Switzerland, Carboniferous rocks are found only in the Alps, in ancient Permo-Carboniferous pits that are now exposed on the surface. One of these coal deposits was mined near Dorénaz in Valais. Excursion to the Dorénaz syncline:

F: https://www.swisstopo.admin.ch/fr/connaissances-faits/geologie/geologie-quotidien/geologie-pour-tous/via-geoalpina.html#ui-collapse-821

D: https://www.swisstopo.admin.ch/de/wissen-fakten/geologie/geologie-alltag/geologie-fuer-alle/via-geoalpina.html

To get an idea of the fauna and flora of the Carboniferous, it is also interesting to take a (virtual) tour of the ETH Zurich collection: (category: https://geo-coll.ethz.ch/schubladen (section: Stratigraphische Sammlung, Karbon).

2. Red deserts of the Permian

In Chapter A, we described the red deserts of the Permian and Lower Triassic in Europe. On the one hand, Permian rocks from this period are found in rare, small and unspectacular outcrops in the Rhine valley above Basel (so-called "Rotliegendes"; Fig. C 1). On the other hand, they are found in the form of "Verrucano" in the Alps, in former tectonic depressions in the crystalline bedrock and at the base of tectonic nappes, particularly the Helvetic nappes, e.g. in the Glarus area and the Flums mountains (Flumserberge).

Figure C 1*: Rotliegendes on the embankment of the Fischigerbach (Mumpf, Aargau): alternating layers of dark red and greenish to white sandstone and clayey sandstone. Coo: 47.54195/7.92262, right bank of the Fischigerbach near the road bridge (Wildi & Lambert 2019, Fig. 17).*

The part of the journey through the "Sardona Tectonic Circus" (a UNESCO World Heritage Site) leads from the Murgsee hut to the Spitzmeilen CAS hut through the Verrucano landscape at the base of the Mürtschen Nappe:

D: https://www.erlebnis-geologie.ch/geoweg/sardona-welterbe-weg-etappe-2-murgseehu%cc%88tte-spitzmeilenhu%cc%88tte-sac/

And the information brochure:

D: https://www.erlebnis-geologie.ch/wp-content/uploads/2019/10/Sardona-Welterbe-Weg-Wandern-in-der-Sardona-Region-1.pdf

If this mountain tour seems too difficult for you, we recommend an excursion into the Verrucano landscape of the Murgsee and as a preparation, a visit of the stone path (Steinpfad) Knobel in Schwanden:

D: https://www.erlebnis-geologie.ch/geoweg/steinpfad-knobel/

Figure C 2 : *Erratic blocs of Verrucano are found on all moraine ridges in the valleys of the Swiss Plateau. Figure: Giant Verrucano boulder from the Glarus region on the lateral moraine of the Limmat Glacier in Würenlos ("Bick moraine", photo: A. Lambert, Coo 47.43719/8.37166, Wildi & Lambert 2019).*

3. Permian Volcanites of Melide

The "Melide volcano" is not recognizable on the ground today as such with its cone and volcanic crater. However, the hike proposed here allows to observe its volcanic rocks in a wonderful landscape:

I: https://www.luganoregion.com/it/cosa-fare/lago-e-natura/natura-outdoor/sentieri-tematici/detail/id/12802/un-sentiero-del-passato-melide-carona

4. Salt plains and sebkhas of the Triassic

Salt from the Triassic period is still mined today in Riburg (Möhlin) in the Rhine valley (Aargau) and in the saltworks of Bex (Vaud). Until recently, gypsum mines and quarries also existed in Switzerland. Here are two suggestions for visits to mines, one of salt and the other of gypsum: :

F: https://www.erlebnis-geologie.ch/geoevent/mines-de-sel-des-alpes/

D: https://www.erlebnis-geologie.ch/geoevent/gipsmuseum-schleitheim/

5. Crinoid gardens in the Muschelkalk sea

On this excursion, the visitor will encounter all the geological formations of the Muschelkalk that outcrop in the Folded Jura. At stop no. 3, it is interesting to visit the former "Üselmatt" quarry. It is located behind (to the east) the bus stop, hidden in the forest. Here, the spathic limestone is on a rock face (caution: danger of falling rocks!). In the scree slopes, there are blocks of the same limestone with crinoid debris (Fig. C 3).

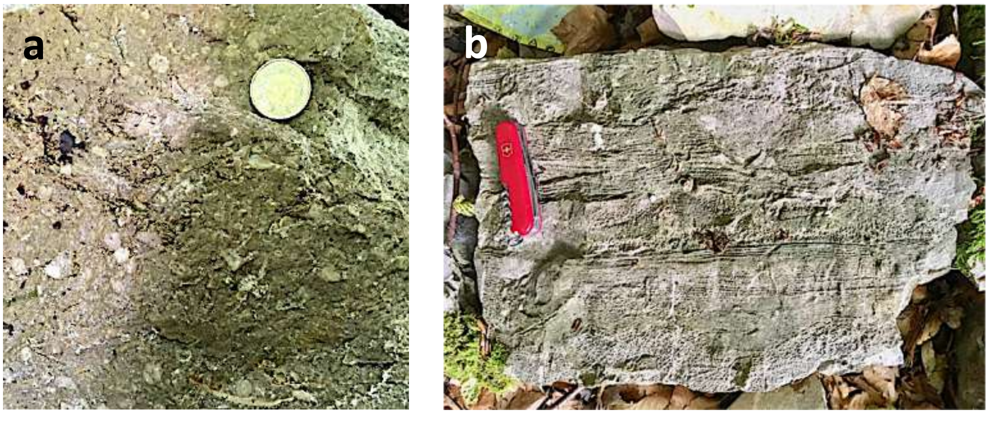


Figure C 3 : *Screes from the Üselmatt quarry.* ***a****: Solid limestone with segments of crinoids; diameter of the piece: 2 cm.*
b: *Finely laminated spathique limestone made of limestone sand in the Muschelkalk sea (Wildi & Lambert 2019).*

F: https://www.erlebnis-geologie.ch/wp-content/uploads/2020/03/StaffeleggFranc%CC%A7ais3_compressed.pdf

D: https://www.erlebnis-geologie.ch/wp-content/uploads/2020/03/StaffeleggDeutsch3_compressed.pdf

6. Tethys breaks into the Southern and Eastern

The first of the publications mentioned below describes three excursions in the Engadine Dolomites. These excursions were offered on the occasion of the 100th anniversary of the Swiss National Park. Excursions 2 and 3 give an overview of the geology. On both sides of the Ova dal Fuorn, the highest mountain ridges are formed by rocks belonging to the Hauptdolomit ("Main Dolomite"). These are mainly grey dolomites, mostly laminated. These structures originate from cyanobacterial mats, which covered the shallow seabed at the end of the Triassic period (Fig. C 4). To observe the stratifications, we recommend the scree blocks.

D: https://naturalsciences.ch/uuid/09c38da1-8eb7-53e8-824e-34c2b9232ebc?r=20190205110021_1549333276_b4beea67-9cb3-5f89-a2e3-b82688099c9f

Figure C 4 : *Doma-stromatolites (grown finger-shaped) from the Main Dolomite (Norian) of the Engadine Dolomites (Munt da la Bescha, north of the Ofen Pass; Palaeontological Museum Univ. Zurich, Photo: H. Furrer).*
a: *weathered surface (width 15 cm).*
b: *polished section (width 10 cm).*

7. Marine saurians from Monte San Giorgio

On Monte San Giorgio, bituminous slates were once extracted in a quarry. A plant at the bottom of the valley produced bitumen. In 1919, the Zurich paleontologist Bernhard Peyer discovered the first remains of ichthyosaurs ("fish dinosaurs"). This marked the beginning of a long history of excavations, fossil preparations, determinations, etc. Today, the fossils are on display in three museums, namely the Museo dei Fossili del Monte San Giorgio in Melide, the Museo dei Fossili di Besano and the Museum of Palaeontology of the University of Zürich:

I: http://www.montesangiorgio.org/Musei/Museo-dei-Fossili-di-Meride.html

I: http://www.montesangiorgio.org/Musei/Museo-dei-Fossili-di-Besano.html

D: https://www.pim.uzh.ch/museum/ausstellung.php

8. Plateosaurs from Frick

The first vertebrate bones were discovered in the mottled marls of the Tonwerke Keller AG factory in Frick in 1961. From 1976 onwards, systematic excavations were carried out and in 1985 the first complete skeleton was discovered. Today, the most beautiful specimen can be admired in the small dinosaur museum in Frick. The museum is particularly proud of a complete plateosaur skeleton. The location and opening hours of the museum can be found on the following website:

D: https://sauriermuseum-frick.ch/

9. Dinosaur footprints from Vieux-Emosson

The footprints at Vieux-Emosson are certainly a little older than Frick's dinosaurs, probably from the Middle Triassic period. The brochure explains the geological setting in detail.

F: https://www.erlebnis-geologie.ch/geoweg/sentier-geologique-du-vieux-emosson/

10. The Ligurian deep-sea basin at Lake Marmorera

On the right (eastern) shore of Lake Marmorera, along the road to the Col du Julier, there are various rocks from the Liguro-Piemontese ocean. At the height and on both sides of the dam, basalts with pillow lava (now tectonically flattened) were cut during the construction of the road (Fig. C 5). On the meadows and in other outcrops near the hamlet of Marmorera, finely layered radiolarites (Dogger, Malm, Fig. C 6) and fine Calpionella limestones (Upper Malm - Lower Cretaceous) can also be found.

p.s. To locate outcrops, it is useful to consult the geological map.

Figure C 5: *Pillow lava in the basalts along the Col du Julier road at the dyke of Lake Marmorera.*

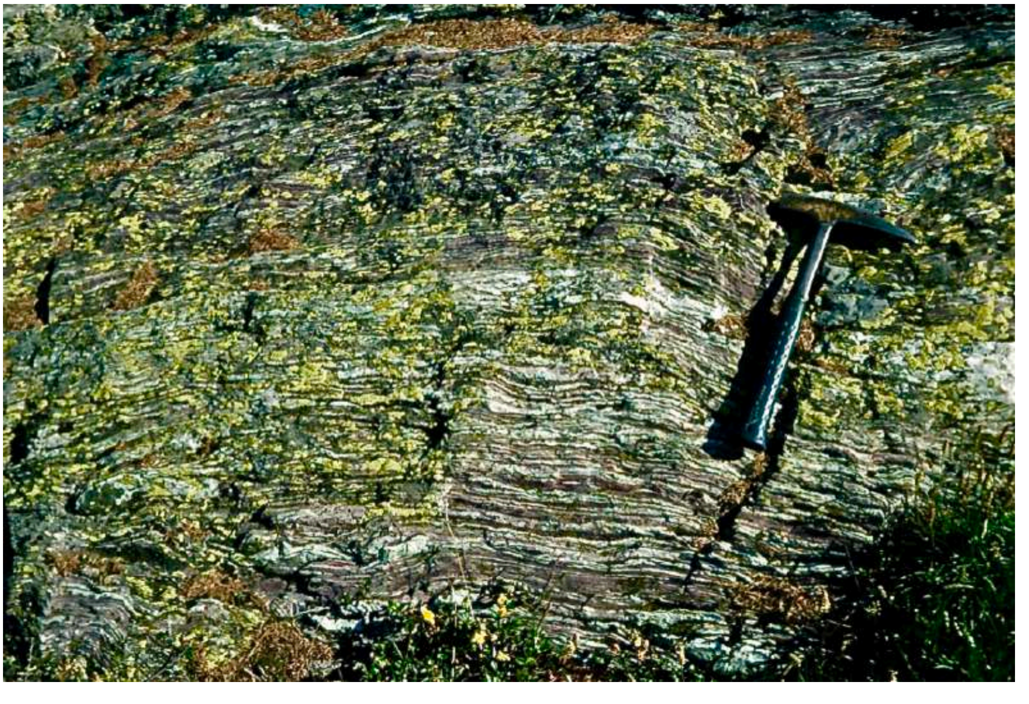


Figure C 6: *Finely layered radiolarites above the village of Marmorera. Lichens of the species Rhizocarpon geographicum grow on siliceous substrates.*

11. The Southalpine deep sea in the Gorge of the Breggia

The Breggia Gorge offers a unique profile through the sediments of the deep sea of the Sudalpine. Literature: Rudolf Stockar 2003: Guida geologica al Parco delle Gole della Breggia, Parco delle Gole della Breggia. La guida è ottenibile al prezzo di Fr. 30.-presso il Parco delle Gole della Breggia, e-mail: info@parcobreggia.ch.

I: https://www.parcobreggia.ch/

D: https://rinifoto.ch/breggia-park

An introdution on youtube:

https://www.youtube.com/watch?v=wIYQ9yWq6dg

12. Iron ore and the ammonite necropolis of Herznach

The Herznach iron mine operated from 1937 to 1967. During this period, it supplied ore with an iron content of 20-32%. After the closure of the mine, the industrial plant became calm again. Thanks to the association Verein Eisen und Bergwerke (VEB), founded in 2004, the mine is accessible again. The ore deposit was formed at the end of the Dogger in a period of low sedimentation. As a result, fossil shells have accumulated. A visit is well worthwhile.

D: https://www.bergwerkherznach.ch/

13. Coral reefs in the Jura mountains

In the shallow sea, at the surface and on the edges of the Rauracian platform, small coral reefs formed in many places during the Dogger and Malm, most of them with a lateral extension of a few dozen meters. These platform reefs (patch reefs) are mostly surrounded and covered with reef debris.

The coral reef of the Gisliflue (Folded Jura, Aargau) developed during the Middle Dogger at the eastern end of the platform of the Hauptrogenstein (or “Great oolithe”). On this platform, in warm shallow water, calcareous sand dunes about one metre high are found (Fig. C 7). The individual corals and coral colonies of the Gisliflue reef limestones are often difficult to recognize due to their internal cementation and recrystallization (Fig. C 8).

The St. Ursanne coral reef (Fig. A 13) does not form clear positive reliefs on the white limestone rock face. It is only on closer inspection that coral colonies can be recognized.

Among the Jurassic deposits, the reef complex of St Germain de Joux, west of the French town of Bellegarde, not far from the Swiss border, deserves a special mention. This site is under protection.

Figure C 7 a: *Former submarine dune of the Middle Dogger in the Great Oolithe (Hauptrogenstein) at the Schellenbrücke near Küttigen (Aargau, Coo. 47.42544/08.05403).* ***b:*** *The sand consisted of small limestone spheres (diameter 1 to 2 mm), called ooids, which formed in the warm, turbulent and shallow water of the maritime platform (Wildi & Lambert 2019).*

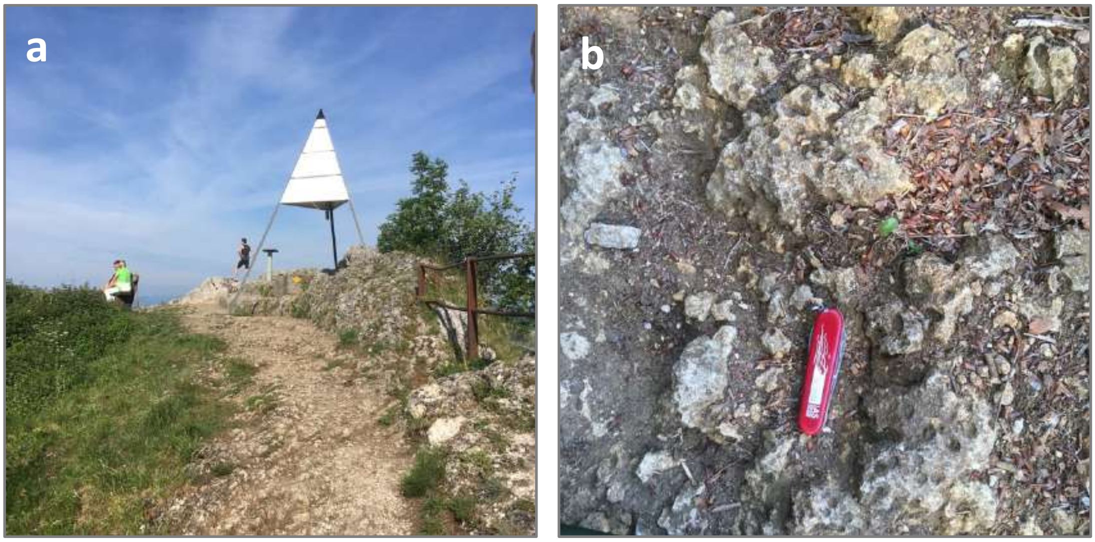


Figure C 8 a: *Reef limestone at the top of the Gisliflue (Aargau, Coo. 47.42544 / 8.10844),* ***b:*** *Coral colony.*

Parmi les gisements jurassiques, le complexe récifal de St Germain de Joux, à l'Ouest de la ville française de Bellegarde, non loin de la frontière suisse, mérite une mention particulière. Ce site est sous protection.

F: https://www.saintgermaindejoux.fr/patrimoine/site-classe/

The reef complex is located on the right bank of the Semine River, just downstream of a fish farm (Coo 46° 11' 42.2 '' N, 45° 59' 38.8 E, Fig. C 9).

The corals form small massifs of a few meters, surrounded by reef debris and other porous limestones. Visiting the reef complex requires good off-road skills and caution. **We ask visitors not to use their geological hammer!**

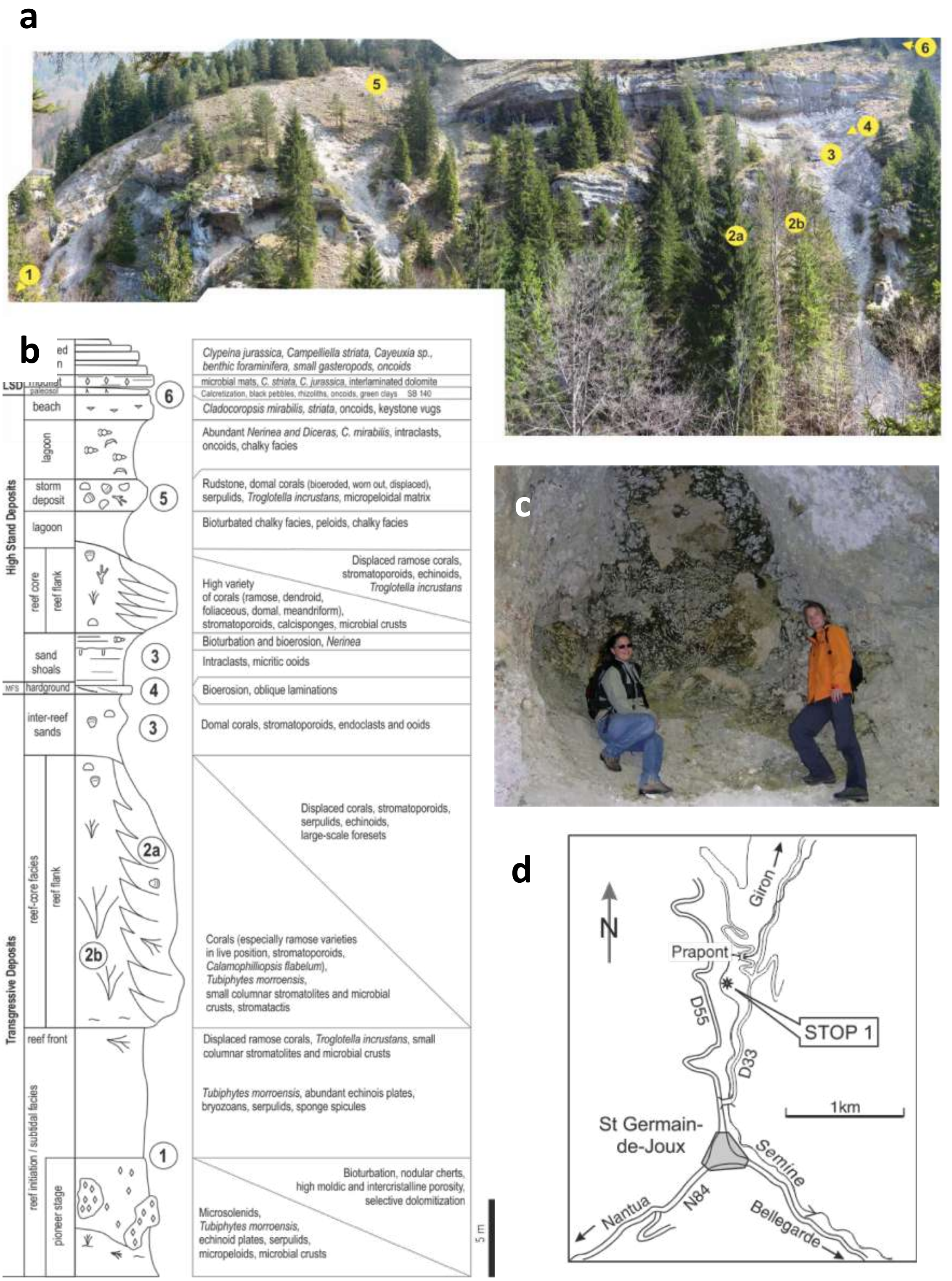


Figure C 9 a: *St Germain de Joux reef complex; numbers in figs**. a and b**: location and stratigraphic position of observation points b: synthetic stratigraphic profile, Davaud et al. (2014).* ***c:*** *coral colony (point 2 b).* ***d:*** *location map (op. cit.).*

14. Dinosaur footprints in the Jura mountains

The dinosaur footprints of Courtedoux (today more than 14'000 footprints) were discovered during the construction of the A 16 motorway. The Jurassica Museum of Porrentruy now manages the site and the nature discovery trail.

F: https://www.jurassica.ch/fr/Satellites/Sentier-didactique/Sentier-didactique.html

Voir également:
F: https://courtedoux.ch/tourisme-economie/a-voir-dans-la-region/traces-de-dinosaures/

15. Turbidites and flysch of the first alpine fold

As shown in Figure A 17, flysch sediments are formed during the deposition of turbidity currents ("sediment avalanches") of fine and coarse erosional material (pebbles, sand, silt and clay) on deep-sea fans. Figure C 10 (see also Figure A 16) shows the typical structure resulting from such a sedimentary event; it starts with erosion, followed by the deposition of graded sand, and then fine sand and silt. Intercalated between the sand deposits one finds layers of silt and clay, known as "hemipelagic". The flysch landscapes generally form gentle morphological terrains, with landslides and wet soil.

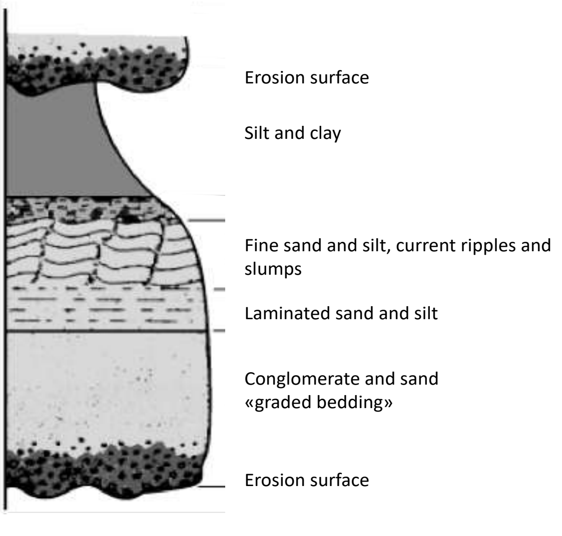


Figure C 10:
Sedimentary structures resulting from the deposition of a turbidity stream (thickness: usually from decimeter to one meter).

Along the Infopfad of the Niesen funicular, there is a very informative explanation of the Niesen Flysch.

D, E: https://www.niesen.ch/file/infopfad/Geologie%20am%20Niesen.pdf

In the following excursion description, the Schlierenflysch in the Habkern syncline is explained in its geomorphological environment:

D: https://www.habkern-archiv.ch/dmxDaten/rubriken/NA/NA_0003_Geomorphologischer%20Exkursionsf%C3%BChrer%20Daniela%20L%C3%BCthi%202009_1.pdf

The "Sentier géologique Gastlosen" leads through the different flysch units of the "Nappe supérieure" of the Pre-Alps of western Switzerland:

D: https://www.erlebnis-geologie.ch/geoweg/sentier-geologique-des-gastlosen-geologischer-pfad-gastlosen/

F: https://www.erlebnis-geologie.ch/fr/geoweg/sentier-geologique-des-gastlosen-geologischer-pfad-gastlosen/

The following museum is dedicated to the mining of roof slates («Engi-Dachschiefer») which is more than a century old.

D, F, E: https://landesplattenberg.ch/schiefertafelfabrik-elm/

These sediments are found just above the last flysch deposits of the Alps. The museum also offers guided tours for the public.

16. Erosion of the early alpine mountain chain: Rigi fluvial fan (Subalpine Molasse)

The first of the following Internet addresses describes a boat trip on Lake Lucerne with a magnificent geological panorama of the Alpine front. The alluvial fan of the Subalpine Molasse of the Rigi holds an important position here.

D, F, E: https://www.erlebnis-geologie.ch/geoevent/geologische-schifffahrt-auf-dem-vierwaldstaettersee-d-e-f/

In the following article, the authors describe the geomorphology of the Mount Pèlerin Molasse:

F:https://www.unil.ch/files/live/sites/igd/files/shared/Travaux_et_recherches/Pralong_Reynard_2004.pdf

Figure C 11: *The most characteristic rocks of the Subalpine Molasse are conglomerates ("Nagelfluh") which were formed by the cementation of coarse river deposits (gravel) on the alluvial debris fans along the Alpine front. Nagelfluh is often found as erratic blocks on the moraines of the valleys of the Swiss Plateau (here on the terminal moraine of the Reuss glacier between Mellingen and Mägenwil, Aargau).*

17. The last alpine foreland sea: the Upper Marine Molasse

The following excursion describes the Upper Marine Molasse near Zofingen and connects the construction of the Gothic town church with the building blocks used for its construction

D, F: https://www.erlebnis-geologie.ch/geoevent/geo-wanderung-stadtkirche-von-zofingen-zu-den-molassesteinbruechen-chuzenhoehle/

The moraine crest of the Reuss glacier of the last ice age near Mellingen is supported on the left side of the valley on Upper Marine Molasse. Here you can find quarries in which shell sandstone, among other things, has been mined since Roman times.

D, F: https://www.erlebnis-geologie.ch/geoevent/geo-wanderung-um-das-zungenbecken-des-reussgletschers-von-mellingen-d-f/

18. Witnesses of the folding of the Alps and alpine nappes

The visitor center for the UNESCO World Natural Heritage Site "Tectonic Arena Sardona" offers the ideal entrance to one of the type localities in which the “Nappe theory” of the Alps was developed.

D: https://www.erlebnis-geologie.ch/geoevent/unesco-besucherzentrum-glaruselm-der-tektonikarena-sardona/

(See also: **D, E:** https://unesco-sardona.ch/)

The walks through the Tectonic Arena of Sardona are presented in the following brochure:

D: https://www.erlebnis-geologie.ch/wp-content/uploads/2019/10/Sardona-Welterbe-Weg-Wandern-in-der-Sardona-Region-1.pdf

Excursions on the Via GeoAlpina::

D: https://www.swisstopo.admin.ch/de/wissen-fakten/geologie/geologie-alltag/geologie-fuer-alle/via-geoalpina.html#dokumente

F: https://www.swisstopo.admin.ch/fr/connaissances-faits/geologie/geologie-quotidien/geologie-pour-tous/via-geoalpina.html

I: https://www.swisstopo.admin.ch/it/conoscenze-fatti/geologia/geologia-quotidiana/geologia-per-tutti/via-geoalpina.html

The Lochsiten site near Schwanden (Glarus): type locality of the Glarus main thrust fault and "most famous outcrop" in Swiss geology:

D: https://www.erlebnis-geologie.ch/geoweg/lochsiten-weg/

The Val d'Hérens presents several excursions into the alpine nappes south of the Rhône valley:

F: http://www.evolene-geologie.ch/data/documents/LeshautslieusgologiquesduvaldHrens.pdf

The Val Piora guide offers a multidisciplinary approach, linking geology, mineralogy, soils, flora, fauna and the economy of the mountain pastures:

https://archive-ouverte.unige.ch/unige:96563

19. The Folded Jura Mountains: last expression of the alpine

D: https://www.erlebnis-geologie.ch/geoweg/geowanderweg-kuettigen-staffelegg/

D, F: https://www.erlebnis-geologie.ch/geoevent/geo-wanderung-von-der-staffelegg-nach-densbueren/

D: https://www.erlebnis-geologie.ch/geoweg/geologische-wanderung-baerschwil/

D: https://www.erlebnis-geologie.ch/geoweg/geologischer-wanderweg-weissenstein/

20. “Deckenschotter”: gravel terraces of the early ice ages

Wildi & Lambert (2019) describe, on pages 95-100, the magnificent outcrops of Upper Cover Gravel on the Egg Schneisingen (Studenland, Canton Aargau; see also Fig. A 31 above) and Lower Cover Gravel on the Bruggerberg (Fig. A 32 above) and in the Tüfels-Chäller near Baden (Figure A 32 b). The "Geo-Pfad Baden" leads the visitor to these conglomerate towers:

D: https://wald.baden.ch/public/upload/assets/20999/Broschuere_Geo_Pfad.pdf

21. Ecoteaux: traces of the first Lake Geneva 800’000 years ago

Perched high above Lake Geneva, Ecoteaux (Palézieux) shelters lake sediments from the ancient and middle Pleistocene. These are the oldest traces of a large lake in the Lake Geneva basin::

F: https://www.erlebnis-geologie.ch/geoevent/ecoteaux-sur-les-traces-du-premier-lac-du-bassin-lemanique-il-y-a-800000-ans/

22. Glacier morphologies on the Swiss Plateau

D, F: https://www.erlebnis-geologie.ch/geoevent/geo-wanderung-um-das-zungenbecken-des-reussgletschers-von-mellingen-d-f/

D, F: https://www.erlebnis-geologie.ch/geoevent/geo-wanderung-im-drumlinzirkus-von-schwand-menzingen/

D: https://www.erlebnis-geologie.ch/geoweg/der-bischofsberg/

23. Climate change, glaciers and landscapes

This excursion to the Mer de Glace glacier in Chamonix illustrates the fluctuations of glaciers and climate during and especially after the Little Ice Age, from 1850 onwards:

F, E: https://www.erlebnis-geologie.ch/geoevent/mer-de-glace-chamonix-mont-blanc-du-petit-age-glaciaire-1850-a-nos-jours/

Glaciers are very sensitive indicators of climate change. The excursion to the glaciers of Mont Miné and Ferpècle (Val d'Hérens) gives an overview of how glaciers have functioned and the history of glaciers and climate since the end of the Little Ice Age:

F: https://www.erlebnis-geologie.ch/wp-content/uploads/2020/03/F-Evole%CC%80ne-Paysagesglaciaires.pdf

D: https://www.erlebnis-geologie.ch/wp-content/uploads/2017/01/D-Evolene-Gletscherlandschaften.pdf

E: https://www.erlebnis-geologie.ch/wp-content/uploads/2020/03/E-Evole%CC%80ne-Glaciallandscapespdf.pdf

The mountain village of Zinal (Valais) lies in a beautiful alpine landscape, shaped by recent glacial history. It was only in 1960 that Zinal became a winter sports resort. Constantly threatened by avalanches and debris flows, the village only developed thanks to extensive protection measures. Climate change is contributing to this precarious situation:

F, E: https://www.erlebnis-geologie.ch/geoevent/zinal-histoire-naturelle-et-presence-humaine/

In the Swiss National Park (Engadine, Graubünden), rock glaciers, debris flows and scree slopes illustrate the link between climate and geological processes.

D: https://www.erlebnis-geologie.ch/geoweg/der-geologische-kreislauf/

General information:

D: https://www.nationalpark.ch/tasks/sites/de/assets/File/Geologie_Focus.pdf

Finally, mention should be made of the Niederweningen Mammoth Museum, which is dedicated to the fauna of the ending ice age and the first human settlement:

D: https://www.mammutmuseum.ch/

24. "Landslides and Human Lives»

On the tour of Firstboden (page 18 of the brochure), the visitor experiences the historic Elm landslide (1881):

D: https://www.erlebnis-geologie.ch/wp-content/uploads/2019/10/Sardona-Welterbe-Weg-Wandern-in-der-Sardona-Region-1.pdf

An excellent description of the historic landslides of Derborence (1714 and 1749) and a suggestion for a hike of about 2 hours ½:

F: http://www.derborence.ch/wp-content/pdf/brochure_Eboulement_ecran.pdf

Geological explanation of the Goldau landslide (1806), visit to the landslide museum and a suggestion for a 6-hour mountain hike:

D: http://www.planat.ch/fileadmin/PLANAT/planat_pdf/alle_2012/2006-2010/Thuro__Rick_et_al_2006_-_Die_Bergstuerze_am_Rossberg.pdf

D: https://www.edwinwandert.com/2017/03/unterwegs-im-goldauer-bergsturz/
https://www.erlebnis-geologie.ch/geoevent/bergsturz-flims/

25. Geology and archaeology

A guide to the geological history and archaeology of the city of Geneva, with three suggestions for excursions.

F, E: https://www.erlebnis-geologie.ch/geoevent/geologie-et-archeologie-de-geneve/

26. Caves and karst

The karst caves are a geological attraction in Switzerland and bring many visitors every year. Subterranean karst is formed by the chemical dissolution of rocks by water. The water either penetrates from the surface through cracks and tectonic fractures in the subsoil and follows underground flow paths under the influence of gravity to an outlet, usually a karst spring (so-called "epigenetic" karst). Or the water (often aggressive thermal waters) follows an upward path and emerges at the surface. In Switzerland, mainly epigenetic caves are well known and have been studied in detail.

The longest and most stable karst caves are found in carbonate rocks (limestones and dolomites), in areas with high relief, such as the frontal chain of Swiss tablecloths, along the northern edge of the Alps (Höllgrotten in Zug, St.-Beatus Höhlen in Thun, etc.), in the "root zone of Helvetic nappes" (underground lake of Saint-Léonard, Valais) and in the folded Jura (Réclère Caves, Orb Caves, Vallorbe, etc.).

Epigenetic caves may have formed in the course of the Earth's history as soon as the corresponding rocks rose above sea level. Caves formed at an early stage (especially horizontal or gently sloping pipes) were later deformed by tectonic movements. Vertical shafts are often younger and have not moved since their origin.

In the Jura, the conditions for the formation of caves already existed in the Upper Miocene (age of the Upper Freshwater Molasse); in the frontal chain of the Swiss Mudflats, the conditions for deep karstification may have been met earlier, but no dating is available at present.

Sedimentary deposits in caves play an important role in the reconstruction of past climate (glacial/interglacial periods), the memory of glacial fauna and the history of human settlement (Audra et al. 2007).

Several websites list and describe caves in Switzerland. Suggestions for visits for everyone can be found (among others) on the following websites:

D: https://www.freizeit.ch/dossier/20385/die-schonsten-hohlen-und-grotten-der-schweiz

D, F, E, I, . . .: https://www.myswitzerland.com/en-ch/destinations/nature/caves-and-grottos/

Glossary

Geographic names: All names of localities and landscapes used here can be found on Swisstopo maps using the search function: https://www.swisstopo.admin.ch/.

The names of the fossils are written in *italic* characters in the text.

For geological ages, see Figures A 2 and B 1.

Anhydrite: mineral name and sedimentary rock formed from anhydrous calcium sulphate ($CaSO_4$; see also: gypsum), deposited in salt lagoons and sebkhas.

Bolus: pea-shaped concretion of iron or limonite (iron oxide), often with concentric shells. Until the middle of the 20th century, bolus was exploited in Switzerland, particularly in the mines of the Jura.

Breccia: consolidated sedimentary rock consisting of angular elements (not rounded) of the order of cm to dm diameter.

Carbonates, carbonate rocks: calcareous and dolomitic rocks.

Collision: when two terrestrial plates come closer together (plate tectonics, continental drift), a plate with dense rocks (oceanic rocks) dives under a plate with less dense rocks (continental rocks) and sinks deeper. Subduction is the opposite of collision of plates with less dense continental rocks. The Alps, with their superimposed nappes, are the result of a collision between Europe and Africa. This followed the subduction of the ocean floor of the Liguro-Piemontese Ocean.

Conglomerate: clastic deposit with rounded elements, consolidated by cement.

Earth's crust: upper rocky layer of thesolid earth. The continental earth's crust consists mainly of granite, gneiss and sedimentary rocks. The oceanic earth's crust consists mainly of basalt.

Effingen Layer: geological formation of limestone of the early Malm (Upper Jurassic) in the Jura region. This lithology is used for the production of cement.

Erratic boulder or block: block of rock transported by the glacier and deposited on the edge of the glacier, mainly of alpine origin.

Dolomite: rock formed from dolomite minerals $CaMg(CO_3)_2$. Origin: sedimentary rock formed in highly mineralized sea water, in lagoons and salt deserts (sebkhas).

Erosion: removal, abrasion of rocks by the action of glaciers, water and wind.

Fault: surface on which two rock compartments have moved against each other.

Folded Jura: southern part of the Jura mountains with folded and sometimes superimposed rock layers.

Folds, folding: layers of rock folded by lateral pressure. The term "alpine folding" refers to the tectonic processes that led to the formation of the Alps.

Fossils: remains of plants and animals from the past.

Glacial period (glaciation): period in the history of the earth with a cold climate and a major advance of the Alpine glaciers.

Gneiss: Metamorphic rock formed by recrystallization, in layers from cm to several dm thick.

Granite: massive magmatic rock formed by the intrusion of magma into the earth's crust and crystallization by cooling. Composition: feldspar, quartz, mica and subordinate minerals.

Günz, Mindel, Riss, Würm: the four classical glaciations of the last 800,000 years of the Pleistocene.

Gypsum: mineral and rocky name for calcium sulphate hydrate ($CaSO_4$ x $2H_2O$). Gypsum is a sedimentary rock (evaporite rock) of lagoons and sebkhas.

Hauptrogenstein, ("Grande Oolithe"): coarsely stratified limestone rock formation from the Middle Dogger. "Rogen" are limestone globules of mm-size (ooides). They were formed in the wave zone of a shallow, rough sea.

Interglacial: period of warm climate between two glaciations. We currently live in an interglacial called Holocene.

Karst: underground cavities (caves) and surface reliefs (dolines, "lapiaz") on carbonate rocks (dolomite, limestone) and evaporites (sulphate, salt). Karst is mainly formed by the dissolution of carbonates and evaporites by the circulation of surface and ground water.

Limestone, calcareous rocks: marine sedimentary rocks consisting of calcium carbonate ($CaCO_3$). Limestone rocks are formed mainly by fine algae (nanoplankton) and various fossil shells.

Loose (soft) rock: rock without firm cohesion, not cemented ('mud', clay, silt, sand, gravel).

Marl: solid and soft rock consisting of a mixture of clay and carbonate.

Metamorphosis: process of transformation of minerals and rocks at high temperatures and pressures (> 200 °C). In the Alps, metamorphosis (or metamorphism) is linked to the alpine folding (orogenesis).

Mica: 'phyllosilicate' (in sheets) and aluminosilicate, composed mainly of aluminium, silicon, calcium and others. The phyllosilicates form thin leaves that shimmer in the sun. Colours: transparent (muscovite, sericite), black to green (biotite), green (chlorite) Origin: formed during the crystallization of granite and during metamorphosis.

Molasse: rock consisting of the products of Alpine erosion: conglomerates, sandstone, marl and clay. A distinction is made between marine molasse deposited in the shallow sea and freshwater molasse formed by rivers and lakes.

Nappes: this term refers to the large geological (or tectonic) units (often several kilometres long) that were pushed one on top of the other during the folding of the Alps (thrusts).

Nagelfluh: a popular term for conglomerates of freshwater molasse and cemented gravel from the Ice Age.

Opalinus Clay: rock formation of black clay about 100 m thick. This clay was deposited at the beginning of the Dogger (Middle Jurassic) in a sea of several tens to more than a hundred metres deep. The clay material probably came mainly from the erosion of the Bohemian Massif.

Platform, carbonate platform, marine platform: shallow sea ("shelf sea"), usually with a water depth of less than about 250 m, in which carbonates are deposited.

Quartz: transparent or whitish mineral composed of silicon and oxygen (SiO_2). One of the most common minerals in the composition of the earth's crust.

Quartzite: rock consisting of quartz, either of sedimentary origin (sand) or resulting from crystallization in cracks and other cavities.

Sebkha: salt-lake or salt plain in an arid climate (desert).

Sedimentary rocks, sediments: continental and marine sedimentary rocks. Detrital sedimentary rocks such as clayey rocks, marls, sandstones, breccias and conglomerates can be distinguished from rocks of biological or chemical origin such as carbonate rocks, gypsum and rock salt.

Silicates, silicate rocks: minerals (rocks) with a high proportion of silicon.

Slate: sedimentary or metamorphic (recrystallized) rocks in thin millimetric layers.

Solid rock: compact sedimentary rock, often cemented by carbonate or siliceous cement, but also metamorphic crystalline rocks and intrusive rocks.

Subduction, subduction zone: when two terrestrial plates approach each other (plate tectonics, continental drift), a plate with dense rocks (oceanic rocks) dives under a plate with less dense rocks (continental rocks) and sinks to depth. Collision is the opposite of subduction.

Syncline: large fold where the "back" (the axis) of the fold is located more or less at the bottom and the flanks in the air.

Tabular Jura: northern part of the Jura mountains. The rocks of the Tabular Jura are generally not folded, but can be offset by fractures and faults (e.g. the Rhine valley rift).

Bibliography

Most descriptions of field and site visits also include a bibliography. The bibliography below is therefore limited to references to the titles cited in the text of Chapters A, B and C.

Audra, P., Bini, A., Gabrovsek, F. & al. 2007: Cave and karst evolution in the Alps and their relation to paleoclimate and paleotopography. Acta Carsologica 36/1, 53-68.

Bini A., Buoncristiani J.-F., Coutterand S., Ellwanger D., Felber M., Florineth D., Graf H.R., Keller O., Kelly M., Schlüchter C. & Schoeneich P. 2009: La Suisse durant le dernier maximum glaciaire. Swisstopo, Wabern.

Bolliger T., Feijar O., Graf H., Kälin D. 1996: Vorläufige Mitteilung über Funde von pliozänen Kleinsäugern aus den höheren Deckenschottern des Irchels (Kt. Zürich). Eclogae Geologicae Helvetiae 89, 1043-1048.

Caron, C., Homewood, P., & Wildi, W. 1989: The original Swiss flysch: a reappraisal of the type deposits in the Swiss prealps. In: Earth-Science Reviews 26, n° 1-3, p. 1-45.

Cuenca-Bescos, G. 2015: The Pleistocene small mammals from Irchel, Switzerland; a taxonomic and biostratigraphic Revision. ENSI, 48 p.

Davaud, E., Gorin, G. & Rusillon, E. 2014: Reef and lagoonal bituminous carbonates from the Kimmeridgian of the western Jura mountains. International sedimentological congress, IAS, Geneva, 17 p.

Decrouez, D., Furrer, H., Weissert, H. & Wildi, W. 1997: Geologie und Zeit. Vfd, Zürich, 62 S.

Eberl, B. 1930: Die Eiszeitenfolge im nördlichen Alpenvorland. – Benno Filser Verlag, Augsburg.

Graf H.R. 1993: Die Deckenschotter der zentralen Nordschweiz, Dissertation Diss. ETH Nr: 10205, ETH Zürich, Zürich.

Heer, O. 1883: Die Urwelt der Schweiz. Schulthess-Verlag Zürich.

Heim, A. 1932: Bergsturz und Menschenleben. Fretz & Wasmuth, 218 S.

Kay, C.E. 2009: Tethyan–Mediterranean organic carbon-rich sediments from Mesozoic black shales to sapropels. Sedimentology 56, 247-266.

Marthaler, M. 2005: Le Cervain est-il Affricain? LEP Loisirs et pédagogie, Lausanne, 96 p.

Marthaler, M. 2019: Moiry: de l'Europe à l'Afrique. Editions LEP, Le Mont sur Lausanne.

Müller, W.H., Huber, M., Isler, A. & Klebot, P.h 1984: Erläuterungen zur Geologischen Karte der zentralen Nordschweiz 1:100'000. Nagra, NTB 84-25, Baden.

Nussbaumer, S.U., Zumbühl, H.J. & Steiner, D. 2007: Fluctuations of the Mer de Glace (Mont-Blanc area, France) AD 1500–2050: an interdisciplinary approach using new historical data and neural network simulations, Zeitschrift für Gletscherkunde und Glazialgeologie 40(2005/2006): 1-183.

Penck, A. & Brückner, E. 1901/1909: Die Alpen im Eiszeitalter. C. H. Tauchnitz, Leipzig , 1199 S. in drei Bänden.

Pfiffner , O.A. 2015: Geologie des Alpen. Haupt Bern, 400 S. dritte Aufl.

Preusser, F., Graf, H.R., Keller, O., Krayss, E. & Schlüchter Ch. 2011: Quaternary glaciation history of northern Switzerland. , E&G Quaternary Science Journal 60/2-3, 282-305

Pugin, A., Bezat, E., Weidmann. M. & Wildi, W. 1993: Le bassin d'Ecoteaux (Vaud, Suisse): Témoin de trois cycles glaciaires quaternaires. Eclogae geol. Helv. 86/2, 343-354.

Schaefer, I. 1957 : Erläuterungen zur Geologischen Karte von Augsburg und Umgebung 1 : 50 000. – Bayrisches Geologisches Landesamt, München.

Schlüchter, Ch. 1976: Geologische Untersuchungen im Quartär des Aaretals südlich von Bern (Stratigraphie, Sedimentologie, Paläontologie). Beitr. geol. Karte Schweiz (N.F.) 148.

Schminke, Th., Frechen, H.-U., & Schlüchter, C. 2008: Quaternary. - In: McCann, T. (Ed.): The Geology of Central Europe, vol. 2, Mesozoic and Cenozoic, Chapter 20: 1287-1347.- The Geological Society (London).

Seguinot, J., Ivy-Ochs, S., Jouvet, G., Huss, M., Funk, M. & Preusser, F. 2018: Modelling last glacial cycle ice dynamics in the Alps. The Cryosphere, 12, 3265–3285.

Shackleton, N. J. 1967: Oxygen isotope analyses and Pleistocene temperatures reassessed; Nature 215, 15-17.

Spratt, M. & Lorraine E. Lisiecki, L.E. 2016: A Late Pleistocene sea level stackRachel. Clim. Past, 12, 1079–1092.

Trümpy, R. 1980: 1980: Geology of Switzerland, a guide-book; Wepf Verlag, Basel.

Ungricht, S. & Pika-Biolzi, M. (ohne Datum): Öhningen am Bodensee. Die Klassische Fossillagerstätte erlaubt eine Rekonstruktion der Lebensbedingungen im Alpenvorland vor 13 Millionen Jahren. ETH Zürich, Earth science collections. https://www.ethz.ch/content/dam/ethz/special-interest/erdw/erdwissenschaftliche-sammlungen/documents/Ohningen_DE.pdf

Weissert, H. & Stössel, I. 2015: Der Ozean im Gebirge. Vdf Zürich, 198 S. dritte Aufl.

Wildi, W. 2017a: Geo-Wanderung im Drumlinzirkusvon Schwand (Menzingen), Univ. de Genève, 8 S., https://www.erlebnis-geologie.ch/geoevent/geo-wanderung-im-drumlinzirkus-von-schwand-menzingen/

Wildi, W. 2017b: Zinal: histoire naturelle et présence humaine / Zinal: Natural history and humanpresence. https://www.erlebnis-geologie.ch/wp-content/uploads/2018/02/Zinal-guide-1.pdf

Wildi, W., Corboud, P., Gorin, G. & Girardclos, S. 2017: Guide : géologie et archéologie de Genève / Guidebook: geology and archaeology of Geneva, 2e éd., 93 p. Section des sciences de la Terre et de l'environnement, Univ. Genève. https://archive-ouverte.unige.ch/unige:92676

Wildi, W., Gurny-Masset, P. & Sartori, M. 2016: Führer durch die Gletscherlandschaften des Val d'Hérens. Section des sciences de la Terre et de l'environnement, Université de Genève, 35 p. http://www.unige.ch/forel/fr/services/guide/valdherens/

Wildi, W. & Lambert, A. 2019: Erdgeschichte und Landschaften im Kanton Aargau. Aarg. Natf. Ges, Aarau, 2. Aufl.

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(Michel Marthaler, photo: Christophe Wildi)