1:500 000

Swiss geological Survey

Tectonic Map of Switzerland

Explanatory notes

Editor: YVES GOUFFON

Authors: DANIEL BERNOULLI, STEPHAN DALL'AGNOLO,
ROBERTO FANTONI, YVES GOUFFON, PETER JORDAN,
HERFRIED MADRITSCH, JON MOSAR, VINCENZO PICOTTI,
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and STEFAN M. SCHMID

Schweizerische Eidgenossenschaft
Confédération suisse
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Federal Office of Topography swisstopo
www.swisstopo.ch

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2024

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with 7 figures, 2 tables and 3 plates

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Citation recommendation

Map sheet
swisstopo (2024): Tectonic Map of Switzerland 1:500 000. – Federal Office of Topography swisstopo, Wabern.

Explanatory notes
GOUFFON, Y. (editor) (2024): Tectonic Map of Switzerland 1:500 000, Explanatory notes. – Federal Office of Topography swisstopo, Wabern.

Cover pictures

Cover
View of the Ringelspitz/Piz Barghis southeastern flank. The Glarus Thrust separates the overthrust Upper Helvetic Verrucano from the underlying Lower Helvetic Sardona Nappe. The Verrucano displays a weakly pronounced stratification which runs parallel to the thrust fault. The banding in the marly shales of the Sardona cover reveals a folding. In addition, the Lochsiten calc-mylonite can be seen in places as a thin whitish band along the Glarus Thrust. A remnant of the Tamins Glacier is visible at the bottom left of the image. Photo A. Pfiffner, 2016.

Cover back
Location of the map within a section of the International Geological Map of Europe 1:5 Million (IGME5000, registered in the European Geological Data Infrastructure [EGDI]; modified).

Map sheet
Simplified tectonic overview of the map draped on the digital elevation model swissALTI$^{\mathrm{REGIO}}$.

Explanatory notes
Fold in the Malm of the Morcles Nappe. South face of the Haut de Cry, summit between Ardon and the Grand Muveran, looking north from the Col du Lein. Photo A. Morard, 2018.

Editor

ISBN 978-3-302-40125-6

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FOREWORD

This 4th edition of the Tectonic Map of Switzerland 1:500 000 represents a major update of the geometry, distribution and nomenclature of the tectonic units in Switzerland and its neighboring regions. This update was necessary because numerous detailed maps – in particular the map sheets of the Geological Atlas of Switzerland 1:25 000 – have been published since the release of the 3rd edition of the map, published in 2005. Moreover, the nomenclature of these units has been harmonized. This harmonization was initiated by the Swiss Geological Survey (swisstopo) as part of the updating of its Geological Data Model, at the same time as the harmonization of lithostratigraphic units. In order to create both a widely accepted concept and an exhaustive list of the tectonic units, the Swiss Geological Survey convened an expert group1) comprising geologists from Swiss universities and private companies, some of them members of the Swiss Geological Commission. The objective of the expert group was to establish a logical, coherent terminology that both reflects the current literature and can be integrated into teaching.

For the first time, the Tectonic Map of Switzerland is accompanied by explanatory notes which provide a brief definition of each unit of the map, and which also explain the reasons for their interpretation or nomenclature. English has been chosen as the language for the text, not only to make it accessible to an international readership, but also because English has become the lingua franca for communications between scientists in the different linguistic regions of Switzerland.

The enclosed cross-sections plate (Pl. II) now contains three sections: the western and eastern sections which were first introduced in the 3rd edition in 2005, as well as a new third (central) section, following the model adopted on Plate 8.2 of the Hydrological Atlas of Switzerland in 1997 (O.A. Pfiffner & L. Jemelin). All these three cross-sections have also been updated with content from the following sources: structures from the new map and many local studies of the shallow subsurface; structures from deeper studies of the subsurfaces (MARCHANT 1993, SCHMID et al. 2017) as well as from the GeoMol model (LANDESGEOLOGIE 2017). The details shown at depth in the central part of the Alps, on both the western and eastern cross-sections, are the result of projecting major features, visible on the surface, laterally up to 80 km. The cylindrical projection of these deep features does

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1) Members of the expert group Harmos Tectonic (in alphabetical order): Dr. Reto Burkhalter[a], Dr. Yves Gouffon[a], Prof. Marco Herwegh[b], Dr. Peter Jordan[c], Dr. Oliver Kempf[a], Prof. Neil Mancktelow[g+], Prof. Henri Masson[d], Dr. Andreas Möri[a+], Prof. Jon Mosar[e+], Prof. Adrian Pfiffner[b+], Dr. Mario Sartori[f+], Prof. Albrecht Steck[d], Dr. Michael Wiederkehr[a].

[a] Federal Office of Topography swisstopo, Wabern; [b] Bern University; [c] Gruner AG, Basel; [d] Lausanne University; [e] Fribourg University; [f] Genève University; [g] ETH Zürich; [+] Swiss Geological Commission (SGK).

not necessarily correspond to the reality at depth and should therefore to be considered with caution.

The legend is presented on separate plates (Pl. Ia–Id), enabling it to be supplied in four languages – the three main Swiss ones in addition to English – thus reducing the size of the map sheet and making it easier to handle.

The Swiss Geological Survey would like to thank the members of the tectonic expert group¹⁾ for the fruitful discussions that made this work possible. We pay a special tribute to Albrecht Steck, who passed away at the beginning of 2021.

Thanks to Anna Rauch for updating the map for the Penninic and Austroalpine domains in Switzerland, supported by the advice of Prof. Stefan Schmid for the Lower Engadine Window and surrounding areas. Many thanks to the authors of the explanatory notes: they have spared no effort writing a text that gives the reader a concise and clear overview of the tectonic units represented on the map; they have also contributed their knowledge and advice for updating the map, especially in the regions bordering Switzerland. Thanks to the members of the Swiss Geological Commission for reviewing the map and its explanatory notes, and for constructive discussions: Neil Mancktelow (chairman), Marco Antognini, Alfons Berger, Thomas Burri, Pierre Gander, Tobias Ibele, Ursula Menkveld, Jon Mosar, Anna Rauch and Stephan Wohlwend.

The editor would like to thank his swisstopo colleagues for their support: Pauline Balland (GIS support), Milena Scrignari (finalization of vector data), Jérémiah Mauvilly (cartography and drawing of figures), Evelyne Guanter (layout of the explanatory notes), Lance Reynolds (proofreading of the final version of the text and improvement of its English), as well as all other colleagues for discussions and sound advice.

March 2024

Federal Office of Topography
Swiss Geological Survey

PRELIMINARY REMARKS

Exhaustiveness: The descriptions in this publication are general and the references given are non-exhaustive. For more details, the reader is advised to consult the explanatory notes of the Geological Atlas of Switzerland 1:25 000 and the Geological Special Maps as well as the scientific literature.

Basis of the map: The present edition of the Tectonic Map of Switzerland is based on its previous edition (2005) and has been updated using a large number of detailed maps which have been published since then. The list of these maps is given at the end of this document.

Toponyms: In general, the names used in these explanatory notes are the same as those shown on the map i.e., in the one of the Swiss national languages. For example: *Thunersee* in German, *Lac de Neuchâtel* in French *Lago di Lugano* in Italian and *Lei da Marmorera* in Romansh. There are three exceptions: the English name *Rhine* has been used instead of the German name *Rhein,* with its two headwaters, the *Vorderrhein* and the *Hinterrhein;* the French name *Rhône* is used instead of the German name *Rotten* referring to its upper portion; the previous exception applies to the German name *Inn,* named *En* in Romansh. In addition, the English name does not always correspond to the literal translation of the local name, for example Lake Geneva = *Le Léman*, Lake Constance = *Bodensee* and Lake Lucerne = *Vierwaldstättersee.*

Format: The Tectonic Map of Switzerland 1:500 000 is available in both print and digital (raster and vector) format. Additional explanatory notes of this map are also provided for the first time. They can be downloaded from swisstopo.ch.

1. INTRODUCTION

Y. Gouffon

1.1. Tectonic data model

1.1.1. Definition

The tectonic nomenclature in Switzerland is strongly influenced by various concepts and also different schools of thought. Authors of scientific publications or geological maps frequently use different terms for similar units or use the same terms in different ways. This is an issue if regional data have to be compiled or if a nationwide data set needs to be produced. Moreover, geographic information systems (GIS) require consistent and unambiguous attributes for each object i.e., for each tectonic unit. Therefore, a tectonic data model is required.

A major challenge for defining a tectonic data model lies in the fact that tectonic units may be described and distinguished by various attributes such as paleogeographic origin, current structural position or changes in the metamorphic grade. All of these attributes are derived from valid approaches but need to be duly separated in a consistent model. Moreover, units representing physiographic areas (e.g., klippe, window) that fulfil none of these criteria should consequently be eliminated.

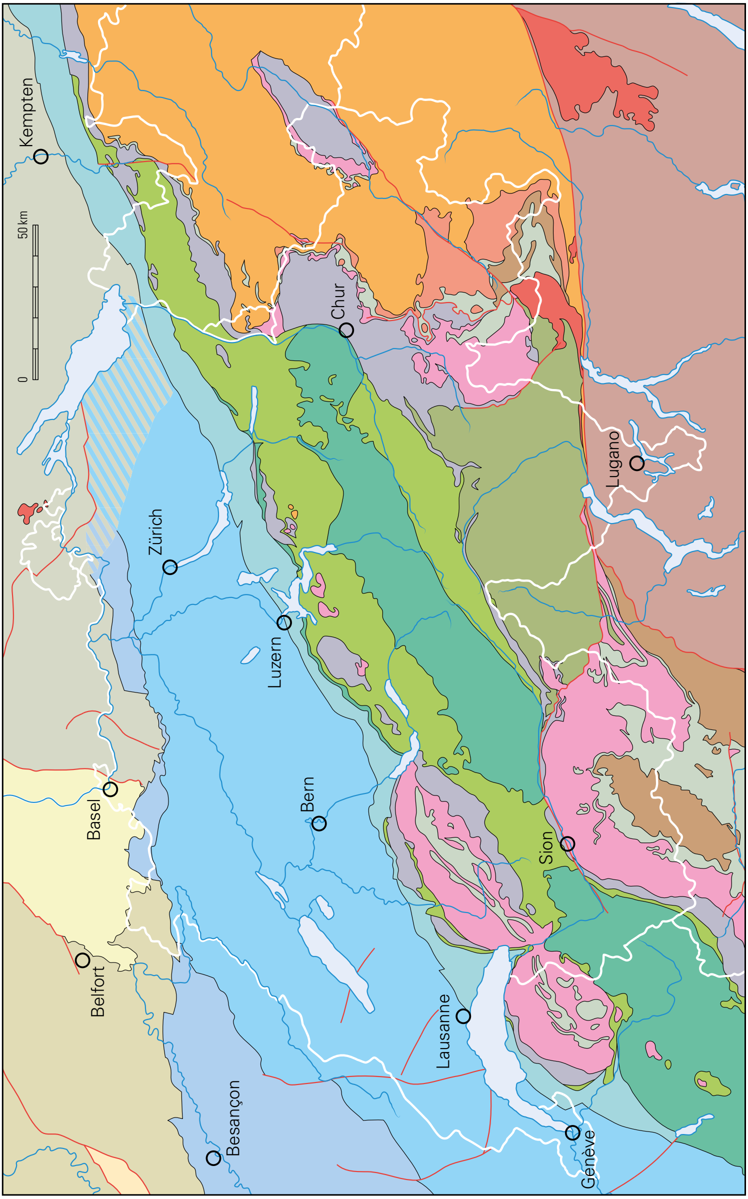
The present map is in accordance with the tectonic part of the Geological Data Model defined by the Swiss Geological Survey. This tectonic data model is primarily based on the present-day structure of the units i.e., their geometry and the nature of their contacts. It comprises four hierarchical classes (1st to 4th order; see Tab. 1). The reference units are the 3rd order units; these are mostly nappes, nappe complexes and slice complexes (see § 1.1.2 for definitions). They all are grouped together into 1st order structural *domains,* which are, in some cases, subdivided into 2nd order *subdomains* (see Fig. 1, Tab. 1). In many cases, the 3rd order units are subdivided into several 4th order units. In the Alpine regions, the 2nd order units express their present-day structural position in terms of Upper/Middle/Lower subdomains. Three additional attributes complete the characterization of each tectonic unit: 1) general lithology, 2) age of this lithology and 3) paleogeographic origin.

By definition, all units are bounded by tectonic contacts, except for the limit between the Molasse sediments (Paleogene–Neogene) of the South German Platform and those of the Internal Folded Jura and Foreland Plateau. This is why two large units distinguished in previous editions, the Molasse Basin and the Internal Folded Jura, now form a single unit: there is no tectonic boundary between the two. The displacement along the basal thrust of each unit, up to the 3rd order, typically exceeds 10 km. The boundaries of 1st order Alpine domains correspond to major thrust faults with displacements of tens or hundreds of kilometers. Their origin is typically due to tectonic plate movement, while the 1st order structural domains themselves mainly correspond to large-scale paleogeographic realms (continental platforms and margins, ocean basins, etc.; see Tab. 2). The further subdivision into the 2nd order subdomains also follows major faults with displacements of tens of kilometers. They can also have a paleogeographic origin, like the Austroalpine and Penninic subdomains, or are of purely tectonic origin like the Helvetic and North Alpine Foreland subdomains.

There are two exceptions in the definition of purely tectonic units: 1) the progressive and conceptual limit between the Detached North Alpine Foreland and the non-detached Autochthonous North Alpine Foreland (see above and § 3.2) and 2) units consisting of Cenozoic magmatic rocks, which generally do not belong to any of the tectonic units.

Table 1: *Schema of the tectonic unit classification according to the tectonic part of the Geology Data Model defined by the Swiss Geological Survey.*

1st order ***Domain***	**2nd order** ***Subdomain***	**3rd order** ***Unit*** *(examples)*	**4th order** ***Subunit*** *(examples)*
South Alpine		Ivrea-Ceneri Complex	–
Austroalpine	Upper Austroalpine	Lechtal Nappe	Madrisa Slice
			Schesaplana Slice
		Quattervals Nappe	–
	Lower Austroalpine	Err Nappe Complex	Murtiröl Slice
			Err Nappe
Salassic	–	Dent Blanche Nappe	Arolla Unit
			Valpelline Unit
Penninic	Upper Penninic	Arosa Zone	Haupterhorn Slice
			Weissfluh Slice
	Middle Penninic	Siviez-Mischabel Nappe	–
	Lower Penninic	Tomül Nappe	–
Lepontic	–	Isorno Zone	–
		Antigorio Nappe Complex	Antigorio Nappe
			Mergoscia Zone
Helvetic	Upper Helvetic	Glarner Nappe Complex	Gonzen-Walenstadt Slices
			Mürtschen Nappe
		Wildhaus Mélange	–
	Lower Helvetic	Morcles Nappe	–
Detached North Alpine Foreland	External Folded Jura	Faisceaux	–
		Plateaux	–
	Internal Folded Jura and Foreland Plateau	–	–
	Subalpine Molasse	Subalpine Slice Complex	Lutry-Thonon Slice
			Blueme-Beichle Slice
Autochthonous North Alpine Foreland	Bresse Graben	–	–
	Haute-Saône Platform	–	–
	Upper Rhine Graben	–	–
	South German Platform	Hegau-Bodensee Graben	–


Kempten
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Lugano
Zürich
Luzern
Basel
Bern
Sion
Belfort
Lausanne
Besançon
Genève

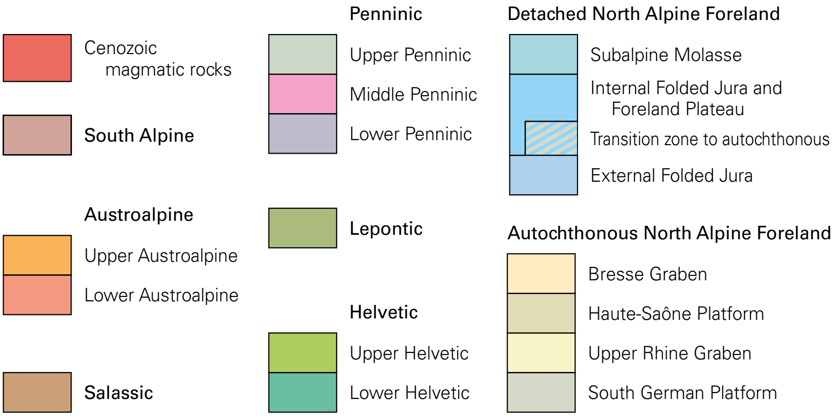

Fig. 1: Simplified tectonic map showing the geographic distribution of the domains and subdomains.

1.1.2. Terminology

According to the nomenclature adopted by the European Commission (INSPIRE registry), all tectonic units represented on the Tectonic Map of Switzerland 1:500 000 and described in these explanatory notes correspond to the definition of a “lithotectonic unit”[1]. In the present text, however, they are referred to as “tectonic units”. The specific terms used to designate these units are defined as follows:

- *Nappe:* A sheet-like rock unit that has been transported on a relatively horizontal surface, usually over a distance of more than 10 km. It generally consists of a coherent rocks that has sometimes been folded or cut by internal thrust faults. The mechanism of nappe formation can be recumbent folding, thrust faulting or a combination of both. Generally, a nappe is a reference unit of the 3rd order, but can be a 4th order unit as an element of a nappe complex.
- *Slice:* A sheet-like rock unit, similar to a nappe, but generally smaller and displaced over a shorter distance with respect to neighboring slices. Typical 4th order unit.
- *Nappe complex:* 3rd order unit made up of several (4th order) nappes and occasionally slices, which show a close relationship to each other (generally structural, or stratigraphic in the case of the Austroalpine).

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[1] see https://inspire.ec.europa.eu/codelist/GeologicUnitTypeValue/lithotectonicUnit

- *Slice complex:* 3rd order unit that groups together several 4th order slices which have a close relationship to each other. In some cases, slices are grouped into a 3rd order [xy] Slices (and not Slice complex) when they occupy the same structural position but are geographically dispersed.
- *Zone:* The term zone is not defined in a tectonic sense. However, it is used here for two main reasons: 1) Historical, the name is well known; moreover, in two specific cases, the French name is used where the zone name is not a locality: Zone Submédiane and Zone Houillère. 2) When the internal structure of the relevant unit is unclear; some of these units resemble a mélange, but metamorphism and deformation have often removed all previous structures (e.g., Orselina-Bellinzona Zone). A zone is usually a 3rd order unit.
- *Mélange, mélange zone:* A mélange is a mappable chaotic unit, the origin of which may be both lithostratigraphic and tectonic; in the latter case it is usually a 3rd order unit. It is characterized by the absence of continuous bedding and the presence of rock fragments of a wide range of sizes (centimeters to kilometers) within a fine-grained matrix. Larger fragments can be defined as slivers or slices, often containing a coherent internal structure. Each mélange is defined by the type(s) of fragment(s) it contains, most often originating from the unit(s) above and/or below. Several different mélanges may be stacked on top of each other or may laterally change their compositions, forming a mélange zone. Some mélanges have been named "wildflysch", at least in part, suggesting a sedimentary origin, but tectonic overprint is often present. A mélange or mélange zone is generally associated with a major tectonic contact and can therefore often be considered as independent with respect to the units forming the hangingwall or the footwall of this contact. However, depending on its affinities, it is attributed either to the overlying or the underlying (sub)domain.
- *Shear zone:* In two specific cases, the mélange is characterized by exceptionally strong deformation, so the names given by the authors have been retained (Roisan-Cignana Shear Zone of MANZOTTI et al. 2014a – see §7.1 – Vinschgau Shear Zone as suggested by SCHMID & HAAS 1989 – see §8.2.6).
- *Complex:* In another specific case, the emplacement mechanism of the unit seems to have nothing in common with the classical formation of nappes, so also here the name Gruf Complex given by the authors has been retained (GALLI et al. 2013; see §5.11).

1.2. Map representation

1.2.1. Tectonic units

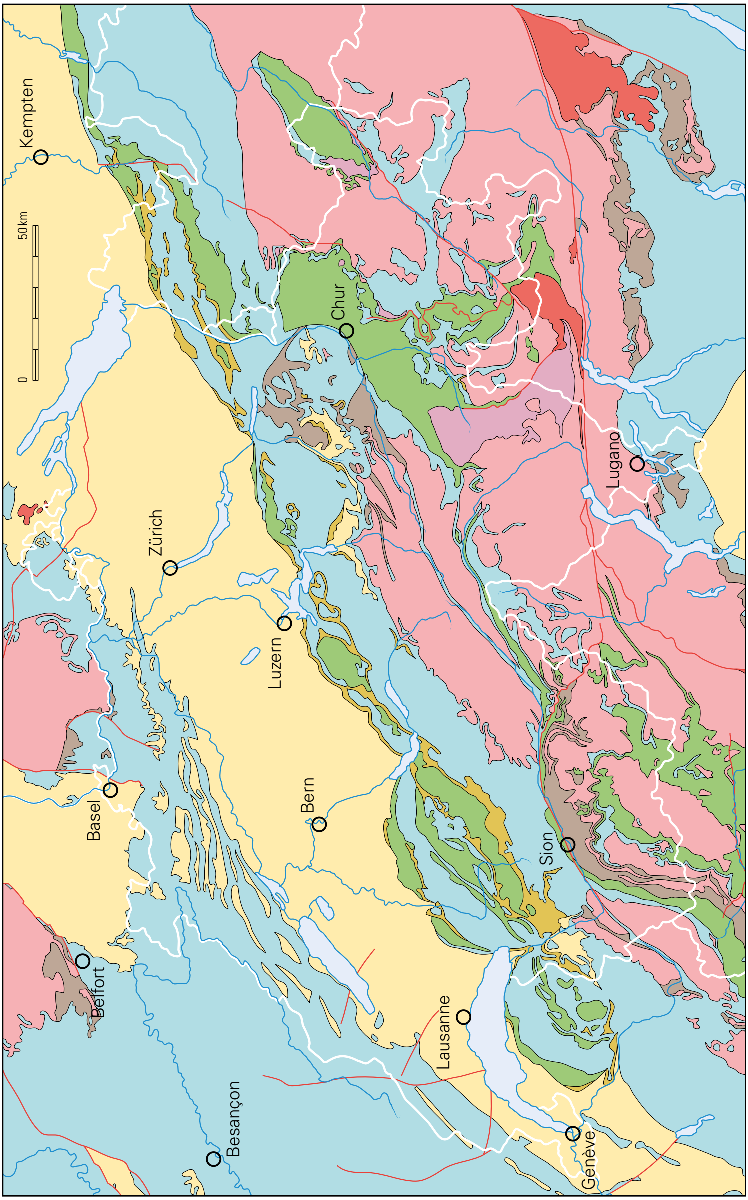
All 1st–4th order tectonic units defined in the area covered by the Tectonic Map of Switzerland (see § 1.1.1) are distinguished in the digital data set. However, for better readability, most of the 4th order units are not shown on the printed map as they are too small to be distinguished at the 1:500 000 scale. Only the largest 4th order units (elements of a nappe complex and particular slices within a nappe) are shown on the map and in the legend (names in brackets). The thrusts that separate the unrepresented units are generally not shown on the printed map, except for those of the Subalpine Molasse and a few other examples that highlight the structures of the 3rd order tectonic units. In many cases, several 3rd order units are represented by the same color and grouped together in the legend; however, they can still be identified by their limits and indexes.

On the other hand, where feasible at the map scale, some units are depicted as separate lithologies; this mainly concerns the crystalline basement and its sedimentary cover. Figure 2 shows the general distribution of the lithologies displayed on the map, independently of their tectonic setting.

In the new edition of the Tectonic Map of Switzerland 1:500 000, 1st order domains are distinguished by different color ranges (e.g., red-orange-yellow for the Austroalpine, green for the Helvetic), with variations for the 2nd order subdomains and the 3rd order units. In contrast to the previous edition (2005), the crystalline massifs of the Autochthonous North Alpine Foreland and of the Helvetic (External Crystalline Massifs) are no longer represented by a specific, different colors but rather by a color tone of the domain to which they belong (e.g., green for the Aar and Mont Blanc Helvetic massifs). This change in the representation of petrographic differences is one of the major color changes seen in the new edition of the map. This is consistent with the concept of a more structural focus chosen here.

1.2.2. Structural elements

Many *faults* with a noticeable displacement are shown on the tectonic map. The *thrusts faults* are always distinguished from other faults by a particular symbology to better understand the kinematics. In the Alps, the thrusts mainly represent boundaries between tectonic units; the symbols always indicate the upper (thrusting) unit, even if the actual position is overturned with respect to the situation during thrusting. Usually, there is no indication of the type of movement along the other faults (strike-slip, normal, reverse) except for important normal faults which are also distinguished by a particular symbology. For readability purposes, faults in the Alps are generally only shown when they offset a nappe boundary or indicate a regional trend.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Genève
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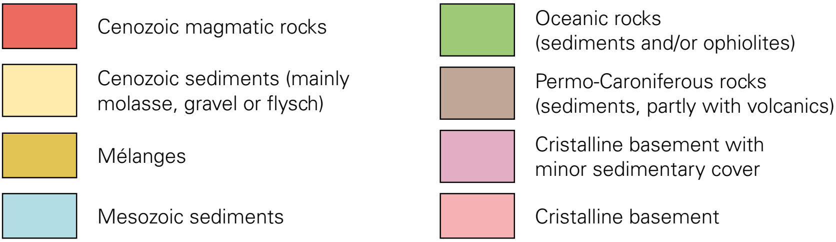


Fig. 2: Simplified map showing the distribution of the lithologies displayed on the Tectonic Map of Switzerland 1:500 000, independently of their tectonic setting.

Fold axes are mostly shown in the North Alpine Foreland: synclines and anticlines in the External Folded Jura and in the Foreland Plateau; only major anticlines in the Internal Folded Jura. In the latter, many major synclines can be identified by their cores filled with Cenozoic sediments (Molasse), which are distinguishable from the Mesozoic sediments shown on the map. In the Alps, only axial traces of major post-nappe folds are shown.

In the North Alpine Foreland, the mapping of faults and fold axes is based on the following: the 1:200 000 tectonic sketches drawn up for each sheet of the Geological Atlas of Switzerland 1:25 000, the compilation of SCHORI (2021), the geological maps of France and Germany.

1.3. Paleogeography

1.3.1. Tectonic vs. paleogeographic terminology

Tectonic terminology is often used in a paleogeographic sense, and vice versa. This can lead to confusion if the context is not clear. Although the two concepts, paleogeography and structural position, are often related, there is no perfect equivalence between them. It is therefore preferable, as far as possible, to differentiate between the two nomenclatures. A paleogeographic origin has been attributed to each unit listed in the tectonic data set. The paleogeographic origin of the tectonic domains and subdomains is given in Table 2; their present-day location is shown in Figure 3. For some tectonic units, the descriptions below specify which sector of a large paleogeographic realm is concerned (e.g., South or North Helvetic sedimentary depositional realm).

The subdivision of domains into lower, middle and upper subdomains closely depicts the structural position of the units. Due to in-sequence nappe stacking during the Alpine orogeny, the originally more southerly units commonly came to lie

Table 2: *The tectonic domains and their paleogeographic origins.*

Tectonic (sub)domain	Paleogeographic origin
South Alpine	Adriatic continental margin
Upper Austroalpine	Adriatic continental margin
Lower Austroalpine	Adriatic continental margin
Salassic	Cervinia Terrane (or continental fragment)
Upper Penninic	Piemonte-Liguria Ocean (also called Alpine Tethys Ocean), Briançonnais distal margins and Adriatic allochthons
Middle Penninic	Briançonnais Terrane
Lower Penninic	(Oceanic) Valaisan Basin and Piemonte-Liguria Ocean
Lepontic	Distal European continental margin
Upper Helvetic	European continental margin (South Helvetic to Ultrahelvetic realm)
Lower Helvetic	European continental margin (North Helvetic realm)
Autochthonous North Alpine Foreland	European continental plate
Detached North Alpine Foreland	European continental plate

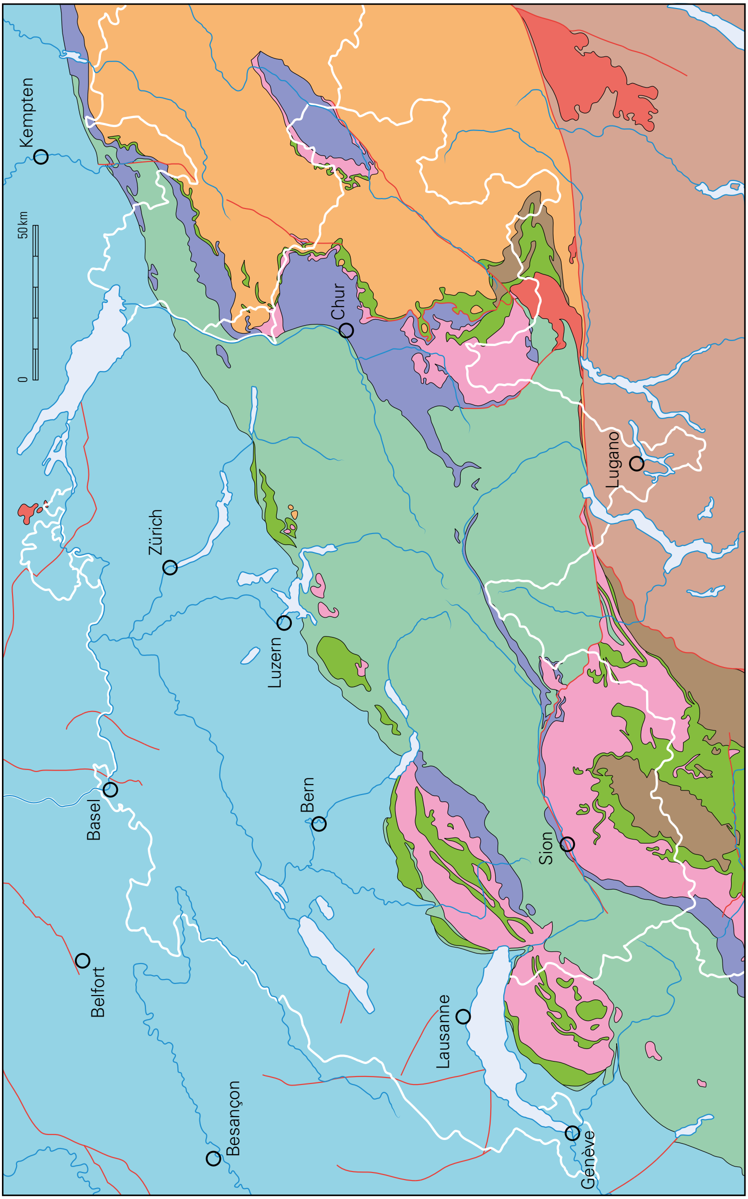
on top of more northerly units in a way that the paleogeography was usually preserved: the higher the unit, the more southerly its origin. However, this is not necessarily the case when thrusting was out-of-sequence and/or the nappes underwent multiphase deformation.

1.3.2. Alpine paleogeographic evolution

The following is a simplified overview of the paleogeographic and kinematic evolution of the tectonic domains of Switzerland and the surrounding regions (see Pl. III, based on HANDY et al. 2010; see also e.g., STAMPFLI & HOCHARD 2009):

- In the Late Paleozoic (Carboniferous-Permian boundary, ca. 300 Ma), all continents merged to form a single continental plate on the globe, the supercontinent Pangea, which persisted until the beginning of the Mesozoic (Late Triassic, ca. 200 Ma) (STAMPFLI et al. 2013).
- At the beginning of the Mesozoic (Triassic), a long extension phase began, the break-up of Pangea started and an ocean opened up to the southeast of the region concerned. It formed several branches that penetrated Pangea; two of these are visible on the sketch at the bottom of Plate III, named the Ionian Sea – between the future Africa and Adriatic plates – and the Vardar Ocean.

- In the Middle Jurassic (Bajocian, ca. 170 Ma), the continuation of the extension phase split Pangea into two parts. The northern part comprised the future North American, European and Asian plates as well as the southern part the remaining continent mass. The rifting of the Piemonte-Liguria Ocean (Alpine Tethys) began between Europe and Adria, while Africa moved in a sinistral transcurrent motion relative to Europe. Further west, the central Atlantic Ocean opened up.
- The Piemonte-Liguria Ocean reached its maximum extension in the Early Cretaceous (Hauterivian, ca. 131 Ma), coinciding with a sinistral movement along a WNW–ESE fault zone that dissected Adria. This fault zone was probably linked to the one that separated Iberia from the rest of Europe. North of this line, extension led to the detachment of part of the distal margins on both sides of the Piemonte-Liguria Ocean.
- Later during the Early Cretaceous (Aptian, around 118 Ma), rifting of the Valaisan Basin, which opened up at the southeastern margin of Europe, gave rise to the Briançonnais Terrane. At the same time, the Cervinia Terrane was separated from Adria, the Eo-alpine (Austroalpine) orogeny was active and the southward subduction of the Piemonte-Liguria Ocean began.
- In the Late Cretaceous (Maastrichtian, ca. 67 Ma), subduction of the Piemonte-Liguria Ocean continued, dragging the Cervinia Terrane below the Adriatic margin. An accretionary wedge formed against this continental margin. Iberia moved closer to Europe, connected to the Briançonnais Terrane.
- The Alpine orogeny occurred during the Cenozoic, primarily during the Eocene, with the closure of the Piemonte-Liguria Ocean and, afterwards, of the Valaisan Basin. This implies the successive subduction of the Piemonte-Liguria Ocean, the Briançonnais Terrane, the Valaisan Basin and finally the European margin.
- During the Oligocene, the Western Alps acquired their arc-shaped form thanks to the westward transportation of the Adriatic plate, which resulted in its indentation into the Alpine orogenic prism. The latter consists of relatively ductile nappes and the former of the rigid wedge of the South Alpine Ivrea lithospheric mantle (SCHMID et al. 2017).
- During the Neogene, the Ionian Sea partially closed, splitting into two basins (Tyrrhenian Sea and Eastern Mediterranean Sea), while the Algerian-Provençal Basin opened through counterclockwise rotation and eastward displacement of the Corsica-Sardinia block and the Ligurian Alps. This movement led to the orogeny of the Apennines.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Zürich
Luzern
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Bern
Sion
Belfort
Lausanne
Besançon
Genève

- 🟥 Cenozoic magmatic rocks
- 🟦 European continental platform
- 🟩 European continental margin
- 🟪 Valaisan Basin
- 🟪 Briançonnais Terrane
- 🟩 Piemonte-Liguria Ocean
- 🟫 Cervinia Terrane
- 🟧 Adriatic continental margin (northern part)
- 🟫 Adriatic continental margin (southern part)

Fig. 3: Present-day location of the paleogeographic origin of the tectonic units.

2. AUTOCHTHONOUS NORTH ALPINE FORELAND

P. Jordan, H. Madritsch & J. Mosar

The Autochthonous North Alpine Foreland consists of the European platform with its Cenozoic graben structures of eastern France, southwestern Germany and northern Switzerland (e.g., Illies 1981, Eisbacher et al. 1989). The boundary between the Autochthonous North Alpine Foreland and the Detached North Alpine Foreland marks the northernmost limit of significant Alpine compressional deformation.

Accordingly, the Autochthonous North Alpine Foreland is widely absent of map-scale compressional structures; small-scale compressive structures however occur in the southern marginal area (Dèzes et al. 2004, Madritsch et al. 2008). According to microscopic strain analyses, the effects of Neogene Alpine deformation extend hundreds of kilometers out into this domain (Craddock et al. 2022 and ref. therein).

2.1. Bresse Graben

The Bresse Graben is entirely located in France and stretches roughly from Lyon to Dijon with a N–S orientation. A NE–SW oriented extension reaches the northwestern corner of the map area and is clearly separated from the Haute-Saône Platform by NNE–SSW to NE–SW oriented normal faults. The Bresse Graben is part of the European Cenozoic Rift System (ILLIES 1972, HINSKEN et al. 2007), is ca. 35–60 km wide and filled with Paleogene–Neogene sediments which are up to 2 km thick (CHAUVE et al. 1980, ROCHER et al. 2003).

2.2. Haute-Saône Platform

The Haute-Saône Platform, which forms the southeastern rim of the Paris Basin, occupies the northwestern corner of the map area. It is mostly located in France except for the Ajoie area. At its eastern boundary, the separation from the northern part of the Upper Rhine Graben is clearly defined by NNE–SSW trending normal faults. In the south, however, the situation is more complex. Here, the limestone plateau of Ajoie, regarded as belonging to the Haute-Saône Platform, is separated from the northward-adjacent Upper Rhine Graben by a W–E trending flexure dissected by N–S trending normal faults (USTASZEWSKI et al. 2005).

To the south, the Haute-Saône Platform is mostly bounded by the Detached North Alpine Foreland, in particluar by the frontal Faisceaux of the External Folded Jura (see § 3.2). South of the Ajoie area, where the External Folded Jura is missing, the Internal Folded Jura is thrust directly onto the Haute-Saône Platform.

The Haute-Saône Platform is formed predominantly by Mesozoic sediments, which are strongly intersected by N–S to NNE–SSW oriented faults associated with the Paleogene development of the European Cenozoic Rift System (LACOMBE et al. 1993). Some post-rift Neogene Molasse sediments can be found south of the lower reaches of the Ognon River that follows a major ENE–WSW trending fault associated with the transfer zone between the Upper Rhine and the Bresse graben structures (MADRITSCH et al. 2009).

The Vosges Massif exposes the basement of the Haute-Saône Platform. It consists of pre-Mesozoic rocks, including Variscan magmatites and metasediments, pre-Variscan metamorphic rocks and, on the southwestern side of the Upper Rhine Graben, unconformably overlying Permo-Carboniferous sediments.

2.3. Upper Rhine Graben

The NNE–SSW trending Upper Rhine Graben is located north of Basel. It is part of the European Cenozoic Rift System (ILLIES 1972, HINSKEN et al. 2007), is up to 40 km wide and separates the Haute-Saône Platform to the west from the South German Platform to the east. The graben shoulders are bounded by steep normal faults and include isolated, lowered blocks of Mesozoic platform sediments along the rift-internal sides (the so-called Vorberg Zone, e.g., Isteiner Klotz north of Basel). The Schwarzwald Fault forms the eastern border of the graben. The southwestern border of the graben with the Haute-Saône Platform forms a flexure (see §2.2). In the southeast, the graben borders the External Folded Jura; the corresponding flexure is accentuated and overprinted by Alpine deformation (USTASZEWSKI et al. 2005). The graben is filled with Paleogene–Neogene sediments of 2–3 km thickness (e.g., ILLIES 1981, SISSINGH 1998, BERGER et al. 2005b).

2.4. South German Platform

Located east of the Rhine Graben, the South German Platform occupies the eastern part of the northern border of the map area. A major normal fault, the Schwarzwald Fault, separates both units. East of this fault, the Schwarzwald Massif exposes the basement of the South German Platform, which consists mainly of metamorphic and plutonic rocks (SCHALTEGGER 2000), with some remnants of Late Paleozoic sediments (NITSCH 2018). The massif is characterized by WNW–ESE striking brittle faults, some of which can be traced further southeast into the Mesozoic overburden where they formed important precursor structures during Neogene deformation events (EGLI et al. 2017).

The autochthonous Mesozoic–Cenozoic sedimentary cover of the South German Platform shows a clear segmentation into tectonically distinct regions. The small western region, between Basel and Frick, is marked by a strong segmentation defined by normal faults. As most of these normal faults are NNE–SSW oriented, the region is considered as the eastern shoulder of the similarly oriented Upper Rhine Graben. LAUBSCHER (1982, 2003, 2004) postulates that a large number of the normal faults were already formed in the Eocene with a decoupling in the evaporites of the Muschelkalk and a multiphase extensive deformation in different directions. He further assumes that the related tectonic processes came to a halt in the Early Miocene, as many of the normal faults are unconformably overlain by younger Molasse sediments. In contrast, PFIRTER et al. (2019) assume that the normal faults are rooted in the crystalline basement. Some compressional structures also occur in this area, such as generally W–E oriented thrusts and the narrow Adlerhof Anticline (MEYER 2001) in the Pratteln–Liestal area. While PFIRTER et al. (2019) interpret these structures to be an expression of a Late Miocene compressional tectonic overprint at the northern margin of the Detached North Alpine Foreland, LAUBSCHER (1973, 1982) argues that they formed due to gravitational sliding of the sedimentary envelope from the uplifted crystalline Schwarzwald Massif further to the north. Whatever the case, this area is regarded as part of the South German Platform in the tectonic map as the main compressional movements of Late Miocene age ended along better-defined thrust faults further south.

Further east, north of the Mandach Thrust that is considered as the northern boundary of the Detached North Alpine Foreland (MALZ et al. 2020; see §3.2), the S-vergent Mettau Thrust is also subject of controversy (gravitational or tectonic structure, see discussion above; Wildi 1975, Laubscher 2003). This structure is thus regarded as belonging to the South German Platform. East of the lower Aare Valley, the tectonic characterization of this platform is comparatively vague. Notable structural features include a series of WSW–ESE trending monoclines around Döttingen and Zurzach (Bitterli et al. 2000, Bittleri-Dreher et al. 2007). The southern boundary of the South German Plattform toward the Detached North Alpine Foreland is defined by contractional structures identified in seismic reflection profiles. However, east of Eglisau, there is no evidence for this boundary (Naef et al. 1995, Birkhäuser et al. 2001; see chap. 3).

Further to the east, the Neuhausen Fault marks the southwestern boundary of the NW–SE trending extensional *Hegau-Bodensee Graben* (Nagra 2008) that represents the southeastern extension of the Freiburg-Bonndorf-Bodensee Fault Zone (Schreiner 1992, Geyer et al. 2003, Egli et al. 2017, Diehl et al. 2023). The Hegau-Bodensee Graben is associated with the Neogene Hegau Volcanic Province (§ 11.1). The Neogene Randen Fault and the Schiener Berg Fault (Zaugg et al. 2008), with a maximum vertical offset of about 250 m (Nagra 2008), together form the southwestern limit of the central graben (Hofmann et al. 2000). Towards the southeast, the Neuhausen Fault intersects the WSW–ENE trending Baden-Irchel-Herdern Lineament (Naef et al. 1995, Malz et al. 2016; see §3.2). It is thus presumed that this intersection results in an accordingly trending bend in the graben system, as similarly observed further to the north according to the interpretation of 3D seismic data (Birkhäuser et al. 2001). However, the precise continuation of the graben bounding fault system towards the southeast remains unclear. The Quaternary basin of the Bodensee also bears witness to faults likely related to the Hegau-Bodensee Graben (Fabbri et al. 2021). The western boundary fault system possibly joins the St. Gallen Fault – presently considered active (Heuberger et al. 2016) – west of Arbon. The northeastern boundary of the Hegau-Bodensee Graben remains poorly defined, but the South German Platform is apparently also affected by normal faulting east of the lake (Ibele 2015 and ref. therein).

3. DETACHED NORTH ALPINE FORELAND

P. Jordan, H. Madritsch & J. Mosar

The Detached North Alpine Foreland refers to the displaced sedimentary cover north of the front of the Helvetic units. The deformation began in Mid to Late Miocene and lasted, depending on the author, until the end of the Miocene, the Pliocene or is still ongoing today (see compilation and discussion in Schori

2021). Decoupling between the thrusted and deformed cover and the underlying basement took place in a décollement zone in the evaporites of Muschelkalk Group east of a line Porrentruy – Biel – Fribourg and of the Keuper Group further west (JORDAN 1992). Deformation includes northwestward and northward displacement, thrusting and folding as well as strike-slip deformation. The northern boundary, which coincides with the front of Alpine deformation, is given by the outermost (distal) significant thrusting and folding. The easternmost clear evidence for décollement-related tectonics is given by the Lägern Anticline east of Baden with some more indications from seismic data found south of Bülach (NAEF et al. 1995, MALZ et al. 2016, MADRITSCH et al. 2024). Further to the east, displacement of the sedimentary cover along the decollement zone is presumed to gradually decrease. Accordingly, no precise eastern boundary can be drawn between the Detached North Alpine Foreland and the autochthonous South German Platform and a conceptual transition zone is defined instead (see § 3.2 for details).

The Detached North Alpine Foreland can be tectonically divided into three subdomains, from distal to proximal:

- External Folded Jura (Faisceaux and Plateaux)
- Internal Folded Jura and Foreland Plateau
- Subalpine Molasse

There is no tectonic boundary between the Internal Folded Jura and the Foreland Plateau, with exception of local backthrusts, but a change in the deformation pattern, mainly caused by the thickness of the sediments above the décollement surface. Morphologically, the Foreland Plateau together with the Subalpine Molasse form the “Molasse Basin”, which also includes an autochthonous part in the South German Platform. The External Folded Jura and the Internal Folded Jura together form the Jura Mountains. The Internal Folded Jura is also known as the “Haute Chaîne”.

Depending on the nature and thickness of sediments involved in deformation, the presence of preexisting deformation features and the direction of shortening, the morphology and tectonic style of the Jura Mountains varies from west to east. They can be divided in three regions (see Fig. 4):

- The *Southwestern Jura* is located west of the Vuache Fault (southwest of Geneva) and its northwestern extension. It is only visible in the southwestern corner of the map area west of Aix-les-Bains.
- The *Central Jura* is situated west of a line Neuchâtel – Col des Rangiers (west of Delémont), which corresponds to a tectonic lineament known as the Caquerelle Fault Zone.

The Eastern Jura is located east of the Caquerelle Fault Zone. Its western part – up to a line stretching roughly from Wehr to Härkingen (southwest of

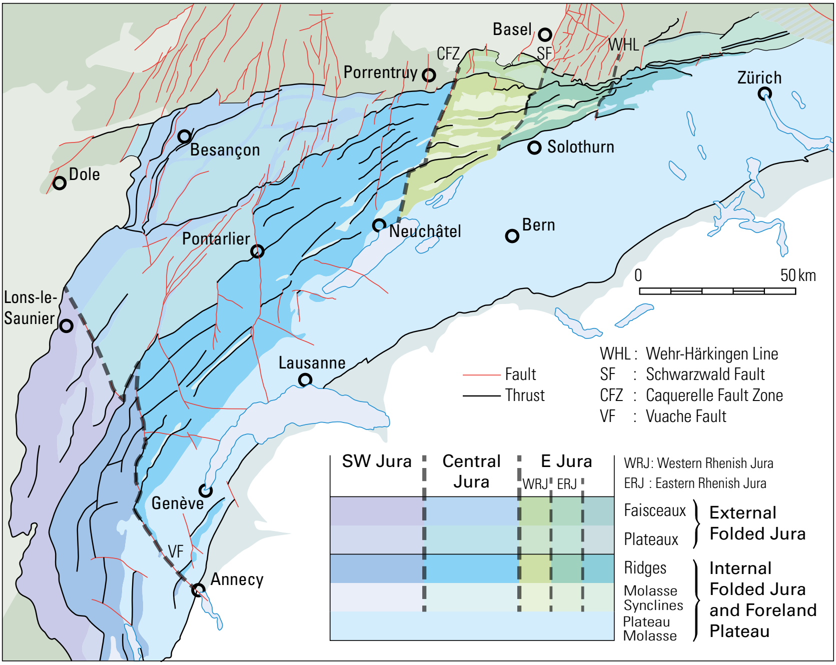

Fig. 4: Geographical subdivision of the Jura Mountains with respect to tectonic elements.

Olten) – is called the "Rhenish Jura" ("Rheintalischer Jura", Laubscher 1965), itself subdivided into a western and an eastern part separated by the southern extension of the Schwarzwald Fault (§2.3), the western part corresponding to the southern continuation of the eastern part of the Upper Rhine Graben and the eastern part to the southern continuation of the eastern shoulder of this graben.

3.1. External Folded Jura

The most prominent features of the External Folded Jura are the largely undeformed or only slightly deformed tabular areas, called *Plateaux*, which are separated by narrow zones of intense deformation known as *Faisceaux* (e.g., CHAUVE et al. 1980).

In the Central Jura, the External Folded Jura forms a very extensive area, better known by its French name "Jura des Plateaux et des Faisceaux". It is completely situated in France except for some disputable square meters in the Haute Ajoie WNW of Porrentruy. It is characterized by extended plateaux separated by narrow but impressive fold belts. West of Salins-les-Bains, at the western edge of the map area, there is evidence that the External Folded Jura is overthrust some 5 km over the Cenozoic series of the Bresse Graben towards the northwest (outside of the map area; MICHEL et al. 1953, BLANC et al. 1991).

In the Eastern Jura southwest of Basel (western part of the Rhenish Jura), the Ferrette region is part of the External Folded Jura. It comprises several relatively small plateaux with the Laufen basin being the most prominent. The frontal fold belts, the Ferrette (or Bürgerwald) and Landskron anticlines are slightly overprinted monoclinal flexures rather than elements overthrust on the Upper Rhine Graben (USTASZEWSKI et al. 2005). In the eastern part of the Rhenish Jura, the External Folded Jura is partly hidden by the overthrust Internal Folded Jura. However, it can be traced as far as the Hauenstein Base Tunnel north of Olten (Sprüssel Anticline). The area east of Frick, known as the Bözberg Plateau, is verifiably detached for a few hundreds of meters to the north and is limited by the significant faisceaux-type frontal Mandach thrust (MALZ et al. 2020). To the south, it is bordered by another faisceaux-type fold belt, partly hidden by the overthrust Internal Folded Jura, and known by earlier authors as the "Vorfaltenzone" (DIEBOLD et al. 2006).

Further east, north of the pronounced Lägern Anticline, the Baden-Irchel-Herdern Lineament – a Cenozoic normal fault coinciding with the southern boundary of the Late Paleozoic Constance-Frick Trough (NAEF et al. 1995, MADRITSCH et al. 2018) – is compressively overprinted between Baden and Bülach resulting in a structurally complex, faisceaux-like fault zone only visible in seismic reflection profiles (MALZ et al. 2016). Further north, seismic reflection data also reveal compressional structures including the Siglistorf Anticline, that are associated with a broad monocline of the Mesozoic sequence. They are considered here to be related to the basal detachment of the Jura thrust belt (NAEF et al. 1995, NAGRA 2014, MADRITSCH et al. 2024) and represent the northern boundary of the External Folded Jura against the autochthonous South German Platform. Notably, these seismic structures could alternatively be interpreted to root in the basement (MALZ et al. 2016) as similarly proposed for the northernmost part of the aforementioned Ferrette region (USTASZEWSKI & SCHMID 2007).

Further east, contraction-related structures identified on the basis of seismic reflection data, the amount of shear and intensity of compression appears to gradually decrease. Accordingly, a distinct eastern boundary of the External Folded Jura cannot be defined (see § 3.2).

3.2. Internal Folded Jura and Foreland Plateau

The Internal Folded Jura and the Foreland Plateau differ in tectonic style, with a change from intensive folding and overthrusting to folds with large wavelengths and small amplitudes. In detail, however, a distinction is difficult and usually based more on morphology than tectonics; there is often no well-defined tectonic element between the two regions (see Pl. II, western cross-section), except for the morphological northwestern boundary of the Foreland Plateau Molasse. The Internal Folded Jura and the Foreland Plateau are therefore considered here as a single tectonic unit: the main part of the detached sedimentary wedge and its heavily deformed frontal part.

The *Internal Folded Jura* represents the most intensely deformed part of the Detached North Alpine Foreland. In a similar manner to the whole Jura Mountains, it forms a prominent arcuate chain in eastern France and northwestern Switzerland.

The delimitation between the Internal and the External Folded Jura is given, in the Eastern Jura, by the northernmost thrust bringing Triassic sediments to the surface, known as the "Jura-Hauptüberschiebung". This thrust front coincides with the southern boundary of the Late Paleozoic Constance-Frick Trough (LAUBSCHER 1986, DIEBOLD et al. 1992, NAGRA 2008, MADRITSCH et al. 2018) and its continuation to the west (USTASZEWSKI et al. 2005). In the Haute Ajoie region (easternmost part of the Central Jura), the Internal Folded Jura directly overlies the Haute-Saône Platform along the Mont Terri Thrust (NUSSBAUM et al. 2017). Further west, from near the French-Swiss border, the Internal Folded Jura overlies the western part of the External Folded Jura up to the Pontalier-Aubonne Fault Zone, a major sinistral strike-slip fault zone that shifts the thrust front to the south, similar to the Mouthe Fault Zone further west.

In the Central Jura, the tectonic style of the Internal Folded Jura is characterized by long, rather cylindric anticlines and large overthrusts. This is due to the thick detached sedimentary pile, ranging from Triassic to Neogene and including thick Mesozoic calcareous intervals alternating with important marl- and clay-rich strata. The main detachment is localized in the thick evaporites of the Keuper Group. This part of the Internal Folded Jura is transected by significant vertical, N–S oriented fault zones, of which the strike-slip Pontarlier-Aubonne Fault Zone is the most important. All of these N–S strike-slip fault zones are sinistral. Important NW–SE oriented strike-slip faults, such as the La Sarraz-Mormont or St-Cergues fault zones, develop in a conjugate manner to the N–S faults and show a dextral displacement. Large, nappe-like thrusts are another characteristic of this region, the Mont Risoux-Mont Tendre Thrust being one of the best documented and most prominent. Field, seismic and borehole evidence document an amount of overthrusting of about 17.5 km (URSPRUNG 2022; see Pl. II, western cross-section). In addition to N-directed thrusting, top-S transport occurs on numerous backthrusts, forming the typical fish-tail geometry observed in many cases (SOMMARUGA 1999). The maximum amount of total shortening in the Central Jura (internal and external parts) is estimated at around 28 km (AFFOLTER & GRATIER 2004).

In the Rhenish Jura, the Internal Folded Jura is characterized by intense dissection by inherited normal faults related to the European Cenozoic Rift System (see § 2.1, 2.3). These normal faults have been involved in the folding and thrusting in many ways. Its western part is characterized by extended Molasse filled synclines, the Delémont basin being the most prominent. The detached Mesozoic sedimentary pile includes Triassic, Jurassic and subordinately Cretaceous strata. Calcareous intervals are prominent. Detachment is mainly localized in the Muschelkalk Group evaporites, and tectonic style varies from nappe-like overthrusts to fold successions. In the eastern part of Rhenish Jura, the detached Mesozoic sedimentary pile includes Triassic to mid-Late Jurassic strata. Calcareous intervals are less prominent than in the adjacent western area. The thickness of the Molasse sediments may have been significantly less than further west. Fold series and prominent folded thrusts (e.g., BUXTORF 1916, BLÄSI et al. 2015) are the predominant characteristic of this region.

East of the Rhenish Jura, the Internal Folded Jura is thrust up to several kilometers over the External Folded Jura (MÜHLBERG e.g., 1881, 1894, 1915). This “Jura-Hauptüberschiebung” is associated with the unique “Schuppenzone”, an intense imbrication of mid-Triassic carbonates sandwiched between evaporite rocks. Internally also, imbrication is the dominant deformation style. This is due to a relatively thin Mesozoic sedimentary pile ranging from Triassic to Middle and, in most places, early Late Jurassic, and consisting predominantly of marly strata with thin calcareous intervals, and a probably thin Molasse cover. The main detachment is localized in the Muschelkalk Group evaporites.

Morphologically, the Internal Folded Jura ends at the eastern end of the Lägern ridge. Seismic evidence indicates a certain continuation to the east covered by Cenozoic and Quaternary sediments.

The *Foreland Plateau* covers the detached part of the Molasse Basin and its Mesozoic basement. It is characterized by NE–SW trending low amplitude folds. Several of these are clearly visible at the surface, exposed due to glacial erosion, e.g., the Mont Vully Syncline between Lac de Neuchâtel and Lac de Morat. Others have been demonstrated early on by careful mapping (e.g., SCHUPPLI 1950). Studies based on seismic surveys have shown these low amplitude structures such as anticlines formed over salt pillows (SOMMARUGA 1997, 1999, SOMMARUGA et al. 2012, GRUBER 2017, MOCK & HERWEGH 2017, HAUVETTE 2023). In addition to the folds, a series of fault zones have been shown to play an important structural role, such as the Fribourg Lineament, a sinistral fault zone, which is seismically still active (Vouillamoz et al. 2016, 2017) and may be related to the change of the main shear horizon from the Keuper Group evaporites (west) to the Muschelkalk Group evaporites. The NW–SE trending La Lance Fault is cutting across Lac de Neuchâtel into the Jura Mountains. Similarly, numerous major faults of the Internal Folded Jura extend into the Foreland Plateau and form a continuous conjugated faults system. In the western part of the Foreland Plateau, these vertical strike-slip faults are confined to the detached terrain like in the Internal Folded Jura, and do not root into the basement. In the more central part north of Bern, however, Mock & Herwegh (2017) also reported NNE–SSW striking, deeply rooted strike-slip faults.

At the southwestern termination of the Foreland Plateau, between Genève and Annecy, the Molasse Basin is divided by the NNE–SSW oriented huge ridge of the Mont Salève. This mountain ridge is made up of a Mesozoic series similar to that of the nearby Internal Folded Jura and is overlain by a series of Molasse sediments. This sequence is separated from the more external Molasse by a thrust fault (Signer & Gorin 1995), which is similar to those intersecting the Jura fold-and-thrust belt. In contrast, it is assumed that the thrusts of the Subalpine Molasse slices are still rooted in the Cenozoic series. Therefore, the Salève Mesozoic is regarded as the most internal part of the Internal Folded Jura (Charollais et al. 2023).

The eastern delimitation of the detached Foreland Plateau is poorly defined. In the present Tectonic Map of Switzerland, it is assumed to extend at least as far east as the pinch out of eastern Jura further to the north (§3.2). Eastward from there, a conceptual transition zone towards the non-detached foreland is proposed and stretched out to the Hegau-Bodensee Graben. This intends to suggest a gradual decrease rather than a distinct boundary of décollement tectonics.

3.3. Subalpine Molasse

F. Schlunegger

The Subalpine Molasse constitutes the southernmost subdomain of the Detached North Alpine Foreland, situated between the Foreland Plateau to the north and the first basal thrust of the Alpine nappes to the south. It consists of a stack of imbricated thrust slices where the beds generally dip towards the SE. The Subalpine Molasse mainly includes coarse-grained foreland basin strata that were deposited between about 32 and 20 Ma (Kempf et al. 1999). They chronicle the change from the underfilled Flysch to the filled/overfilled Molasse stage of foreland basin evolution (Sinclair & Allen 1992).

3.3.1. Marbach-Berneck Triangle Zone

In the Entlebuch area, situated west-southwest of Luzern, and between the Zürichsee and Lustenau in the Alpine Rhine Valley, Early Miocene Molasse units are wedged in between a S-vergent backthrust that delineates the southern boundary of the Foreland Plateau Molasse and a N-vergent thrust, which marks the northern boundary of the Subalpine Molasse. In cross-section, this area forms a triangle (see Pl. II, eastern and central cross-section).

In the Entlebuch region, the backthrust of the Foreland Plateau is very steep and sometimes even overturned where the thrust plane and overlying strata are steeply dipping to the south. Near Luzern and particularly in the region between the Vierwaldstättersee and the Zugersee, the triangle zone transitions into a tectonic architecture that is characterized by multiple isoclinal thrust sheets where the involved beds dip towards the SE. This transition occurs mainly at the northernmost of these thrust slices, i.e., the Höhronen Slice, which buried the backthrust possibly during the Late Miocene phase of out-of-sequence thrusting (Mock et al. 2020).

South of the Zürichsee, between this lake and Einsiedeln, a NW–SE striking right-lateral fault, which extends as far south as the Sihlsee, delineates the eastern boundary of the Höhronen Slice. Movement along this fault possibly accommodated a different style of shortening on either side: imbricate thrusts characterize the tectonic style west of this fault, whereas the broad triangle zone overlain by Subalpine Molasse klippen and a well-developed backthrust developed east of this fault. The Marbach-Berneck Triangle Zone thins very rapidly and disappears in the Toggenburg Valley. It then reappears farther east of this valley, forming a thin ribbon that extends as far as the Rhine Valley. The same triangle zone occurs also east of this valley, in Vorarlberg and in Germany (Ortner et al. 2015). Mapping has shown that a triangle zone developed where the proximal Plateau Molasse consists of an alternation of sandstones and mudstones. In cases where thick conglomerate packages occur at the southern border of the Plateau Molasse, which is, for example, the case east of Thun, then the triangle zone is replaced by a sequence of SE-dipping thrust sheets (e.g., Mock et al. 2020).

3.3.2. Subalpine Slice Complex

The Subalpine Slice Complex of the Molasse Basin defines the northwestern limit of the Alpine nappes over the whole width of the territory covered by the Tectonic Map of Switzerland. In the west, it gradually begins in France in the Annecy region, extends across Switzerland from Le Léman to south of the Bodensee, and continues into Austria and Germany over the eastern edge of the map (Ortner et al. 2015 and ref. therein).

According to a seismic study by Dupuy et al. (2014), the different slices defined north of Le Léman continue below the lake. In Savoy, on the southern shore of the lake, the scarcity of outcrops makes it impossible to recognize all these slices. It is assumed that only one of them continues, accompanied by another slice south of Thonon. Between Annemasse and Annecy, seismic studies may well have revealed the presence of several slices (SIGNER & GORIN 1995 and ref. therein).

The various slices, from Le Léman in the west to the Alpine Rhine Valley in the east, have been studied and described in detail by numerous authors, including those involved in the survey of the relevant sheets of the Geological Atlas of Switzerland. These surveys have shown that the tectonic style largely depends on the mechanical characteristics of the Molasse sediments, where several km-thick sequences of conglomerate deposits that coarsen and thicken upward resulted in the formation of broad thrust sheets. The basal thrust of these tectonic slices is generally situated where finer-grained deposits with a lower mechanical strength prevail, which is generally the case at the base of these conglomerate suites. In Switzerland, such examples can be found mainly in four regions situated 1) northeast of Le Léman where the ca. 1 km-thick Mont Pèlerin conglomerates constitute such a unit with a high relative abundance of Late Oligocene conglomerate beds (BURRI & BERSIER 1972, WEIDMANN 1988), 2) east of the Thunersee where the more than 4 km-thick Late Oligocene to Early Miocene conglomerates of the Thun Formation are exposed (SCHLUNEGGER et al. 1993, 1996), 3) northeast of the Vierwaldstättersee where a nearly 3 km-thick suite of Late Oligocene conglomerates underlies the Rigi and Rossberg mountains (STÜRM 1973, SCHLUNEGGER et al. 1997), and 4) the region surrounding Appenzell where several imbricates of Late Oligocene to Early Miocene conglomerate units characterize the stratigraphic architecture of the Subalpine Molasse (HABICHT 1945a, b, KEMPF et al. 1999). In contrast, in regions where the Subalpine Molasse mainly comprises sandstone and mudstone alternations, the deformation has been partitioned in small thrust sheets, for example west of Thun (MOCK et al. 2020).

The chronology of thrusting can only indirectly be constrained because direct physical contacts between thrusts and tilted Molasse beds or progressive unconformities are missing. An exception, however, was mapped at Gstelmflue in the Entlebuch region (coord. 2649 600/1201 400) where an angular unconformity separates Late Oligocene conglomerates from each other (SCHLUNEGGER et al. 2016). This site provides clear evidence for the occurrence of tectonic deformation while sedimentation was ongoing. Furthermore, because individual thrust slices overlie progressively younger Molasse strata from south to north, it is generally accepted that the deformation progressed in-sequence from the proximal basin edge towards more distal sites as sedimentation continued (PFIFFNER 1986). Recently, however, MOCK et al. (2020) documented the occurrence of out-of-sequence thrusting in the Subalpine Molasse, which occurred during the Late Miocene. This could explain some of the tectonic unconformities within the Subalpine Molasse and between the basal Alpine thrust and the underlying Molasse thrust slices (e.g., HAUS 1935, 1937).

4. HELVETIC

O.A. Pfiffner & Y. Gouffon

The Helvetic domain is generally located between the Subalpine Molasse in the north and the Penninic and Lepontic nappes in the south. The Penninic nappes occur on top of this domain, but in western Switzerland the Penninic nappes of the Prealps (s. § 6.1) reach farther north than the Helvetic nappes and so lie directly on top of the Subalpine Molasse, although in places separated by a mélange zone considered Helvetic.

The Mesozoic–Cenozoic sedimentary sequences of the Helvetic units were deposited on a Proterozoic–Paleozoic crystalline basement belonging to the European continental margin. Parts of this basement constitute the External Crystalline Massifs (Belledonne, Aiguilles Rouges, Mont Blanc, Aar, Gotthard; the latter recently classified as a nappe) which, together with their attached autochthonous and parautochthonous sedimentary cover, represent real tectonic units. Other sedimentary sequences are detached from their basement and partly form the so-called "Helvetic nappes".

The current structure of the Helvetic domain is the result of a multi-phase tectonic evolution (MILNES & PFIFFNER 1977, PFIFFNER 1977, 2015, BURKHARD 1988) that can be resumed in three main phases:

1. During the first phase, detached Mesozoic–Cenozoic sediments from the distal European continental margin (southernmost Helvetic to Ultrahelvetic palaeogeographic realm) formed slivers and nappes which were thrust on top of the Mesozoic–Cenozoic sediments of the more proximal European continental margin (Helvetic platform), probably at the base of Penninic units during their transport to the north. These early detached Helvetic units are known in the literature as the "Ultrahelvetic nappes". The thrust zone is often characterized by the presence of mélanges.
2. During the second phase, the Helvetic platform was shortened and subject to the development of fold and thrust structures. Major out-of-sequence thrust faults with large displacements separated two nappe stacks: the Lower and Upper Helvetic subdomains.
3. The third phase involved the updoming of the External Crystalline Massifs.

There is a significant change in the structure and tectonic style of the Helvetic domain from west to east. East of the Thunersee, the boundary between the Lower Helvetic and the Upper Helvetic is formed by major out-of-sequence thrusts of the second phase, which cut the entire structural framework formed during the first phase; from west to east these are the Axen and the Glarus thrusts. As a consequence of this out-of-sequence thrusting, units of Ultrahelvetic origin are now found both above and below these major thrust faults, i.e., in the Upper Helvetic and in the Lower Helvetic subdomains, respectively.

West of the Thunersee, the early detached sediments of the Ultrahelvetic realm crop out in various positions: 1) on top of the Lower and Upper Helvetic nappes, 2) in a wide band between the Helvetic nappes and the Penninic units of the Prealps and 3) between the Subalpine Molasse and the Prealps nappes. The 2nd phase Diablerets and Wildhorn thrusts cut across the older basal thrust of these "Ultrahelvetic" units (JEANBOURQUIN 1994, STECK et al. 2001, PFIFFNER et al. 2010) in the same way as the out-of-sequence thrusts east of the Thunersee. Consequently, the units originated from the Helvetic platform and situated below the Diablerets and Wildhorn thrusts belong to the Lower Helvetic and those above these thrusts to the Upper Helvetic domain. As the Diablerets and Wildhorn thrusts have a significantly smaller displacement (10–15 km) compared to the Axen Thrust (20–25 km) and Glarus Thrust (30–35 km) in the east (PFIFFNER 2011), not all the units of Ultrahelvetic origin are involved and thus cannot be allocated to either the Upper or Lower Helvetic. For this reason, they are all considered as Upper Helvetic west of the Thunersee and are included in the Pillon and Bulle mélange zones (see § 4.2.7 and 4.2.8).

4.1. Lower Helvetic

The Lower Helvetic subdomain comprises all the sedimentary and crystalline units below the Glarus (eastern Switzerland), Axen (central Switzerland), Diablerets and Wildhorn major thrusts (western Switzerland). It corresponds to the External Crystalline Massifs and what was formerly called the "Infrahelvetic complex" (PFIFFNER 1977, MILNES & PFIFFNER 1977) that includes imbricates with North Helvetic facies as well as sedimentary nappes with South Helvetic to Ultrahelvetic facies.

4.1.1. External Massifs: Belledonne, Aiguilles Rouges, Mont Blanc and Aar massifs

Only the northern end of the *Belledonne Massif* is present in the map area. Its pre-Mesozoic basement is separated from those of the Aiguilles Rouges and Mont Blanc massifs by the axial depression of the Val Montjoie, but correlations between them are highly probable. Considering their sedimentary covers, EPARD (1990) links the Aiguilles Rouges Massif with the external part of the Belledonne Massif and the external part of the Mont Blanc Massif with the internal part of the Belledonne Massif. According to GIDON (2020), the most external part of the Belledonne Massif does not extend to the northeast of the Megève Window. Thus, only the middle part of this massif is equivalent to the Aiguilles Rouges Massif; however, their corresponding sedimentary covers are separated by a thrust near St-Gervais-les-Bains. The Belledonne Massif is composed of crystalline rocks and metasediments of Precambrian to Early Carboniferous age, of Variscan granites and of a Mesozoic sedimentary cover.

The *Aiguilles Rouges Massif* is made up of the same rocks as the Belledonne Massif, but also includes Permian sediments. It has a relatively thin autochthonous Mesozoic–Cenozoic sedimentary cover, except in the Val d'Illiez and on the slopes of the Rhône Valley between Monthey and St-Maurice, where the series ends with an autochthonous Molasse formation, which has long been considered an internal slice of the Subalpine Molasse. The Dent de Valère Flysch outcropping north of the Dents du Midi – considered as "Ultrahelvetic" on the previous versions of the map – seems to belong to the autochthonous flysch (JEANBOURQUIN et al. 1992).

The Aiguilles Rouges Massif is separated from the Mont Blanc Massif by a thin band of Mesozoic sediments often referred to as the "Chamonix Syncline" in the literature. Most of these sediments can be considered as belonging to the cover of the Mont Blanc Massif, although its basal contact is strongly tectonized, even tectonic (PFIFFNER et al. 2010). This band hides important tectonic contacts, not only that between both massifs and their sedimentary cover, but also a probable SW extension of the Rhône-Simplon Fault (MANCKTELOW 1992, HUBBARD & MANCKTELOW 1992, EGLI & MANCKTELOW 2013).

The *Mont Blanc Massif* is divided into an external and an internal part by a major fault. Each of these two parts includes a sedimentary cover. The external part is made of gneisses and granites and its sedimentary cover lies in its external, reverse limb and forms the main part of the sediments of the "Chamonix Syncline". The Morcles Nappe is supposed to be rooted in this external part (STECK et al. 2001). The internal part is characterized by a large Late Carboniferous intrusion (Mont Blanc Granite) and a thin Mesozoic cover occurs on its normal limb. This Internal Mont Blanc Massif is considered to be the substratum of the Ardon Nappe (STECK et al. 2001).

The *Aar Massif* and its autochthonous-parautochthonous sedimentary cover occupies a belt about 20 km wide and 160 km long in the central part of the Alps, between Sierre in Valais and Landquart in Graubünden. It is subdivided by several faults into a large External Aar Massif, making up almost the entire width of the Aar Massif in its central part, and a thinner Internal Aar Massif, which is subdivied into two submassifs: the Baldschieder-Gletsch Submassif, which crops out in upper Valais region, south of the Rote Kuh-Gampel Shear Zone – a reactivated paleofault – and its possible continuation between Aletsch and Rhône glaciers, and the Trun-Punteglias Submassif in the Surselva (Graubünden). North of the Lötschental, the External Aar Massif overthrusts the Gastern Submassif. The contact is marked by a thin band of Triassic and Jurassic sediments (the "Jungfrau Wedge"), which includes overturned sediments of the External Aar Massif. The entire Aar

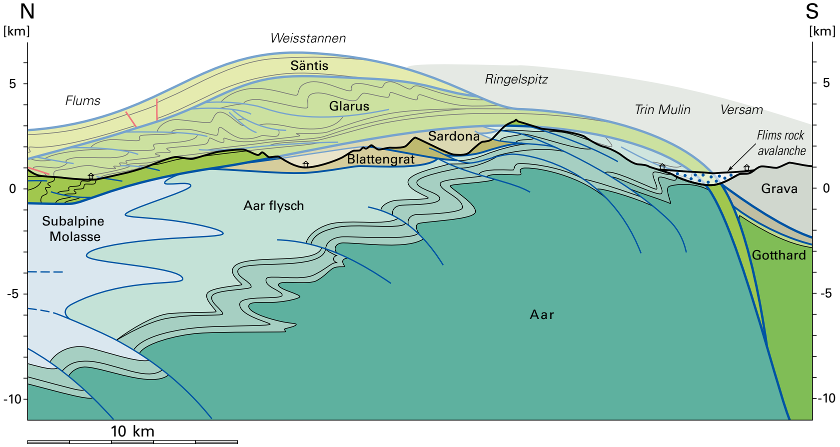

Fig. 5: Cross-section of the Helvetic domain in eastern Switzerland (modified after Pfiffner 2015).

Massif is made up of a pre-Variscan to Variscan polycyclic metamorphic basement with Variscan intrusions. Several large-scale structures follow the general strike of the External Aar Massif. They include longitudinal faults and very tight synclines exposing Late Paleozoic and Mesozoic sediments.

The autochthonous cover of the Internal Aar Massif is present at its southwestern end near Raron (Baldschieder-Gletsch Submassif) while in the Trun-Punteglias Submassif only Triassic sediments remained attached to the crystalline basement.

At the southwestern end of the External Aar Massif, the Triassic and part of the Early Jurassic cover remained autochthonous, whereas the Jurassic and Cretaceous cover was transported progressively towards the north to build the Doldenhorn Nappe. East of the Gastern Submassif, the cover thickens rapidly and is complemented by Late Jurassic to the Paleogene sediments. Even further east, from the Haslital, the Upper Paleocene North Helvetic Flysch is added to the sequence.

At the northeastern end of the Aar Massif, the crystalline basement dips to the NE below its sedimentary cover; it reappears as a small occurrence in the Vättis Window about 30 km further northeast. In this region, a late out-of-sequence thrusting involves the basement and cover of the Aar Massif as well as the overlying Blattengrat and Sardona nappes. The displacement along each of these thrust faults is approximately 1–2 km (Fig. 5). These thrusts define post-nappe units; from bottom to top: the Kaminspitz, Stelli, Marchegghorn, Orglen, Calanda, Mirutta and Tschep slices (see Pfiffner 1978 for a review).

Between Erstfeld (Reuss Valley) and the Klausenpass, the Hoch Fulen Slice, a parautochthonous slice made up of Late Jurassic to Paleogene series, lies on top of the Paleogene series of the Aar Massif.

4.1.2. Chaines Subalpines, Morcles and Doldenhorn nappes

The *Chaines Subalpines Nappe* is constituted by a Jurassic–Cenozoic sedimentary series affected by a succession of large folds with NW vergence to the north of the latitude of Annecy and with W vergence to the south. Its eastern contact is a thrust fault plunging NW over the Aiguilles Rouges and Belledonne massifs. It is overlain to the north by the Pillon Mélange Zone just below the Penninic Prealps, and overlies the southern end of the Subalpine Molasse to the west. The Chaines Subalpines Nappe is subdivided into several units by thrust faults. All these units are composed of Jurassic–Cenozoic sediments of North Helvetic origin, except the most external one, located south of Annecy, whose series is similar to that of the Internal Folded Jura. As is the case with the Upper Helvetic Drusberg and Säntis nappes further east, the Chaines Subalpines Nappe forms a broad synform, south of the Arve Valley, in the core of which klippen of the Pillon Mélange Zone and the Middle Penninic Préalpes Médianes Nappe are preserved.

The *Morcles Nappe* consists of the same Jurassic–Cenozoic sedimentary series as the Chaines Subalpines Nappe. It is defined inside the bend that the Rhône forms at Martigny, and consists of a large recumbent fold overlying the northeastern end of the Aiguilles Rouges Massif. This large fold extends on the other side of the Rhône, in the Dents du Midi area.

According to EPARD (1990), the Morcles and the Chaines Subalpines nappes are both rooted on the External Mont Blanc Massif and its continuation in the most internal part of the Belledonne Massif. They are separated from each other by the continuous thrust fault of the Chaines Subalpines Nappe over the Morcles Nappe (PFIFFNER et al. 2010) between the Mont Buet and Samoëns south of the Swiss-French border.

At the southwestern end of the Aar Massif, the upper part of the External Aar Massif sedimentary cover is detached and forms the *Doldenhorn Nappe.* This nappe is stratigraphically and structurally comparable to the Morcles Nappe.

4.1.3. Ardon, Plammis, Jägerchrüz and Gellihorn nappes

The *Ardon Nappe* is a very thin unit consisting mainly of Early Cretaceous sediments. It appears on the north side of the Rhône between Ardon and the Mont Gond, below the Diablerets Thrust (STECK et al. 2001). It is rooted on the internal Mont Blanc Massif (MASSON et al. 1980).

On the slopes between Sierre and Gampel, the autochthonous cover of the External Aar Massif and the Doldenhorn Nappe are overlain by the *Plammis*

Nappe, a Jurassic series interpreted as the detached part of the autochthonous cover of the Internal Aar Massif (Baldschieder-Gletsch Submassif). The Plammis Nappe itself is overlain by the *Jägerchrüz Nappe*, which is composed of a Triassic–Paleogene series and overlain by the Upper Helvetic Wildhorn Nappe Complex. Further north, the thin *Gellihorn Nappe* occupies the same structural position as the Plammis-Jägerchrüz couple. It is composed of Late Jurassic to Paleogene limestones. Contrary to STECK et al. (2001), BURKHARD (1988) does not consider the Gellihorn Nappe a continuation of the Plammis and Jägerchrüz nappes as it does not show the same grade of metamorphism.

4.1.4. Kammlistock and Griessstock nappes, Clariden Slice Complex, Fiseten-Orthalden Slices, Cavistrau Nappe

In the Klausenpass region, several small units are wedged between the sedimentary series of the Aar massif and the Axen Thrust. These are the *Kammlistock* and *Griessstock nappes,* the *Clariden Slice Complex* and the *Fiseten-Orthalden Slices.* The sediments of all these units are Late Jurassic to Paleogene in age and were deposited further south than the autochthonous-parautochthonous sediments of the Aar Massif, but still in the North Helvetic realm.

A peculiar unit is the *Cavistrau Nappe* (KÄCH 1969, 1972, PFIFFNER 1978, 1985), which crops out on the northern flank of the Surselva. This nappe represents an overturned sequence of Permian to Late Jurassic sediments, which was emplaced onto the Trun-Punteglias Submassif as a W-facing recumbent fold and replaced the autochthonous Jurassic–Paleogene strata that were detached and transported farther nothwestwards. This fault-bend fold formed at the western margin of the Glarus Verrucano basin during inversion of this basin (PFIFFNER 2014). It represents an embryonic stage of the Glarus Thrust that subsequently cut the Cavistrau Nappe by out-of-sequence thrusting.

4.1.5. Blattengrat, Sardona and Bad Ragaz nappes

Three allochthonous units, which were emplaced in an early phase onto the future Helvetic domain (see p. 31), crop out in the area between Linthal and Sargans. They are composed mainly of Late Cretaceous to Paleogene sediments deposited in the very distal part of the Helvetic realm: *Blattengrat* and *Bad Ragaz nappes* of South Helvetic, *Sardona Nappe* of Ultrahelvetic affinity. The three units were subsequently truncated by the Glarus Thrust, which is the basal thrust of the Upper Helvetic subdomain, and simultaneously cut by out-of-sequence thrusts also involving both the basement and the cover of the Aar Massif (see §4.1.1, Fig. 5).

4.1.6. Mättental and Schabell mélanges, Chropfsberg-Pizalun and Tschingelhörner slices

Mélanges were created in the footwall of the Upper Helvetic basal thrusts. The *Mättental Mélange* lies below the Axen Thrust or the small Lower Helvetic units in the Klausenpass area (§ 4.1.4), in both cases on top of the Aar Massif sedimentary cover. This mélange consists of a "wildflysch" with slices of rocks of South Helvetic origin (Cretaceous – Paleogene).

The *Schabell Mélange* underlies the Glarus Thrust and also consists of a "wildflysch", in this case with many lenses and slices of rock stemming from the immediately underlying units (parautochthonous flysch of the Aar Massif, Blattengrat and Sardona nappes). It is continuous but is only represented on the map where its thickness is great enough to be visible at the 1:500 000 scale.

The *Tschingelhörner Slices* occur on top of the Schabell Mélange and consist mainly of Cretaceous limestones. They are characteristic of the footwall of the Glarus Thrust. These slices were torn off their substratum during the thrusting of the Glarus Nappe Complex. They are too thin to be depicted individually on the map and consequently have been grouped with the Schabell Mélange. Further north, under the Glarus Nappe Complex, thin slices of similar but more deformed limestones occupy the same structural position; they are known as the "Lochsiten- Kalk".

The term *Chropfsberg-Pizalun Slices* groups four isolated slices situated south of Sargans on the top of the nappe stack made up of the Blattengrat, Sardona and Bad Ragaz nappes. They include Triassic, Jurassic and Cretaceous strata and occupy the same structural position as the Tschingelhörner Slices, but without direct contact with the Glarus Thrust due to erosion.

4.1.7. Subalpine Flysch Zone

The Subalpine Flysch Zone extends along the front of the Alps in a narrow, almost continuous band from the Thunersee to the Toggenburg. It lies between the Subalpine Molasse and the Upper Helvetic Drusberg and Säntis nappes. It is a heterogeneous mélange zone (e.g., FUNK et al. 2020), consisting of "wildflysch" and various elements of all sizes (meter to kilometer scale), of predominantly North Helvetic (mainly flysch of Paleogene age) and South Helvetic (Cretaceous and Paleogene shallow to deep marine sediments) origin, but also Subbriançonnais. Between the Vierwaldstättersee and the Walensee, this zone presents characteristic slices that consist in a sequence of Cretaceous and Paleogene sediments; they are defined as External Einsiedeln Slices.

The Subalpine Flysch Zone can be seen as a mélange zone at the base of the Upper Helvetic nappes, having carried fragments of the units thrust over the European continental margin during the first phase of Helvetic deformation (see p. 31).

4.2. Upper Helvetic

The Upper Helvetic subdomain includes the classic "Helvetic nappes" and the overlying units of South Helvetic to Ultrahelvetic paleogeographic origin. In western Switzerland, this subdomain includes the Wildhorn Nappe Complex, which is correlated with the Mont Chétif Nappe south of the Rhône Valley (STECK et al. 1999) and with the Roselette Nappe southwest of the Mont Blanc Massif. The Pillon and the Bulle mélange zones complete the Upper Helvetic subdomain west of the Thunersee.

In central and eastern Switzerland, the Helvetic nappes consist of two pairs of overlapping nappes, respectively the Drusberg Nappe above the Axen Nappe and the Säntis Nappe above the Glarus Nappe Complex. The two lower nappes consist mainly of Jurassic sediments, which are in places capped by Cretaceous–Paleogene sediments. Moreover, the base of the Glarus Nappe Complex consists of a thick series of Permian and Triassic rocks. The two upper nappes consist exclusively of Cretaceous and Paleogene sediments. The Tavetsch and Gotthard nappes, mainly consisting of crystalline basement, are considered to be the substratum of the "Helvetic nappes". The sedimentary units behind the Gotthard Nappe are also part of the Upper Helvetic subdomain (Camosci and Scopi nappes, Piora-Peiden Slice Complex). Thin slivers of South Helvetic to Ultrahelvetic sediments or mélanges overlie the Drusberg and Säntis nappes (Habkern Mélange Zone, Iberg and Wildhaus mélanges, Internal Einsiedeln Slices, Fläscherberg and Liebenstein nappes).

The base of the Upper Helvetic subdomain corresponds to prominent thrusts, from west to east, with increasing displacement (see p. 32): Diablerets, Wildhorn, Axen and Glarus thrusts. In central and eastern Switzerland, as the upper nappes mentioned above have moved further north than the lower ones, their basal thrust faults become the base of the Upper Helvetic in front of the lower nappes, from west to east: Drusberg Thrust and Säntis Thrust.

4.2.1. Mont Chétif and Roselette nappes

A band of sedimentary rocks overlies the sedimentary cover of the Internal Mont Blanc Massif from Saxon in the Rhône Valley up to south of the Mont Blanc summit. It seems to be autochthonous above the small Mont Chétif Massif in the Valle d'Aosta, so this crystalline basement and its sedimentary cover form the *Mont Chétif Nappe*. This nappe is assumed to be the root of the Wildhorn Nappe Complex situated north of the Rhône (STECK et al. 2001).

The *Roselette Nappe* is a small unit situated further west around the southwestern end of the Mont Blanc Massif. It consists of similar basement and sediment rocks as the Mont Chétif Nappe and occupies a similar structural position above the crystalline basement and sedimentary cover of the Mont Blanc Massif. It is characterized by the presence of several internal thrust faults.

4.2.2. Tavetsch, Ilanz and Gotthard nappes

The *Tavetsch Nappe* crops out in a large part of the upper Surselva (Vorderrhein Valley). It shows two contrasting parts: In the west, a narrow crystalline "massif" (formerly "Tavetsch-Zwischenmassiv"), consisting mainly of paragneisses, lies between the Aar Massif in the north and the Gotthard Nappe in the south. In the east, this crystalline basement thins and terminates towards the east in the core of an anticline, surrounded by Permian Verrucano sediments. The continuation of these sediments is found in the Glarus Nappe Complex.

The *Ilanz Nappe* extends south of the eastern part of the Tavetsch Nappe and consists of Permian Verrucano sediments locally capped by Triassic sediments.

The *Gotthard Nappe* extends from Brig in Valais to Ilanz in Graubünden. Its crystalline core (former "Gotthard Massif") consists of pre-Caledonian and pre-Variscan para- and orthogneisses and Late Variscan granitic intrusions. The sedimentary cover of this nappe varies from place to place. It was defined as the "Urseren-Garvera Zone" at the northern border of the nappe, as the "Termen Zone" and "Nufenen Zone" at the southern border between Brig and Airolo. The former zone consists of Permian sediments overlain by Triassic and Jurassic strata while the two latter zones are composed of a Triassic to Early Jurassic series. East of Airolo, the thin cover series is essentially Triassic; between Airolo and the Passo del Lucomagno, it is in contact with the Triassic of the Piora-Peiden Slice Complex, so the boundary between the two is sometimes difficult to identify. The very narrow "Goms Massif", located near Fiesch in the upper Rhône Valley, is embedded in the Permian of the "Urseren-Garvera Zone" and can be considered as a slice or a fold of the Gotthard crystalline or as a tectonically independent small unit due to its striking affinity to the Aar Massif.

4.2.3. Camosci and Scopi nappes, Piora-Peiden Slice Complex

The *Camosci Nappe* is a small unit located south of the Nufenenpass and sandwiched between the Lower Penninic Sion-Courmayeur Nappe to the north and the Lepontic Monte Leone and Lebendun nappes to the south (CARRUPT 2003). It is made up of sediments with South Helvetic to Ultrahelvetic affinity.

The *Scopi Nappe* extends southeast of the Gotthard Nappe between the Passo del Lucomagno and Ilanz. It consists of an overturned sedimentary sequence of Triassic to Middle Jurassic age and of South Helvetic to Ultrahelvetic origin. The *Piora-Peiden Slice Complex* is a set of thin slices that occur continuously from Airolo to Ilanz between the Gotthard or Scopi nappes to the north and the Leventina-Lucomagno or Grava nappes to the south. These slices consist of Triassic to

Early Jurassic sediments similar to those of the Scopi Nappe. As this slice complex underwent a first Alpine metamorphic phase of high pressure (WIEDERKEHR et al. 2008), it could also be considered as Lepontic.

4.2.4. Wildhorn Nappe Complex

The Wildhorn Nappe Complex comprises a complete stratigraphic series ranging from Triassic to Paleogene. It occupies the Rawil axial depression: southwest of Rawilpass, the axes of the main folds dip to the NE, while northeast of the pass they dip to the SW. The nappe complex continues to the northeast up to the Kander Valley, where it is replaced by the Axen and Drusberg nappes. The Axen Nappe contains Jurassic strata, whereas the Drusberg Nappe is made up of Cretaceous – Paleogene strata. HÄNNI & PFIFFNER (2001) set the northeastern limit of the Wildhorn Nappe Complex at the Mesozoic synsedimentary Bachli-Giesenen Fault, which was reactivated by Alpine nappe stacking. This fault induced an abrupt lateral increase in the thickness of the Cretaceous sediments toward the east which in turn caused an important change in structural style (HÄNNI & PFIFFNER 2001).

The Wildhorn Nappe Complex consists of three superposed nappes: the *Diablerets Nappe*, present only in the southwest, at the base of the complex, is linked by a tight syncline to the *Mont Gond Nappe*, which is also outcropping mainly in the southwestern part of the complex. The highest *Sublage Nappe* forms the main body of the complex; it overlies the thin Jägerchrüz Nappe north of Sierre and the Gellihorn Nappe further northeast (see § 4.1.3).

4.2.5. Axen and Drusberg nappes

From the Kander Valley, the *Axen* and *Drusberg* nappes represent the eastward continuation of the Wildhorn Nappe Complex. The transition is caused by a synsedimentary fault (Bachli-Giesenen Fault, HÄNNI & PFIFFNER 2001), which led to the development in the east of a very thick marl sequence (earliest Cretaceous Palfris Formation) that acted as décollement layer during Alpine nappe stacking. Up to the Engelberg Valley, the stratigraphic series of the Axen Nappe and that of the Drusberg Nappe are practically complementary. The Axen Nappe is composed of a Jurassic series with some Triassic fragments in its base and Cretaceous and Paleogene sediments in the eastern part of the area. The Drusberg Nappe consists only of Cretaceous to Paleogene sediments. Between the Engelberg Valley and the Klöntal, where the Axen Nappe series is complemented by overlying Paleogene sediments, the internal structure of the nappe becomes more complex due to the presence of numerous thrusts following additional décollement levels which split the nappe into several slices. In contrast, the stratigraphic series of the Drusberg Nappe does not change. However, three slices of Late Jurassic limestone (Quinten

Formation) are present at its base; one is located in the Muotatal and underlies the Palfris Formation (Wissenwand Slice, Hantke et al. 2013), the other two crop out between the Engelberg Valley and the Vierwaldstättersee, intercalated into the Palfris Formation (Maisander Slices, Menkveld 1995); the latter are considered part of the Axen Nappe.

Between the Thunersee and the Vierwaldstättersee, the Drusberg Nappe contains a large-scale open synformal structure which preserves tectonically higher units in its core, from bottom to top: the Habkern Mélange Zone, the Lower Penninic Schlieren Nappe and klippen of the Middle Penninic Préalpes Médianes Nappe. The internal structure of the Axen Nappe changes abruptly across the Engelberg Valley (Pfiffner et al. 2010, Pfiffner 2011) owing to a fault perpendicular to the fold axes and active during nappe formation. In a similar manner, a fault must be assumed along the southeastern part of the Vierwaldstättersee which explains the very different nappe structure of the Axen and the Drusberg nappes on both sides of the lake (Pfiffner et al. 2010, Pfiffner 2011).

East of the Vierwaldstättersee, the two nappes can be traced all the way up to the Linth Valley. On the western flank of this valley, they are underlain by the Glarus Nappe Complex (including the Mürtschen Nappe), while they are replaced by the Glarus Nappe Complex and the Säntis Nappe on the eastern flank. A major N–S oriented fault is assumed to be present along the Linth Valley in order to explain the dramatic change in internal structure of the Helvetic nappes on either side of the valley.

4.2.6. Glarus Nappe Complex, Säntis and Hohenems nappes

From the Linth Valley to the Rhine Valley, the Upper Helvetic subdomain contains the Glarus Nappe Complex and the Säntis Nappe. The stratigraphic series of the *Glarus Nappe Complex* consists of a thick Verrucano (Permian), Triassic and Jurassic series, as well as Cretaceous and some Paleogene sediments depending on the subunit of the complex. The Verrucano Group crops out south of the Walensee–Seeztal and forms klippen in the south, within the area of the Tectonic Arena Sardona, a UNESCO World Heritage Site. The klippen offer a spectacular view of the Glarus Thrust and ignited the discussion about nappe tectonics in the 19th Century (Trümpy & Westermann 2008).

The *Säntis Nappe* overlies the Glarus Nappe Complex north of the Walensee and Seeztal and is composed of Cretaceous and rare Paleogene sediments. It extends from the Linth Valley in the west to the Rhine Valley in the east, including the Fläscher Berg east of Sargans. The Säntis Nappe forms a broad synform north of the Walensee, in the core of which are preserved klippen consisting of Upper Helvetic mélanges, as well as Lower and Middle Penninic units. In the Säntis area, the internal structure is characterized by fold trains and fold-parallel thrust faults (Pfiffner et al. 2010, Sala et al. 2014). Between Sax and Appenzell, an important

N–S oriented fault, the Sax-Schwende Fault, can be shown to have been active during the nappe internal deformation (PFIFFNER 2011).

The folds of the Säntis Nappe form a depression extending east across the Rhine Valley, and culminate in the Vorarlberg region where the fold core comprises Jurassic strata visible in the Kanisfluh (PFIFFNER et al. 2010). In Vorarlberg the Säntis Nappe is underlain by the *Hohenems Nappe* (WISSLING 1985), a nappe that crops out solely around Hohenems, in the Rhine Valley, and dips southward below the Säntis Nappe, extending in the subsurface as far as Liechtenstein (ZERLAUTH et al. 2014).

4.2.7. Pillon Mélange Zone

S. Dall'Agnolo

The Pillon Mélange Zone consists of a chaotic system of discontinuous slivers – some of them of several kilometers long, often described as "nappes" – in a few matrix. This mélange zone is known in the literature as the "Ultrahelvetic nappes". The paleogeographic origin of the slivers is located south of that of the Wildhorn Nappe Complex, i.e., in the most distal part of the European continental shelf (see p. 38). These slivers were thrust onto the sediments of the Helvetic platform, most likely at the base of the Penninic units during their emplacement onto the southern European continental margin. They underwent later deformation during the formation of the Helvetic nappes. The mélange zone can be subdivided into lower mélanges, associated with a specific Helvetic nappe, and upper mélanges, related to the base of the Prealps nappes (MOSAR et al. 2001; more details in JEANBOURQUIN et al. 1992, JEANBOURQUIN 1994). It is located on top of the Lower and Upper Helvetic nappes and forms a wide band between the Helvetic units and the Penninic units of the Prealps; this band was formerly called the "Zone des Cols" ("Sattelzone") or "Internal Prealps".

The matrix part of the mélanges is relatively poorly developed; little "wildflysch" is found between the slivers. However, a chaotic deposit dominated by block-in-matrix fabrics – the Plaine Morte Mélange (JEANBOURQUIN 1994) – directly overlies many Lower and Upper Helvetic units (Aiguilles Rouges Massif, Morcles and Jägerchrüz nappes, Wildhorn Nappe Complex). In many cases, this mélange lies directly above the Helvetic flysch and has therefore occasionally been considered as the top of the Helvetic sedimentary series.

The different slivers (former "nappes") of the mélanges are characterized by their lithology and their structural position. They are composed of the following sedimentary series:

- The Anzeinde-type slivers, composed of a Malm–Cretaceous series, often overlie the Plaine Morte Mélange.

- The Sex Mort-type slivers consist of a Malm and Eocene series and occur exclusively on top and in front of the Sublage Nappe (Wildhorn Nappe Complex).
- The Arveyes-type slivers (Dogger and Eocene), the Bex-Laubhorn-type slivers (Trias–Lias) and the Meilleret-type slivers (Eocene flysch) occur between the Prealps nappes and the frontal folds of the Lower and Upper Helvetic nappes, forming together the upper part of the Pillon Mélange Zone.

In the Sulens Klippe, east of the Lac d'Annecy, the Nantbellet Mélange lies above the Chaines Subalpines Nappe and below a series related to the Préalpes Médianes Nappe. It is also considered to be part of the Pillon Mélange Zone. Its upper part consists of "wildflysch" that contains lenses of Subbriançonnais and Ultrahelvetic origin. Its lower part consists mainly of one large Anzeinde-type sliver containing here also a transgressive Cenozoic flysch (ROSSET et al. 1976, DOUDOUX et al. 1992).

It should be noted that, in some places, the Zone Submédiane, attributed to the Middle Penninic as a mélange at the base of the Préalpes Médianes Nappe, appears to be cartographically continuous with the Pillon Mélange Zone, in particular the Bex-Laubhorn-type slivers.

4.2.8. Bulle Mélange Zone

S. Dall'Agnolo

The Bulle Mélange Zone lies between the Subalpine Molasse and the Prealps nappes (Gurnigel, Voirons or Préalpes Médianes nappes). It comprises the Infraprealpine Mélange ("wildflysch") in which slivers are embedded. The four bigger slivers, of kilometer scale, have been defined as slices: Bois de Bouleyres and Montsalvens slices near Bulle, Pléiades Slice north of Montreux and Faucigny Slices north of Bonneville in Savoie. The lithologies of these slivers are of similar types to some of the Pillon Mélange Zone described in the previous paragraph. In the Romandes Prealps (see §6.1), the Gurnigel Nappe is interrupted near Bulle, where the Bulle Mélange Zone and two of these slivers occur, all in contact with the Préalpes Médianes Nappe. From there, this mélange zone crops out for more than 10 km in both directions between the Gurnigel Nappe and the Préalpes Médianes Nappe.

4.2.9. Internal Einsiedeln Slices, Fläscherberg Nappe

The *Internal Einsiedeln Slices* overlie the Drusberg Nappe and underlie the Wägital Nappe in the region between Schwyz and Wägitalersee. They consist of slices of Late Cretaceous and Paleogene sediments of South Helvetic origin.

The *Fläscherberg Nappe* is a small unit that overlies the Säntis Nappe at the southeastern end of the Fläscher Berg, a hill east of Sargans. It is made up of Jurassic sediments of South Helvetic to Ultrahelvetic origin.

4.2.10. Habkern Mélange Zone, Iberg and Wildhaus mélanges, Liebenstein Nappe

The *Habkern Mélange Zone* overlies the Drusberg Nappe between the Thunersee and the Vierwaldstättersee. It is located in a synformal structure and overlain by klippen of the Lower Penninic Schlieren Nappe and Middle Penninic Préalpes Médianes Nappe. Several mélanges are defined in this zone (BAYER 1982). Further east, the *Iberg Mélange* overlies the Drusberg Nappe in the Iberg Klippen, where it is overlain by Penninic and Austroalpine units. All these mélanges contain some “wildflysch” with Late Cretaceous and Paleogene lenses, slices of South Helvetic origin and slices from the overlying Penninic units (BAYER 1982).

The *Wildhaus Mélange* overlies the Säntis Nappe in a large-scale synform north of the Walensee and consists of slices of Late Cretaceous and Paleogene strata of South Helvetic to Ultrahelvetic origin packed in a “wildflysch” matrix. Locally it is overlain by klippen of flysch of the Üntschen Nappe (Lower Penninic) or even of the Falknis Nappe (Middle Penninic). In Austria, the Wildhaus Mélange continues in the *Liebenstein Nappe,* which consists of a slice complex including the “Feuerstätter Nappe” (“Wildflysch”; FRIEBE 2007).

5. LEPONTIC

F.L. Schenker & Y. Gouffon

The internal part of the Central Alps is characterized by the presence of a structural and metamorphic dome designated as the Lepontine Dome, occupying the geographic region known as the Lepontine Alps. It comprises nappes made up predominately of crystalline basement rocks, locally bounded by a thin autochthonous or parautochthonous Mesozoic sedimentary cover (syntheses in, e.g., BERGER et al. 2005a, STECK et al. 2013). Most of these units are derived from the most distal part of the thinned European margin. For purely structural reasons, they have been described as Lower Penninic (e.g., ARGAND 1911, PREISWERK 1921, NIGGLI et al. 1936, STECK et al. 2013). However, because these units have a different paleogeographic origin from that of the other Lower Penninic units (Valaisan Basin), they have been termed “Subpenninic” (MILNES 1974b, SCHMID et al. 2004, BOUSQUET et al. 2012), or “Infrapenninic” (Tectonic Map of Switzerland 1:500 000, ed. 2005). These last two terms, meaning “below the Penninic”, are not appropriate because they do not designate a precise tectonic domain. The paleogeographic origin of these units is situated between that of the Helvetic units and that of the Penninic units. The internal structural position and the specific characteristics of the sedimentary cover – when present – of these units lead us to group them together in a new tectonic domain. As they occupy almost the entire structural Lepontine Dome, the term *Lepontic* is adopted here.

This Lepontic domain is bounded below by the basal thrust of its units on the Upper Helvetic units, visible only at the front of the Leventina-Lucomagno Nappe, and above by the basal thrust of the Lower Penninic units. Moreover, the structural Lepontine Dome is bounded to the west by the Simplon Fault (see § 10.3), a major SW-dipping normal fault that has exposed the Lepontic units (footwall) beneath the Lower and Middle Penninic nappes (hangingwall). However, two small units, the Berisal Nappe and the Gälmji Zone (see § 6.2.2), located in the core of the synformal Berisal Backfold on the northwestern side of the dome, are considered as equivalents of Briançonnais derived units situated further west and thus as Middle Penninic.

Symmetrical to the Simplon Fault, a penetrative orogen-parallel ductile shear zone which late activity is likely marked by the ENE-dipping Forcola Fault, partially delimits the structural Lepontine Dome to the southeast. The Lepontic units also dip below the Lower and Middle Penninic units along this ductile fault. To the north, the ENE-shearing disappears north of the Passo del San Bernardino at the base of the Lower Penninic units. The continuation of the Forcola Fault to the southeast under the Mera Valley alluvium is unclear, however it is also observed within the northwestern end of the Novate Intrusion (MEYRE et al. 1998).

The northern boundary of the Lepontic nappes – corresponding to the northern boundary of the structural Lepontine Dome – is characterized by a complex, steep synformal zone (internal part of the “Northern Steep Belt”, MILNES 1974b), the core of which is occupied by Lower Penninic units. To the north of this synformal zone occur three units of South Helvetic to Ultrahelvetic origin (Gotthard Nappe, Scopi Nappe and Piora-Peiden Slice Complex), the southern part of which is also steeply dipping (external part of the “Northern Steep Belt”). Contrary to some authors who consider these three units as “Subpenninic” (see above), they are considered here as belonging to the Upper Helvetic and not to the Lepontic, especially because the Gotthard crystalline is considered as have formed the bedrock for the sedimentation of the future Upper Helvetic Drusberg and Säntis nappes.

The southern flank of the Lepontic domain is very steep (“Southern Steep Belts”, MILNES 1974b) and is bounded to the south by the Centovalli Fault west of Locarno, and to the east by the Tonale Fault and the associated Bregaglia Intrusion tail.

The bell-shaped architecture of the Lepontine Dome consists of two subdomes: the Toce Culmination in the west and the Ticino Culmination in the east. They are separated by the NNW–SSE trending “Maggia Synformal Zone”.

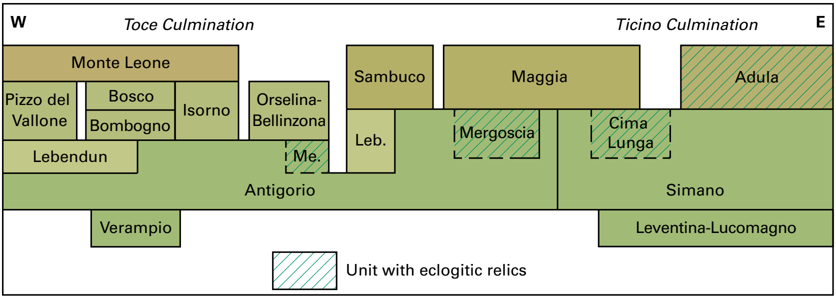

Fig. 6: Diagram of the superposition of the Lepontic units. The dashed lines represent the questioned nappe contacts (see description of the concerned units below).

The currently observed stacking relationships of the Lepontic units along a W–E transect of the structural Lepontine Dome are summarized in Figure 6. However, the structural relationships between the different units are not always clear and sometimes controversial. In particular, the tectono-stratigraphy in the northwestern part of the Ticino Culmination is still strongly debated due to complex superposed folding (see different interpretations in GRUJIC & MANCKTELOW 1996, MAXELON & MANCKTELOW 2005, BERGER et al. 2005a, STECK et al. 2013, 2019).

The structural dome is formed by rocks that have reached amphibolite-facies conditions at their metamorphic peak during the Oligocene–Miocene. A prior high-pressure stage which locally reached eclogitic conditions is now recorded in minor rock volumes. The Barrovian metamorphism is described by concentric, asymmetrical isograds, with high-grade rocks exposed to the south around Bellinzona along the migmatitic “Southern Steep Belt” (e.g., TODD & ENGI 1997). The maximum temperatures reached more than 650° at ca. 0.7 GPa to the south (BURRI et al. 2005) and ca. 500–575 °C at ca. 0.7 GPa to the north (WIEDERKEHR et al. 2008). Their timing has been established in the south as a continuous thermal event between 32 and 22 Ma (RUBATTO et al. 2009), in the central domain in two distinct age populations at 32 and 22 Ma (TAGLIAFERRI et al. 2023) and at the northern limit between 19 and 18 Ma (WIEDERKEHR et al. 2009).

Isograds within the Lepontine Dome cutting across tectonic boundaries are commonly interpreted as evidence supporting a Barrovian overprint that occurred between 22 and 18 Ma, after the nappe emplacement (e.g., BERGER et al. 2011). However, recent U-Pb zircon ages of syntectonic migmatites along the Adula and Maggia tectonic nappe contacts show that Barrovian metamorphic conditions had already been reached at 32 Ma during nappe exhumation. It is still debated whether the overall Barrovian isograds reflect 1) a single post-nappe thermal relaxation with a heat source located deeper in the crust (e.g., WIEDERKEHR 2008), 2) a downward conduction of heat transported by the advection of the Maggia and Adula nappes (TAGLIAFERRI et al. 2023), or 3) a complex scenario involving multiple mechanisms (BERGER et al. 2011).

5.1. Verampio Nappe, Antigorio Nappe Complex

The *Verampio Nappe* is the lowest unit of the Toce Culmination. It appears as a window in the Valle Antigorio. This nappe consists of a paragneiss basement intruded by a Variscan granite (289 ± 3 Ma, BERGOMI et al. 2007) and overlain by a thin Mesozoic sedimentary cover. The same Mesozoic series occupies the reverse limb of the overlying Antigorio Nappe. STECK et al. (2001) suggest the contact between these two nappes is a thrust isoclinal recumbent syncline.

The Antigorio Nappe and the Mergoscia Zone have been grouped under the term *Antigorio Nappe Complex* because the boundary between the two is not clear and has been defined differently by the authors (e.g., BURRI 2005, BERGER & MERCOLLI 2006, PFEIFER et al. 2018). Furthermore, this boundary is completely unidentifiable in the Southern Steep Belt (or “root zone” north of the Tonale Fault), where the rocks of each of these units are no longer recognizable due to their migmatization. In addition, isoclinal folds parallel to the schistosity affect the contact between these two units.

The *Antigorio Nappe* consists mainly of Variscan granitoids (ca. 290–300 Ma, BERGOMI et al. 2007). In its northwestern part, this basement is surrounded by an autochthonous Mesozoic–Paleogene sedimentary cover, which could be connected to the cover of the Verampio Nappe via an early thrust syncline. Late folding is responsible for two multi-kilometer-scale isoclinal structures: the Alpe Bosa-Wandfluhhorn Fold and the Ziccher Fold (e.g., MILNES 1974a, STECK et al. 2013).

The *Mergoscia Zone* is heterogeneous as it is composed of ortho- and paragneisses, metapelites, calcschists, metabasites and meta-ultrabasites. Both metabasites and meta-ultrabasites contain rare relics of high-pressure metamorphism (retrogressed eclogites and garnet-metaperidotites). This zone, displaying a high degree of deformation, is also interpreted as a mélange rather than as an originally stratified framework. BERGER et al. (2005a) considered the Mergoscia Zone to have formed within a tectonic accretion channel during the Alpine subduction.

The Antigorio Nappe Complex presents some similarities with the couple made by the Simano and the Cima Lunga nappes (TAGLIAFERRI et al. 2023): similar lithologies, same diffuse contact between both couple members, same structural position in respect to the Maggia Nappe, the first complex to the west, the second couple to the east of the latter nappe. So, the Mergoscia Zone would be a pre-Variscan sedimentary sequence intruded by Late Paleozoic magmas, which are the protoliths of the orthogneisses of the Antigorio Nappe.

5.2. Lebendun Nappe

The Lebendun Nappe overlaps the Antigorio Nappe on its northwestern edge. It is overlain by the Pizzo del Vallone in the west and by the Sambuco Nappe in the northeast. In the north, it is bordered by the calcschists of the Sion-Courmayeur Nappe. The end of the Lebendun Nappe to the east is not clearly established, as its rocks around the Sambuco Nappe – mainly siliceous and carbonate schists – are quite similar to the metasediments of neighboring units. Its extension on the map is in accordance with PROBST (1980; including his "San Giacomo Unit") and LEU (1986; including his "Sabbione Zone", without the basal part that constitutes the Pizzo del Vallone Nappe). To the southwest, it ends near the Swiss-Italian border in the valley descending from the Simplonpass. Further east, it forms a narrow band between the Antigorio Nappe and the Bombogno Zone in Italy, which is too thin to be drawn on the map. The Lebendun Nappe is constituted by foliated metasediments of arkose origin (shales and conglomerates) and is surrounded by calcschists and marbles. Pebbles of dolomites in the conglomerates suggest a post-Triassic deposition age for all these rocks (RODGERS & BEARTH 1960, SPRING et al. 1992).

5.3. Pizzo del Vallone Nappe

The Pizzo del Vallone Nappe surrounds the Monte Leone Nappe mainly in the large synformal Berisal Backfold (CARRUPT 2003). It is composed of a detrital sedimentary series covering the entire Mesozoic and possibly the Paleogene, characterized by Jurassic basaltic rocks. In the western part of the nappe, both north and south of the Monte Leone Nappe, occur the crystalline basement of these metasediments.

5.4. Monte Leone and Moncucco nappes

The *Monte Leone Nappe* is the highest of the Lepontic units in the Toce Culmination. It is involved in the large synformal Berisal Backfold and further east, after following the Rhône-Simplon Fault, in the Alpe Bosa-Wandfluhhorn double fold (e.g., STECK et al. 2001). This nappe consists mainly of a crystalline basement made of various orthogneisses (Ordovician and Permo-Carboniferous) and paragneisses, covered by a relatively reduced Triassic–Cretaceous(–Paleogene?) sedimentary series. A particularity of this nappe is the presence of a large ultramafic body (Geisspfad) within the gneisses.

The *Moncucco Nappe* occupies the core of the Vanzone Antiform in the Valle d'Ossola. It consists of a crystalline basement intruded by a Permian granite and is interpreted as the equivalent of the Monte Leone Nappe in the hangingwall of the Simplon Fault. Similar to that nappe, the Moncucco Nappe contains a large ultramafic body at its top (STECK et al. 2015).

5.5. Bosco, Bombogno, Isorno and Orselina-Bellinzona zones

The Bosco, Bombogno, Isorno and Orselina-Bellinzona zones include various rocks (micaschists, para- and orthogneisses, calcschists, marbles, amphibolites and few ultramafics), probably Paleozoic and Mesozoic in age, which can locally be interpreted as a mélange. The *Bosco* and the *Bombogno zones* appear between the Antigorio and Monte Leone nappes in the large polyphase Alpe Bosa-Wandfluhhorn Fold located between the Maggia and Antigorio valleys. In the southern part of the eastern (upper) limb of this fold, these two units have not been distinguished and are grouped together in the *Isorno Zone.*

The *Orselina-Bellinzona Zone* is continuous between the Valle d'Ossola and Bellinzona, located between the Antigorio Nappe and the Centovalli Fault west of Locarno and between the Mergoscia Zone and the Tonale Fault further east. The Orselina-Bellinzona Zone is lithologically similar to the Isorno Zone. STECK et al. (1999, 2001, 2013) see a continuity from one to the other unit on both sides of the Masera Synform near Domodossola, whereas other geologists do not see any structural connection between these two units (pers. comm. S.M. Schmid, N. Mancktelow, T. Burri). To the east of Bellinzona, the Orselina-Bellinzona Zone may include the extension of the Mergoscia Zone (see §5.1), which has not been distinguished in this area by the authors. As the Mergoscia Zone is also a mélange zone, the only criterion of distinction between these two units is the presence of eclogitic relics in the Mergoscia Zone (STECK et al. 2013 and ref. therein).

5.6. Maggia and Sambuco nappes

The Maggia and Sambuco nappes occupy the NNW–SSE oriented transverse synformal zone in the middle of the structural Lepontine Dome, but are not in cartographic continuity. These two units are made up of similar basement rocks intruded by Variscan granitoids (Late Carboniferous) but, in contrast to the Maggia Nappe, the Sambuco Nappe has a thin sedimentary cover, the facies of which have a Helvetic affinity (STECK et al. 2019). These units have undergone polyphase deformation (e.g., MAXELON & MANCKTELOW 2005) which makes the interpretation of their relationships with each other and with adjacent units difficult. Some authors see them as structurally continuous, at the top of the nappe stack, others as tectonically distinct units, at different structural levels (see discussion in BERGER et al. 2005a, STECK et al. 2013, 2019). Some authors (e.g., BERGER et al. 2005a, SCHMID et al. 2004) consider these two nappes as Middle Penninic because they are located above units originating from a subduction zone (Cima Lunga Nappe and Mergoscia Zone), implying a Briançonnais origin. This upper position is contested by MAXELON & MANCKTELOW (2005) and STECK et al. (2019). Moreover, their sedimentary cover and the latest Carboniferous age of their magmatic rocks are more in concordance with a paleogeographic origin in the European margin that justifies placing the Maggia and Sambuco nappes in the Lepontic domain. In addition, by grouping the Simano and the Cima Lunga nappes (§5.8), TAGLIAFERRI et al. (2023) proposed the existence of a lateral continuity between the Maggia Nappe and the Adula Nappe.

5.7. Leventina-Lucomagno Nappe

The Leventina-Lucomagno Nappe is the lowest unit of the Ticino Culmination. The lower part of the nappe ("Leventina Unit") is made up of several orthogneisses forming a deformed Late Variscan magmatic edifice composed of several magmatic pulses. Along the northeastern flank of the Valle Leventina, the Leventina orthogneisses are covered by a thick stack of paragneisses and micaschists ("Lucomagno Unit"). Along this boundary, sparse quartzitic gneisses ("roof quartzites") were interpreted as being Mesozoic in age by several authors and hence used to discriminate between a "Leventina Nappe" and a "Lucomagno Nappe". However, these quartz-rich horizons above the orthogneisses form metasomatically altered zones – in places sheared – and cannot be considered as Mesozoic metasediments (RÜTTI et al. 2005; see Fig. 7). The "Lucomagno Unit" can therefore be regarded as a pre-Alpine sedimentary shell of the Leventina magmatic edifice deformed during the Alpine orogeny. Quartzitic horizons, similar to those mentioned above, also occur where the Simano Nappe directly overlies the Leventina orthogneisses. The northern part of this nappe contact is often characterized by a mylonitic band (RÜTTI et al. 2005 and ref. therein). To the south, this mylonitic shear zone dissipates within the Leventina orthogneisses in an anastomosing network of shear bands (Fig. 7). There, the upper limit of the Leventina-Lucomagno Nappe is difficult to trace since paragneiss and calcsilicate lenses – traditionally used to trace the tectonic contact – are in fact deformed xenoliths within the Leventina orthogneisses.

Remnants of Triassic rocks crop out around the frontal part of the Leventina-Lucomagno Nappe, although for some of them it is not clear whether they belong to the Leventina-Lucomagno Nappe or to the adjacent units. Permo-Triassic metasediments crop out also within the Leventina-Lucomagno Nappe, likely as pinched synclines (e.g., Molare Syncline; see Fig. 7) or as intranappe slices.

5.8. Simano and Cima Lunga nappes

The *Simano Nappe* consists of a heterogenous metamorphosed magmatic complex intruded into pre-Variscan paragneisses, forming today the orthogneisses that dominate the southern and the western part of the Simano Nappe. The eastern part contains Ordovician orthogneisses within paragneisses and the northern part consists of semi- to metapelitic gneisses, micaschists, amphibolites and sporadic lenses of ultramafic rocks, locally covered by Permian and Triassic sedimentary rocks (e.g., PREISWERK et al. 1934). In its frontal part, the Simano Nappe forms

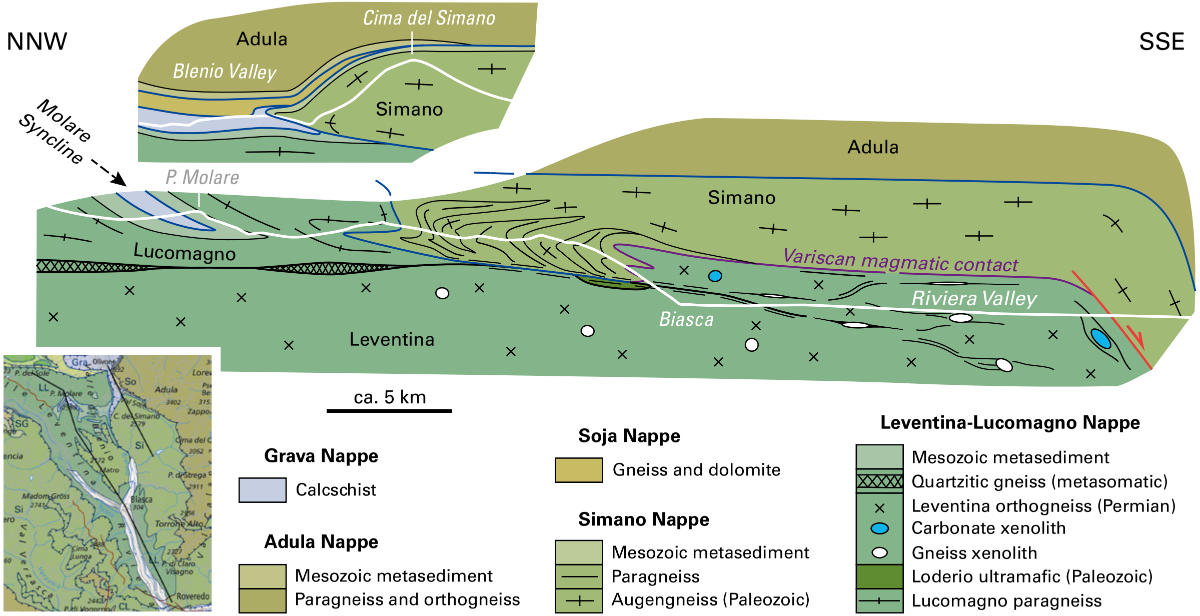

Fig. 7: Tectonic cross-section through the Lepontic tectonic units in the Ticino Culmination. Vertical axis not to scale. Note that the basal thrust of the Simano nucleated and localized between the Riviera and the Blenio valleys to the north. To the south, the boundary between the Leventina and the Simano units is a slightly reactivated magmatic contact.

a large-scale recumbent fold – characterized by a thinned and disrupted inverted limb – over the Leventina-Lucomagno Nappe. This contact is characterized by a shear zone that spreads out southwards, forming a multitude of shear bands in the Leventina orthogneisses. There, the boundary between the Simano and the Leventina-Lucomagno nappes consists of a sheared Variscan magmatic contact (RÜTTI et al. 2005, SCHENKER et al. in prep.; see Fig. 7). The upper limit of the eastern part of the Simano Nappe is defined by a prominent shear zone, the result of the overthrusting of the Adula Nappe (TAGLIAFERRI et al. 2023). The frontal part of the Simano Nappe is bordered by metacarbonates, considered to be the Mesozoic sedimentary cover of the nappe. To the west, this nappe is capped by the Cima Lunga Nappe and to the northwest by the Maggia Nappe. This latter contact is intensely sheared.

The *Cima Lunga Nappe* is made up of paragneisses, orthogneisses, sheets of marble and calcschist as well as lenses of mafic and ultramafic rocks that locally have an incoherent character. Eclogitic mineral assemblages are widespread in the mafic and ultramafic rocks. Sheath folds around the disrupted competent mafic and ultramafic lenses suggest intense shearing within a shear zone at the base of the Maggia Nappe (MAINO et al. 2021). The Cima Lunga Nappe shows lithological and deformational similarities to the Mergoscia Zone (see § 5.1). The contact between the Cima Lunga Nappe and the underlying Simano Nappe is tentatively defined by the calcschists and the higher degree of strain within the paragneisses. The boundary to the overlying Maggia Nappe follows generally the base of the orthogneisses of the Maggia Nappe. According to most authors, the Cima Lunga Nappe is connected in the east to the Adula Nappe in the lower Valle Mesolcina. Several authors (e.g., EVANS et al. 1979, ENGI et al. 2001) consider the Cima Lunga Nappe to be an exhumed high-pressure nappe or a tectonic mélange from a subduction channel, such as the Adula Nappe (see below). According to TAGLIAFERRI et al. (2023), the Cima Lunga Nappe is a pre-Variscan sedimentary sequence that was intruded by Permian magmas, which are the protoliths of the orthogneisses of the Simano Nappe; in this interpretation, Cima Lunga and Simano are two distinct lithologic units of a single nappe.

5.9. Piz Terri-Lunschania and Soja nappes, San Giorgio Slice

The *Piz Terri-Lunschania Nappe* consists of several slices made up of Permian and Mesozoic sediments. This nappe forms the large isoclinal Lunschania Antiform surrounded by the Grava Nappe. This antiform is situated in front of the Adula Nappe and is rooted below this nappe (see Pl. II, eastern cross-section). Despite the overall structure of the antiform, GALSTER et al. (2012), based on the Triassic facies, assumed a more internal paleogeographic origin of the Piz Terri-Lunschania Nappe than that of the Adula Nappe.

The small *Soja Nappe* includes a polycyclic crystalline basement covered by Permian to Jurassic sediments. It is located below the Adula Nappe in its frontal part, where it is wedged between this latter nappe and the Simano Nappe. To the north, it extends into the Garzott Slices located in the core of the Lunschania Antiform and surrounded by the Piz Terri-Lunschania Nappe. Due to this structural position, GALSTER et al. (2012) attached the Garzott Slices to the Piz Terri-Lunschania Nappe, but the facies analogies bring them closer to the Soja Nappe (VÖGELI et al. 2013). A paleogeographic origin of the Soja Nappe between the Piz Terri-Lunschania Nappe and the Adula Nappe is plausible.

The small *San Giorgio Slice*, located in the Valle Leventina, consists of a crystalline basement – micaschists with metaconglomerate layers – and its Triassic sedimentary cover. It is comparable to the Soja Nappe in the following ways: 1) they both occupy the same structural position on both sides of the Leventina-Lucomagno Nappe and in front of the Simano Nappe, 2) their lithologies are very similar (BIANCONI & STRASKY 2015 and ref. therein).

5.10. Adula Nappe

The Adula Nappe consists of a Paleozoic crystalline basement made up of orthogneisses (Variscan and older), paragneisses (mostly clastic metasediments, containing also Paleozoic carbonate rocks) and lenses of mafic and ultramafic rock. Several mafic lenses experienced high-pressure Alpine metamorphism under eclogite-facies conditions, followed by decompression at Barrovian conditions between amphibolite to greenschist metamorphic facies. Relics of Variscan high-pressure metamorphism have also been observed (SANDMANN et al. 2014). Lithostratigraphic and tectonic studies of the Adula Nappe show a coherent structure dominated by large folds (e.g., LÖW 1987, CAVARGNA-SANI et al. 2014b). This nappe was also interpreted as a slice complex created in a tectonic accretionary channel (e.g., BERGER et al. 2005a, PFIFFNER 2016).

In places, the basement contains a reduced series of Mesozoic sediments preserved in the cores of the synclines (CAVARGNA-SANI et al. 2014a, b); these Mesozoic sediments were earlier defined as the “internal Mesozoic” (e.g., LÖW 1987). Mesozoic sediments may also cover the basement gneisses at the nappe border. From north of the Zervreilasee to San Bernardino, Triassic slices alternate with basement slices in a 300 m thick mélange zone known as the “Lower Vals Slices”, which is considered the top of the nappe. As in the other Lepontic units, these sediments are also typical for the most distal part of the thinned European margin (see p. 44).

The lower boundary of the Adula Nappe follows the shear zone on the top of the Simano Nappe (§ 5.8), the frontal part is bordered by the Soja and the Piz Terri-Lunschania nappes, up to the Valser Tal. From here to the south, the Adula Nappe is overlain by Lower Penninic units: first the Vals Slices (previously described as "Upper Vals Slices"), then the Aul Nappe and finally the Tomül Nappe.

5.11. Gruf Complex

The Gruf Complex is a migmatitic body that directly underlies the Tambo Nappe and the ophiolitic Chiavenna Nappe to the north along a steeply N-dipping fault and follows the base of the Bregaglia Intrusion to the south. This complex consists of granulites, charnockites and migmatites representing polymetamorphic lower crust that was dragged up by the rise of the Bregaglia Intrusion (GALLI et al. 2013). This complex is therefore lithologically distinct from other migmatitic Lepontic units, in particular the Adula Nappe. The Gruf Complex is either regarded as a singular lower crustal unit that has nothing in common with all the other units of the Lepontic nappe stack nor any other tectonic domain (GALLI et al. 2013), or alternatively, due to its tectonic position below the Tambo and the Chiavenna nappes, is interpreted as the southernmost part of the Adula Nappe that became differentially exhumed during the rise of the Bregaglia Intrusion (SCHMID et al. 1996a, b).

6. PENNINIC

The Penninic domain comprises all tectonic units situated between the Helvetic or the Lepontic domains and the Austroalpine or the Salassic domains. It also includes units that were transported further north on the Helvetic and which are currently found as klippen on top or in front of this domain (e.g., Prealps).

The Penninic domain is subdivided into Lower, Middle and Upper Penninic subdomains that are bounded by major thrust faults. These subdivisions closely depict the structural position of the units, and also their paleogeographic origin: as a result of nappe stacking during the Alpine orogeny, the originally more southerly units were thrust onto more northerly units (see Tab. 2 and Pl. III): the Lower Penninic units are derived from the Valaisan Basin, the Middle Penninic from the Briançonnais Terrane and the Upper Penninic nappes from the Piemonte-Liguria Ocean. However, this simple model is challenged by major exceptions, for example the Upper Penninic Antrona Nappe which is situated below the Middle Penninic Monte Rosa Nappe. A metamorphic gap characterizes the Lower/Middle Penninic boundary with high-pressure blueschist facies in the former juxtaposed against greenschist facies in the latter subdomain. This case demonstrates the presence of a subduction zone where Lower Penninic and Lepontic units were subducted and subsequently rapidly exhumed (BOUSQUET et al. 2002).

The boundary between the Penninic and the Salassic or the Austroalpine domains corresponds, in eastern Switzerland, to the reactivated ocean-continent transition and, in western Switzerland, to the upper boundary of the subduction zone of the Piemonte-Liguria Ocean plate – together with some allochthons of Adriatic origin – below the Adriatic margin.

The original boundary between the Helvetic and the Penninic domains is the thrust fault of the Valaisan sedimentary units on top of the European continental margin sediments, referred to as the "Penninic Basal Thrust" by some authors. More generally, the "Penninic Front" refers to the outer boundary of the Penninic domain, whether it is due to the initial thrust fault or to a more recent fault, sometimes strike-slip (e.g., Rhône Fault; CARDELLO et al. 2019) or normal faulting (GRASEMANN & MANCKTELOW 1993, SARTORI & EPARD 2011 and ref. therein).

In the Prealps and klippen of central Switzerland, the boundary between the Helvetic and Penninic domains is represented by the thrust fault juxtaposing Lower – or in rarer cases Middle – Penninic nappes (e.g., Niesen, Gurnigel, Schlieren, Wägital nappes) onto Helvetic nappes. This major thrust is highlighted by mélanges and slivers that are attributed to either the Upper Helvetic (see §4.2.7, 4.2.10) or the Lower Penninic (STECK et al. 1999).

6.1. PREALPS

S. Dall'Agnolo

A number of nappes consisting of sedimentary rocks, originating from regions located further south than the European continental margin, form klippen resting in front or on top of the Helvetic nappes (e.g., SCHARDT 1898, JEANNET 1922, TRÜMPY 1960). Several klippen can be recognized from the west (Annes and Sulens klippen) to the east (e.g., Mythen Klippe; see §6.3). The largest lies south and west of Le Léman, known as the Prealps, and is distributed in two distinct regions: 1) the Chablais Prealps situated between the Arve Valley and the Rhône Valley, 2) the Romandes Prealps between the Rhône Valley and the Thunersee. The Prealps contain the most complete nappe stack; the other klippen contain only one or two of the units described in this chapter.

The Prealps were previously structurally subdivided into "Lower", "Middle" and "Upper Prealps" (ref. in MASSON 1976 and SARTORI 1990). The search for the root and origin of each nappe of the Prealps has led them to be considered as Penninic. However, the Prealps are a particular entity, having experienced a tectono-metamorphic history distinct from that of the Penninic units located further south in the internal part of the Alps.

6.1.1. Lower Penninic

6.1.1.1. Voirons and Gurnigel nappes

The Lower Penninic units in front of the Prealps comprise the Voirons Nappe in the Chablais Prealps and the Gurnigel Nappe in the Romandes Prealps; both are composed of flysch. Besides their structural position, both nappes show great similarity in terms of sedimentology. However, the Gurnigel flysch is dated Late Cretaceous to Eocene (VAN STUIJVENBERG 1979), while the Voirons flysch is only of Paleogene age (VAN STUIJVENBERG & JAN DU CHÊNE 1980, RAGUSA et al. 2018, 2021). The position of these two nappes below the front of the Préalpes Médianes Nappe implies that they are considered as Lower Penninic. The paleogeographic origin of these flysch formations is however still debated. Due to their close lithological and petrographical similarity with those of the Sarine Nappe (Upper Penninic), the flysches of the Gurnigel and Voirons nappes are thought to have originated in the Piemonte-Liguria Ocean (VAN STUIJVENBERG 1979, CARON et al. 1980, 1989, WINKLER 1983, GASINSKI et al. 1997). A possible origin in the Valaisan Basin is also suggested (SCHMID et al. 2005, TRÜMPY 2006, PFIFFNER 2014). The first hypothesis implies that these flysches were transported over and beyond the Préalpes Médianes Nappe, and then, that the latter was emplaced above the Voirons and Gurnigel Nappes by an out-of-sequence thrust fault.

Both the Voirons Nappe and the Gurnigel Nappe are discontinuously bordered by the Bulle Mélange Zone (§4.2.8), which separates the former nappes from the underlying Subalpine Molasse. In the Romandes Prealps, the Gurnigel Nappe is overturned at the contact with the Préalpes Médianes Plastiques (§6.1.2.2). This is the result of an out-of-sequence thrust bringing the Préalpes Médianes Nappe over the internal part of the Gurnigel Nappe (DE KAENEL et al. 1989). The contact between the two nappes is characterized by the presence of the Bulle Mélange Zone, which also marks an internal thrust fault within the Gurnigel Nappe in its western part.

At the eastern end of Le Léman, both nappes become extremely thin. No remnants of neither the Voirons Nappe nor the Gurnigel Nappe were encountered between the Bulle Mélange Zone and the Préalpes Médianes Nappe (DUPUY et al. 2014) in the deep well Chessel-1001 drilled about 5 km south of the Rhône's mouth into the lake. It is therefore assumed that the Voirons Nappe is not connected to the Gurnigel Nappe beneath the alluvium of the Rhône Valley.

The Gurnigel and Voirons nappes can be correlated towards the east with the Schlieren and Wägital nappes, which consist of similar flysches and occur on top or in front of the Helvetic nappes (§6.3.1.1).

6.1.1.2. Niesen Nappe

The Niesen Nappe is located in the rear part of the Romandes Prealps, in front of the Helvetic nappes and on top of the Pillon Mélange Zone. It consists of a thick succession of Late Cretaceous to Paleocene flysch and forms the highest peaks of the Prealps. Slices of rocks similar to those of the Niesen Nappe occur west of the Rhône in the Val d'Illiez region (Chablais Prealps). They are small and isolated occurrences and have therefore been included in the Zone Submédiane (see § 6.1.2.1). The origin of the rocks of the Niesen Nappe is unanimously assumed to be located in the Valaisan Basin (HAUG 1925, TRÜMPY 1955, HOMEWOOD 1974, ACKERMANN 1986).

The base of the Niesen Nappe is marked by the Infra-Niesen Mélange, which is composed of slivers of pre-flysch series within a mainly gypsum-anhydrite and rarely "wildflysch" matrix. These slivers consist of rare gneiss, Triassic to Late Jurassic sedimentary rocks as well as Niesen Flysch (ACKERMANN 1986 and ref. therein).

6.1.2. Middle Penninic

6.1.2.1. Zone Submédiane

The Zone Submédiane (MCCONNEL & DE RAAF 1929, WEIDMANN et al. 1976) is a mélange that is generally found at the base of the Préalpes Médianes Nappe. In the Romandes Prealps, the zone runs continuously from the Rhône Valley to the Thunersee and morphologically determines a succession of mountain passes (e.g., Col des Mosses) and valleys.

West of the Rhône Valley, a mélange zone, located between the Pillon Mélange Zone and the Préalpes Médianes Rigides or the Breccia Nappe ("mélange suprahelvétique supérieur" of JEANBOURQUIN et al. 1992), is considered to be part of the Zone Submédiane. It contains dispersed Niesen-Nappe-like flysch blocks as well as Early to Middle Jurassic slivers and Eocene breccias.

The Zone Submédiane contains slivers of varying composition and size within a matrix comprising evaporites or "wildflysch". The facies found in the mélange are not typical of a specific paleogeographic realm. It seems that many of these slivers have been collected over different paleogeographic areas, from the Ultrahelvetic to the Subbriançonnais realms.

6.1.2.2. Préalpes Médianes Nappe

The Préalpes Médianes Nappe is located in the central part of the Prealps; it is also called Klippen-Decke in German. It is subdivided into an external part, called the *Préalpes Médianes Plastiques*, and an internal part, the *Préalpes Médianes Rigides.* The Préalpes Médianes Plastiques are characterized by a succession of large fault-related folds with axes oriented E–W to SSW–NNE; its extent is roughly the same in the Romandes Prealps and the Chablais Prealps. The Préalpes Médianes Rigides consist of large imbricates (LUGEON & GAGNEBIN 1941, PLANCHEREL 1979, MOSAR 1991) and its main part is located in the Romandes Prealps. These two subunits differ also sedimentologically (see below). The Gastlosen range, 15 km ESE of Bulle, shows intermediate structural and sedimentological characteristics (MOSAR et al. 1996).

The origin of the Préalpes Médianes Nappe is assumed to be located within the Subbriançonnais and Briançonnais realms. This is due to the occurrence of equivalent stratigraphic units in the Middle Penninic nappes south of the Rhône Valley. Sediments range from Triassic to Paleogene in age. The different subsidence rates of the two realms led to a different sedimentary record in the Préalpes Médianes Plastiques compared to the Préalpes Médianes Rigides (BAUD & SEPTFONTAINE 1980, BOREL 1997, BOREL & MOSAR 2000). The subsiding Subbriançonnais realm led to a thick post-Triassic succession of limestones and marls in the Préalpes Médianes Plastiques while the Briançonnais structural high led to a sedimentary record marked by an important hiatus in the Early Jurassic and Cretaceous sequences of the Préalpes Médianes Rigides.

A more or less complete series, similar to that of the Préalpes Médianes Nappe, is found in klippen (e.g., Stanserhorn) overlying the Habkern Mélange Zone or the Iberg Mélange (§ 4.2.10), east of the Thunersee. The klippen just east of Schwyz, some of them being very small, have been grouped together in a subunit called the *Mythen-Roggenegg Slice.*

6.1.2.3. Breccia Nappe

In the nappe stack of the Prealps, the Breccia Nappe (LUGEON 1896) overlies the Préalpes Médianes Nappe and is itself overlain by the Upper Penninic units. In some places, structurally lower units are absent and the Breccia Nappe also comes into contact with other units (Zone Submédiane, Helvetic units).

A large part of the Breccia Nappe is located in the Chablais Prealps, overlying the Pillon Mélange Zone or the Helvetic nappes in the trailing part and the Préalpes Médianes Plastiques in the frontal part. It is deformed into a large syncline with a frontal anticlinal fold.

In the Romandes Prealps, however, the Breccia Nappe is less extensive and overlies the Préalpes Médianes Rigides. The close connection with the latter “brittle” unit influences the structure of the Breccia Nappe, which is itself fragmented by several faults. JACCARD (1904) observed three folds in these fragments while DOUSSE (1965) and LONFAT (1965) interpreted these as slices. The frontal slice takes the form of an overturned anticline, the others of synclines or monoclines.

The stratigraphic sequence spans the Triassic to the Paleocene and is characterized by two thick formations of Jurassic breccias giving the nappe its name. The origin of these formations is located between the thinned internal margin of the Briançonnais Terrane and the Piemonte-Liguria Ocean. The breccias contain elements eroded from this micro-continent and reflect the break-up of the continental crust. The fine-grained Cretaceous lithologies indicate a tectonic calming, while the overlying flysch and mélange indicate compressive tectonics. In the Chablais Prealps, the stratigraphic sequence of the Breccia Nappe shows more or less a continuous sedimentation, similar to that of the Préalpes Médianes Plastiques. In contrast, in the Romandes Prealps, significant sedimentation gaps are observed comparable to the Préalpes Médianes Rigides (DALL'AGNOLO 1997, 2000).

6.1.3. Upper Penninic

6.1.3.1. Sarine, Dranses, Simme and Gets nappes

The "Upper Prealps" designate a flysch complex, which structurally tops both the Préalpes Médianes Nappe and the Breccia Nappe. The origin of the flysch complex is generally accepted to be the Piemonte-Liguria Ocean (ELTER el al. 1966, CARON 1972, CARON et al. 1989 and ref. therein). Stratigraphic and structural arguments allow a subdivision of the complex into four nappes. These are from bottom to top: the Sarine Nappe, the Dranses Nappe, the Simme Nappe and the Gets Nappe.

The *Sarine Nappe* (Saane-Decke in German) was not recognized as an independent nappe for a long time, because some of the lithologies strongly resemble those of the Dranses Nappe. However, the Sarine Nappe is characterized by two distinctive lithologies (CARON 1972, BUGNON 1995): 1) very fine-grained, light-colored limestones with trace fossils (*Chondrites* isp.) and 2) polymict micaceous conglomerates, often containing various crystalline rocks. The age of these rocks is latest Cretaceous to earliest Paleocene.

The *Dranses Nappe* consists of a shaly basal complex followed by a thick succession of calcareous flysch rich in trace fossils (*Nereites* isp. [formerly *Helminthoidea* isp.]) and occasional conglomerate beds. The age of this series is Late Cretaceous.

The *Simme Nappe* has a more complicated structure especially visible in the Romandes Prealps, because this nappe is more extensive here then in the Chablais Prealps. The sequence contains pelagic Mesozoic sediments of Adriatic affinity (Middle Jurassic–Early Cretaceous, CLÉMENT 1986) overlain by a Turonian–Santonian flysch. This succession is disrupted by internal thrusts that repeat part of the sequence and create an internal mélange. This internal structure of the Simme Nappe implies a north to south thrust of the northern part over the southern part during Late Cretaceous times (PLANCHEREL et al. 2020).

The *Gets Nappe* is the highest nappe of the "Upper Prealps". Like the Simme Nappe, it features a very complicated structure. The stack begins with a complex which groups together three main lithologies: 1) argillites containing slivers of ophiolites, fine-grained limestones, radiolarites and conglomerates, 2) a Turonian flysch, bearing ichnofossils and a few conglomeratic layers, and 3) a layer of shales with slivers of acid and mafic crystalline rocks (CARON & WEIDMANN 1967). The thickness of this series is highly variable due to folding. It is overlain by a thick flysch sequence with massive coarse sandstones and conglomerates. The conglomerate clasts are of the same lithology as the slivers in the previous series (ELTER et al. 1966, FLÜCK 1973).

The Gets Nappe is the only one of these four nappes to contain ophiolitic rocks. Its origin would thus be in a more external position than the Simme Nappe because of the presence of rocks with Adriatic affinity in the latter. The flysch of the Dranses and Sarine nappes would have been deposited in an even more external region, more distant from the Adriatic margin than the source regions of the Gets and Simme nappes. According to the kinematic principle that the more internal rocks form nappes that overlap the more external ones, the order of superposition given above is logical, except for the Gets Nappe which overlies the Simme Nappe. TRÜMPY (1976) proposed left lateral displacement of the Piemonte-Liguria units during the Late Cretaceous in order to acquire the vertical arrangement of the Gets and Simme nappes. GASINSKI et al. (1997) suggest an asymmetrical extension leading to an extensional allochthon where parts of the future Simme Nappe formed in a more external position than the future Gets Nappe. PLANCHEREL et al. (2020 and ref. therein) explain this anomaly by a north to south thrusting of the Gets Nappe onto the future Simme Nappe during the beginning of the subduction of the Piemonte-Liguria Ocean under the Adriatic plate. This was followed by a change in thrusting direction i.e., south to north: the Gets and Simme nappes were together placed on top of the Dranses Nappe; these three were then thrust onto the Sarine Nappe.

6.2. WESTERN SWITZERLAND

Y. Gouffon

In western Switzerland, the Penninic domain occupies a large portion of the canton Valais south of the Rhône Valley and extends southward into adjacent Italy. A major thrust fault, known as the "Penninic Basal Thrust" or more generally "Penninic Front", limits this domain to the west. Along the Rhône Valley between Saxon and Visp, the northern border is represented by the Rhône-Simplon Fault Zone, except between Sion and Sierre, where the Penninic Basal Thrust is preserved in some places. To the southeast, the Penninic is bounded by the thrust of the Sesia Nappe, which is the hangingwall of the Piemonte-Liguria Ocean subduction zone. In western Switzerland, the Penninic domain is overlain by the klippen of the Salassic Dent Blanche and Mont Mary nappes.

6.2.1. Lower Penninic

In the area described here, the Lower Penninic is only represented by the Sion-Courmayeur Nappe, which extends along the entire front of the Penninic domain. As described in the introduction to Chapter 6, the Lower Penninic units were formed in the subduction zone below the Middle Penninic units.

6.2.1.1. Sion-Courmayeur Nappe

The Sion-Courmayeur Nappe is particularly well developed in Savoy (south of the map area) and around Courmayeur in the Valle d'Aosta (on the southern edge of the map area), then extends through the Valais to Airolo in the Valle Leventina (Ticino). This unit is dominated by flysch-type rocks, deposited during the Cretaceous in the Valaisan Basin, and has undergone high-pressure/low-temperature metamorphism (BOUSQUET et al. 2002). In its western part, southwest of Sion, the Sion-Courmayeur Nappe is overlain by the Zone Houillère along a thrust fault that may be the former subduction surface of the Valaisan Basin. Further east, the upper contact of the Sion-Courmayeur Nappe lies beneath the alluvium of the Rhône Valley up to Leuk, and from there to Visp, this nappe is bounded by faults related to the Rhône-Simplon Fault. East of Visp and this major fault zone, the Sion-Courmayeur Nappe lies as a synform (LEU 1986) between the Upper Helvetic Gotthard Nappe to the north and some Lepontic units to the south (from west to east successively: Pizzo del Vallone, Lebendun and Sambuco nappes), with a short break south of the Nufenenpass where the Upper Helvetic Camosci Nappe appears as an antiform at its internal margin. The emplacement of the Sion-Courmayeur Nappe seems to be independent (posterior to?) of the formation of the Lepontic nappes. Northeast of the Simplonpass, the Sion-Courmayeur Nappe forms also a narrow band in the Berisal synform, between Middle Penninic units (Berisal Nappe and Gälmji Zone) and the Lepontic Monte Leone Nappe (JEANBOURQUIN & BURRI 1989, 1991).

The Sion-Courmayeur Nappe is subdivided into several slices:

- The *Moûtiers Slice* is present only in Savoy and in the Valle d'Aosta where it forms the external part of the nappe; in the map area, it comprises Carboniferous, Triassic and Cretaceous metasediments.

- The *Ferret Slice* occupies the external part of the nappe north of the previous slice and consists mostly of Cretaceous metasediments.
- The *Roignais-Versoyen* Slice extends from the Savoy to the upper Valais; its very characteristic lithology includes the Cretaceous "Valaisan Flysch" (also called "Valaisan Trilogy"; e.g., JEANBOURQUIN & BURRI 1991) and a pre-flysch series with ophiolites ("Versoyen Complex", Südegg Complex of SARTORI et al. 2017 near Visp). The latter series is very important for the paleogeographic reconstruction of the Sion-Courmayeur Nappe, which is still a matter of debate (e.g., MASSON et al. 2008, BELTRANDO et al. 2012, DE BROUCKER et al. 2021).
- The *Pierre Avoi Slice* consists of a Paleogene mélange zone above the Roignais-Versoyen Slice. It is overlain by the Zone Houillère, which provided most of the material constituting the Pierre Avoi Slice as a result of early erosion. This sedimentary mélange was most likely formed at the foot of the Briançonnais continental margin during the subduction of the Valaisan Basin under this micro-continent.
- The *Petit Saint-Bernard Slice* is restricted to the area of the eponymous pass on the French-Italian border and just reaches the southern border of the map, east of La Thuile. It consists of a series of Triassic–Jurassic sediments with Subbriançonnais facies and is often considered as an independent tectonic unit thrust over the Sion-Courmayeur Nappe and, together with it, thrust under the Middle Penninic Zone Houillère.
- The *Rosswald Slice* is present only east of the Rhône-Simplon Fault. In the Brig area (upper Valais), the Roignais-Versoyen Slice forms the reverse limb of a large anticline, whereas the Rosswald Slice forms the normal, thrusting limb. Both are present for the first 20 km east of the Rhône-Simplon Fault; only the Rosswald Slice continues further east. This slice contains only the upper formation of the "Valaisan Flysch". It borders the Lepontic units to the north between the Visp–Brig area and the Valle Leventina. Its eastern termination is not clear. PROBST (1980) splits it in several units and connects one of them with the Grava Nappe, through the large synform east of Airolo where it would have been partly eroded.

6.2.2. Middle Penninic

The Middle Penninic subdomain of the Western Alps comprises units between the Lower Penninic subduction surface and the major thrust of the Upper Penninic. In the area described here, they were first grouped together within the "Grand St-Bernard Nappe" (ARGAND 1911), which was then subdivided into several nappes (e.g., ESCHER 1988) described below.

In the Valle d'Aosta, the Middle Penninic units are crosscut by the Col de Bard Fault (Gouffon 1993, Gouffon & Burri 1997), which separates two structurally very different sectors. In the hangingwall, north of the fault, the nappes overlie each other regularly towards the west and their structures dip E–SE. In the footwall, south of the fault, only the Zone Houillère and the Ruitor Nappe are present; their structures are backfolded and dip W–NW, while a large isoclinal synform (Avise) with a core attributed to the Tsaté Nappe splits the Ruitor Nappe. The Col de Bard Fault is related either to the Aosta-Ranzola Fault (Gouffon & Burri 1997) or to the Cogne Fault Zone (Malusà et al. 2009) (see § 10.4).

The Middle Penninic units are thought to be derived from the Briançonnais Terrane, which consisted of a polycyclic crystalline basement cut by Late Cambrian (ca. 500 Ma) and Permian (ca. 270 Ma) granitic intrusions, Permo-Carboniferous sediments that filled narrow basins and a characteristic Mesozoic–Paleogene sedimentary cover. Much of this Briançonnais cover was detached at the level of the Triassic evaporites to form some of the nappes in the Prealps (§ 6.1). This detachment probably occurred during an early phase of the Alpine orogeny, following the closure of the Piemonte-Liguria Ocean, when the Briançonnais Terrane was subducted below the Adriatic margin. The Middle Penninic subdomain in turn formed the hangingwall during the closure and subduction of the oceanic Valaisan Basin.

6.2.2.1. Zone Houillère, Gälmji Zone

The *Zone Houillère* is the lowest unit of the Middle Penninic subdomain. It is subdivided into an external and an internal part by a thrust fault. The external part is dissected into numerous slices, whereas the internal part seems to be more continuous. The Zone Houillère is the only unit in this subdomain that comprises mainly Late Carboniferous to Permian metasediments, locally rich in coal, as its name implies. The series is completed by Early and Middle Triassic sediments. The rest of the series, from the Middle Triassic upward, was detached to form the Préalpes Médianes Plastiques (§ 6.1.2.2). The Zone Houillère is continuous from the Valle d'Aosta to the area east of Sierre, where it is broken up by longitudinal faults related to the Rhône-Simplon Fault.

Between Visp and the Simplonpass, two graphitic schist and paragneiss slices are attributed to the Zone Houillère by analogy with the rocks of this unit further west. The *Visperterminen Slice* occupies the core of a fold within the Sion-Courmayeur Nappe. The *Lower Stalden Slice* is overlain by the Upper Stalden Nappe and separated from the Sion-Courmayeur Nappe by the southern branch of the Rhône-Simplon Fault.

The *Gälmji Zone* is a thin band of green gneisses and micaschists comparable to those of the Visperterminen and Lower Stalden slices. Thick amphibolite layers are interbedded in these metasediments, and scarce remains of Triassic sediments represent the rest of the sedimentary cover. The Gälmji Zone lies between a thin band of the Sion-Courmayeur Nappe and the Berisal Nappe in the large synformal Berisal Backfold, to the northeast of the Simplonpass. Previous authors had interpreted it as belonging to one or other of these two units. Because of its structural position equivalent to that of the Zone Houillère, this unit is interpreted by JEANBOURQUIN & BURRI (1989) to be a metamorphic equivalent of the latter, east of the Rhône-Simplon Fault.

6.2.2.2. Ruitor, Upper Stalden, Berisal and Ruginenta nappes

The *Ruitor Nappe* extends from the Valle d'Aosta (southern edge of the map) into the Val de Bagnes, where it pinches out between the Zone Houillère and the Siviez-Mischabel Nappe. In the Valle d'Aosta, the Ruitor nappe becomes thinner to the north of the Col de Bard Fault (see p. 63), while it is much wider immediately to the south of this fault, where it is split in two parts by an isoclinal synform (Avise) with a core attributed to the Tsaté Nappe. The Ruitor Nappe is characterized by a polycyclic basement with numerous pre-Alpine relics. Permian clastic rocks cover this basement and are in contact with the Permian cover of the Siviez-Mischabel Nappe; therefore, the tectonic contact that separates these two nappes is rarely recognizable in the field. The polycyclic basement of the Ruitor Nappe overlies the Permian metasediments of the Zone Houillère.

In the upper Valais region, between Visp and the Simplonpass, the *Upper Stalden Nappe* is similar in structural position to the Ruitor Nappe – between the Zone Houillère and the Siviez-Mischabel Nappe – and is composed of a crystalline basement identical to that of this nappe, but without sedimentary cover. However, GENIER et al. (2008) interpreted the Permian contact of the lower limb of the St. Niklaus syncline (§6.2.2.3) as autochthonous and thus linked the Upper Stalden Nappe to the lower part of the Siviez-Mischabel Nappe through that fold.

ESCHER (1988) grouped the Ruitor and Upper Stalden nappes with a "Pontis Slice" (south of Sierre, comprising mainly Triassic limestones) under the name of "Pontis Nappe". It turns out that this "Pontis Slice" belongs to the Zone Houillère, so the term "Pontis Nappe" has to be abandoned (SARTORI et al. 2006).

The *Berisal Nappe* is lithologically similar to the Upper Stalden Nappe: for this reason it is interpreted as the continuation of this unit to the east, in the footwall of the Rhône-Simplon Fault. It occupies the core of the large synformal Berisal Backfold.

South of the Simplonpass, the *Ruginenta Nappe* consists of a polycyclic basement, comparable to that of the previous two units, intruded by a granite and overlain by a Carboniferous–Triassic sedimentary cover. The Ruginenta Nappe overlies the Moncucco Nappe and is overlain by the Camughera Nappe in the huge Vanzone Antiform (STECK et al. 2015). If the Camughera Nappe is a continuation of the Siviez-Mischabel Nappe (see below), the Ruginenta Nappe may be a continuation of the Upper Stalden Nappe.

6.2.2.3. Siviez-Mischabel and Camughera nappes

The *Siviez-Mischabel Nappe* is made up of a crystalline basement and a typical Briançonnais sedimentary cover. The crystalline basement comprises rocks of sedimentary and magmatic origin of Proterozoic to Ordovician age. The lower, older part of this basement displays traces of polycyclic metamorphism, while the upper, junger part contains only mineral assemblages characteristic of the Alpine metamorphism. A Permian metagranite (Randa Orthogneiss) intruded the crystalline basement and the Permian cover. The sedimentary cover includes Permian to Triassic formations, completed by Jurassic to Eocene formations only in the normal limb of the nappe between Zermatt and the Val d'Anniviers (SARTORI et al. 2006), especially well developed in the Barrhorn region. Further west, the sedimentary cover is detached at the level of the Middle Triassic evaporites and form the Préalpes Médianes Rigides (SARTORI 1990; see §6.1.2.2).

The Siviez-Mischabel Nappe occupies a large region of the Valais Alps south of the Rhône. In its central part, it overlies the Zone Houillère, but in many places the contact between these two units is marked by the extended and steep longitudinal faults related to the Rhône-Simplon Fault. From the Val de Bagnes southward, the Siviez-Mischabel Nappe overlies the Ruitor Nappe and decreases in thickness; it terminates in the Valle d'Aosta on the Col de Bard Fault (see §6.2.2.2 and 10.4).

Between Visp and the Simplonpass, Permian–Triassic rocks form the St. Niklaus syncline which separates the overlying Siviez-Mischabel Nappe from the underlying Upper Stalden Nappe. The upper and lower contacts of the syncline are strongly sheared. SARTORI et al. (2017) postulate that these rocks belong to the Siviez-Mischabel Nappe and that they thrust over the Upper Stalden Nappe, while GENIER et al. (2008) consider that this syncline connects the two nappes.

In its western part, the Siviez-Mischabel Nappe is overlain by the Mont Fort Nappe. Their contact is tectonic, although a zone of Permian–Triassic rocks can be observed between these two units and interpreted as a tectonized syncline in the Verbier region. From the Val d'Hérens to the Zermatt Valley, the nappe is overlain by the Tsaté Nappe. In the latter valley and further east, the Siviez-Mischabel Nappe forms the large Mischabel Backfold, in whose steep overturned flank the nappe is in contact with, from west to east, the Zermatt-Saas Fee Nappe, the Portjengrat Nappe and the Antrona Nappe (see Pl. II, western cross-section). The contact with the latter terminates against the Simplon Fault, part of the Rhône-Simplon Fault. The Antrona Nappe seems to form here a synform truncated by this fault.

On the southeastern limb of this synform, the Antrona Nappe is in contact with the *Camughera Nappe*. The latter consists of rocks similar to the crystalline basement of the Siviez-Mischabel Nappe and may be the continuation of this nappe. It is folded by the large Vanzone Antiform and overlies the Ruginenta Nappe, a probable extension of the Upper Stalden Nappe (§ 6.2.2.2) located below the Siviez-Mischabel Nappe.

6.2.2.4. Portjengrat and Stockhorn nappes

The *Portjengrat Nappe*, exposed east of Saas Fee, occupies a special position as a buffer zone between the Siviez-Mischabel and Monte Rosa nappes on the one side and between the Zermatt-Saas Fee and Antrona nappes on the other side. It consists mainly of a crystalline basement resembling that of the Siviez-Mischabel and Monte Rosa nappes, overlain by a very thin Mesozoic sedimentary cover. Both basement and cover are crosscut by mafic veins, such as in the adjacent "Furgg Zone" (§ 6.2.2.6). The Portjengrat Nappe was related either to the Monte Rosa Nappe (e.g., ARGAND 1911), which underwent the same Alpine high-pressure metamorphism, or to the Siviez-Mischabel Nappe (e.g., BEARTH 1939), with which it is in apparent tectonic continuity but which exhibits Alpine metamorphism only under greenschist-facies conditions. STECK et al. (2015) categorize it as an independent tectonic unit. The Portjengrat Nappe is separated from the Monte Rosa Nappe by the "Furgg Zone", considered here as the sedimentary cover of the Monte Rosa Nappe (§ 6.2.2.6). The contact with the Siviez-Mischabel Nappe is difficult to map in the field, because no metasediments are observed between the gneisses of each of these two units; STECK et al. (2015) trace it along a shear zone.

The *Stockhorn Nappe* is a small unit located on top of the Monte Rosa Nappe and separated from the Zermatt-Saas Fee Nappe by the thin Gornergrat Nappe (§ 6.2.3.3). It is lithologically similar to the Portjengrat Nappe and can thus be correlated with it.

6.2.2.5. Mont Fort Nappe

The Mont Fort Nappe extends from the Valle d'Aosta in the SSW, south of the Col du Grand St-Bernard, to the Val d'Anniviers in the NNE. Its basement ends as an anticline in the Val d'Hérémence, just downstream of the Grande Dixence Dam, but its Permian–Mesozoic sedimentary cover continues towards the east and forms pinched recumbent frontal folds with the lower part of the Tsaté Nappe up to the Lac de Moiry. Southward, the Mont Fort Nappe is interrupted by the Col de Bard Fault (see p. 63 and § 10.4), but equivalent units are found further south in the Valle d'Aosta and in the Vanoise mountain range (GOUFFON 1993). This nappe overthrusts the Siviez-Mischabel Nappe, while a tectonized synclinal zone could link these two nappes in the Verbier area (§ 6.2.2.3). Through the Val d'Hérémence and the Val d'Hérens, the contact between these two nappes is intersected by the basal thrust of the Tsaté Nappe which forms here a narrow recumbent syncline (Montset Syncline, SARTORI & EPARD 2011) stretching for more than 20 km.

The crystalline basement of the Mont Fort Nappe is similar to the upper, monocyclic part of that of the Siviez-Mischabel Nappe (Cambrian–Ordovician; SARTORI et al. 2006). The sedimentary cover comprises Permian to Cretaceous rocks which are variously distributed (ESCHER 1998, PANTET et al. 2023). It is missing from most of the reverse limb, while a thick Permian–Triassic series surrounds the frontal part of the basement. On the normal limb of the nappe, a Permian–Jurassic series occurs intermittently, the top of which is characterized by a large accumulation of breccias; a deep marine Cretaceous series continuously covers the older sediments as well as the bedrock. Correlation with the stratigraphy of the Breccia Nappe in the Prealps (§ 6.1.2.3) allows the origin of the Mont Fort Nappe to be placed within the pre-Piemonte paleogeographic realm.

The discontinuity of the Permian–Jurassic cover against the basement is interpreted as the result of synsedimentary faulting creating tilted blocks during the phase of rifting. This also explains why the basement and the Permian–Jurassic cover are discontinuous below the Cretaceous sediments, which are considered to be the unconformity-bounded post-rift cover (PANTET et al. 2020, 2023). In another way, these discontinuities have been interpreted as overthrusts of the Permian–Jurassic series ("Sasseneire Nappe") onto the Mont Fort Nappe (crystalline basement and Permian–Triassic sediments), and the Cretaceous series considered as the base of the Tsaté Nappe overthrusting the "Sasseneire Nappe" (MARTHALER et al. 2020 and ref. therein). The same sedimentary series is found further east in the form of narrow and elongated bands or folds intercalated in the Tsaté Nappe. These bands are considered to be a continuation of the Mont Fort Nappe (ARGAND 1909, ESCHER 1988, PANTET 2022) or individually as Frilihorn Nappe and Cimes Blanches Nappe (ESCHER et al. 1993; see § 6.2.3.3).

6.2.2.6. Monte Rosa Nappe

The Monte Rosa Nappe comprises mainly crystalline basement made up of polycyclic paragneisses and orthogneisses that represent granitic intrusions of Carboniferous and Permian age. This basement is subdivided in two parts by the thick Stellihorn Shear Zone. A sedimentary series, known as the "Furgg Zone", surrounds the crystalline basement in a discontinuous manner. It separates in particular the Monte Rosa gneisses from those of the Portjengrat Nappe and consists of Permian to Jurassic metasediments, which are crosscut by mafic sills and dykes. However, the "Furgg Zone" is considered as an allochthonous cover of the Monte Rosa Nappe (STECK et al. 2015) because these intrusion veins do not intersect the underlying gneisses and the contact between the "Furgg Zone" and the Monte Rosa gneisses is typically of tectonic nature. The allocation of the "Furgg

Zone" remains a matter of controversy, with some authors considering it as a cover of the Portjengrat Nappe (BEARTH 1957, KELLER & SCHMID 2001) or even as a mélange zone (FROITZHEIM 2001).

All the rocks of the Monte Rosa Nappe have undergone a metamorphism with higher pressure (eclogite facies) than those of the Siviez-Mischabel and Mont Fort nappes (high-greenschist to blueschist facies), indicating a deeper burial in a subduction zone. Two hypotheses may explain this feature: 1) The Monte Rosa Nappe has a more internal paleogeographic origin than the Siviez-Mischabel and Mont Fort nappes, all three were caught in the same underthrusting surface as the Piemonte-Liguria Ocean, whereby the Monte Rosa Nappe went deeper (STECK et al. 2015); 2) the Monte Rosa Nappe has a more external origin than the other two and was caught in the same subduction zone as that of the oceanic Valaisan Basin – from which the origin of the Antrona Nappe is hypothesized in that case – thus below the Siviez-Mischabel and Mont Fort nappes (PLEUGER et al. 2005).

6.2.3. Upper Penninic

The Upper Penninic subdomain of western Switzerland contains mainly magmatic and sedimentary rock units of oceanic origin. Some thin continental margin sedimentary series and small continental crust slices are intercalated within these units. All of these units were driven into a subduction zone under the Salassic nappes, some exposed to high-pressure metamorphic conditions, others remaining under lower pressure conditions.

6.2.3.1. Zermatt-Saas Fee and Antrona nappes

The *Zermatt-Saas Fee Nappe* consists of rocks derived from the Piemonte-Liguria Ocean. They are mostly large bodies of serpentinites, metagabbros (Middle–Late Jurassic, RUBATTO et al. 1998) and metabasalts in which pillow structures are locally well preserved. Oceanic sediments overlie these ophiolites, in particular metacherts (metaradiolarites). All of these rocks display relics of Early Eocene high-pressure metamorphism in eclogite facies (BARNICOAT & FRY 1986, RUBATTO et al. 1998).

The *Antrona Nappe* corresponds to the same oceanic rocks with eclogitic relics as that of the Zermatt-Saas Fee Nappe, except for the metacherts that are missing in the Antrona Nappe. Structurally, it is situated below the Monte Rosa Nappe, but above the Siviez-Mischabel Nappe and its probable extension in the Camughera Nappe (see Pl. II, western cross-section). This peculiar position between two Middle Penninic units raises questions concerning its kinematic history and paleogeographic origin. Because of its similarity to the Zermatt-Saas Fee

Nappe, and assuming transport over the Middle Penninic nappes, the Antrona Nappe is thought to have an origin in the Piemonte-Liguria Ocean (e.g., ESCHER et al. 1997). However, a thrusting of the Middle Penninic nappes over the Antrona Nappe is also postulated, implying its attribution to the Lower Penninic and origin in the Valaisan oceanic Basin (e.g., KELLER & SCHMID 2001, PLEUGER et al. 2005).

6.2.3.2. Mont Emilius Nappe, Theodulgletscher Slice, Etirol-Levaz Slice, Châtillon-St-Vincent Slices

The Mont Emilius Nappe, the Etirol-Levaz Slice, the Châtillon-St-Vincent Slices (DAL PIAZ 1999 and ref. therein) and the Theodulgletscher Slice (BUCHER et al. 2020), located between the Zermatt-Saas Fee Nappe and the Tsaté Nappe, comprise eclogitic continental basement rocks. Due to the similarity of their pre-Alpine lithology with that of the Dent Blanche and Sesia nappes, their origin is probably the Adriatic continental margin. However, these units occupy a lower structural level than the Dent Blanche and Sesia nappes that belong tectonically to the Salassic domain. They exhibit a tectono-metamorphic history similar to that of the Zermatt-Saas Fee Nappe, including the Early Eocene age for their high-pressure metamorphism (DAL PIAZ et al. 2001, WEBER et al. 2015). These units likely derived from extensional allochthons, formed during the Jurassic opening of the Piemonte-Liguria Ocean in a more distal position than the Cervinia Terrane from which the Salassic nappes originate (see chap. 7).

6.2.3.3. Frilihorn, Gornergrat and Cimes Blanches nappes

In the Val d'Anniviers, Zermatt Valley and Valtournanche, a few thin tectonic units are located at the contact between the Middle and Upper Penninic *(Gornergrat Nappe)* or are intercalated within the Tsaté Nappe *(Frilihorn and Cimes Blanches*[1] *nappes).* They are all composed of a series of Briançonnais-type Permian–Triassic sediments overlain by Jurassic breccias and limestone and calcschists probably of Cretaceous age. As their lithology is quite similar to that of the Mont Fort Nappe, their paleogeographic origin can also be located in the pre-Piemonte realm (transition zone between Briançonnais Terrane and Piemonte-Liguria Ocean); however, an Adriatic origin has also been proposed ("Austro-alpine", DAL PIAZ 1999 and ref. therein). An eastward extension of the Mont Fort Nappe was often considered for these three narrow nappes (e.g., ARGAND 1909, ESCHER 1988, PANTET 2022).

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[1] Also known as Pancherot-Cime Bianche Unit (DAL PIAZ 1988, DAL PIAZ et al. 2015) or Theodul Décollement Nappe (BUCHER et al. 2004).

6.2.3.4. Tsaté Nappe

The Tsaté Nappe crops out in southern Valais and in the Valle d'Aosta. It comprises oceanic metasediments, mainly calcschists and black shales of Cretaceous age, and ophiolitic rocks of Jurassic age. They originate from the Piemonte-Liguria Ocean. This nappe is characterized by a chaotic aspect and metamorphism under conditions of blueschist facies followed by greenschist facies. It is interpreted as the result of the formation of an accretionary wedge at the foot of the active Adriatic margin and the subsequent subduction below this continental plate (MARTHALER & STAMPFLI 1989, STAMPFLI et al. 1998, 2002). Depending on the location, the Tsaté Nappe overlies the Mont Fort, Siviez-Mischabel or Zermatt-Saas Fee nappes, in some cases with small units (Theodulgletscher and Etirol-Levaz slices, Mont Emilius Nappe and Châtillon-St-Vincent Slices) between the two nappes. It is overlain by the Dent Blanche Nappe west of Valtournanche (lateral valley of the Valle d'Aosta) and by the Sesia Nappe further east.

Some authors (e.g., BUCHER et al. 2004, DAL PIAZ 1988, 1999, DAL PIAZ et al. 2015, PLEUGER et al. 2007) group the Tsaté Nappe with the Frilihorn, Gornergrat and Cimes Blanches nappes under the term "Combin Zone", which was defined by ARGAND (1909) in an even broader sense.

6.3. CENTRAL AND EASTERN SWITZERLAND

S.M. Schmid

The Penninic domain in central and eastern Switzerland extends in several areas. One is located in an external position and comprises Lower Penninic flysch nappes and some klippen of Middle Penninic units overlain by rare remnants of Upper Penninic and Austroalpine units (from west to east: Giswilerstock, Stanserhorn, Buochserhorn, Mythen and Iberg klippen). However, most of the Penninic units of this region are located in a more internal position. They are confined to Graubünden and continue slightly south into the Italian valleys of San Giacomo and Malenco. External and internal units are also present east of the Rhine in the Vorarlberg (Austria) and converge eastward in the Allgäu (Germany) at the eastern end of the Helvetic domain.

Some Penninic units form the Lower Engadine Window, a large antiformal structure surrounded by Austroalpine nappes and bordered to the south by the Engadine Fault. This tectonic window owes its origin to late-stage extensional updoming and takes the form of a large lens of 54 x 18 km located half in Graubünden and half in the Austrian Tyrol. The units of the Lower Engadine Window were often defined with different names in its western (Swiss) part and in its eastern (Austrian) part. The Swiss nomenclature is mainly used here and correspondences with the Austrian names are also given.

As in western Switzerland, the northern boundary of the Penninic domain is formed here as well by a major overthrust of Penninic units over the Helvetic units. To the west, the Penninic units are in contact with the Lepontic units at the eastern border of the structural Lepontine Dome (see chap. 5). To the east and south, the Penninic nappes are overlain by nappes of the Austroalpine domain and, to a lesser degree, of the Salassic domain.

6.3.1. Lower Penninic

The Lower Penninic subdomain of central and eastern Switzerland is represented by flysch nappes of controversial origin in the external part of the Alps and essentially by metasedimentary, mostly shaly-calcareous units (so called "Bündnerschiefer") further south, deposited in the oceanic Valaisan Basin. Ophiolitic remnants are found at the base of some of the "Bündnerschiefer-type" nappes. The Chiavenna Nappe is a large ophiolitic slice found below the Middle Penninic Tambo Nappe and against the Gruf Complex, and thus considered as a remnant of the Valaisan oceanic crust. Lower Penninic sediment units form the Prättigau Half-Window and the core of the Lower Engadine Window.

6.3.1.1. Schlieren, Wägital, Üntschen, Sigiswang and Oberstdorf nappes, Triesenberg Slice Complex

Between Thunersee and Vierwaldstättersee, the Upper Helvetic Drusberg Nappe contains a large synform occupied by the tectonically higher Habkern Mélange Zone overlain by the *Schlieren Nappe*. This nappe only consists of Cretaceous–Paleogene flysch very similar to the Voirons and Gurnigel flysches in the Prealps (§6.1.1.1). Further east, up to the Walensee, a similar flysch forms the *Wägital Nappe*, which is located at the front of the Drusberg Nappe and surrounded by the Iberg Mélange and the Internal Einsiedeln Slices of the Upper Helvetic. As the Schlieren and Wägital nappes are overlain by Middle Penninic klippen, they are considered to be Lower Penninic. The paleogeographical allocation of all these nappes is a matter of debate. While WINKLER (1983) envisaged the origin of the Schlieren Flysch in the Piemonte-Liguria Ocean, these units were considered by others (TRÜMPY 2006, PFIFFNER 2014, RAGUSA et al. 2017) to be of Valaisan origin.

Along strike further east, a similar flysch nappe forms klippen overlying the Wildhaus Mélange in a few synforms within the Upper Helvetic Säntis Nappe. These klippen are laterally correlated with the *Üntschen* and *Sigiswang nappes* east of the Rhine, located south and north of the Säntis Nappe respectively. The Üntschen and Sigiswang nappes are made up of the Late Cretaceous Vorarlberg Flysch and are the westernmost occurrences of a flysch belt referred to as the Rhenodanubian Flysch Zone (MATTERN 1999). The age of the Rhenodanubian Flysch is constrained to the period between the Early Cretaceous and the Paleocene (HESSE 2011 and ref. therein). Further east, the Üntschen and Sigiswang nappes are overlain by the *Oberstdorf Nappe* made of the same flysch as the other two nappes. The Rhenodanubian Flysch Zone extends all the way to Vienna and is considered to originate from the Valaisan paleogeographical realm (SCHMID et al. 2004).

In Liechtenstein, the small *Triesenberg Slice Complex* (formerly "Liechtenstein Flysch") probably represents the transition zone between the Üntschen Nappe to the northeast and the more southerly Prättigau Flysch, which belongs to the Tomül Nappe (see next §) and is exposed in the Prättigau Half-Window. This slice complex is located at the base of the Austroalpine units, the Arosa Nappe or the Falknis Nappe. It comprises two slices (ALLEMANN 2002), the northern one composed of the Vaduz Flysch (Late Cretaceous), more or less equivalent to that of the Oberstdorf Nappe, and the southern one of the Triesen Flysch (Late Cretaceous to Paleogene), which has an affinity with the Prättigau Flysch.

6.3.1.2. Vals Slices, Aul, Grava and Tomül nappes

Mesozoic shaly-calcareous-sandy marine sedimentary units, called "Bündnerschiefer", surround the Adula Nappe (STEINMANN 1994) and other Lepontic units located at the front of this nappe (Piz Terri-Lunschania and Soja nappes). The Grava and Tomül nappes display traces of an early Alpine blueschist-facies metamorphism (WIEDERKEHR et al. 2008). The roots of all these units are located in the "Misox Zone", which separates the Adula and Tambo nappes, and are interrupted southeast of Mesocco by the Forcola Normal Fault in its hangingwall. MEYRE et al. (1998) see in contrast the Forcola Fault overlying the "Bündnerschiefer" units and these to be in the footwall of this fault that displaces them with respect to the ophiolitic Chiavenna Nappe in its hangingwall.

The *Vals Slices* (former "Upper Vals Slices"; see § 5.10) overlies the Adula Nappe in its northeastern frontal part. It is mainly composed of "Bündnerschiefer" with some ophiolitic rocks of Late Jurassic age (LIATI et al. 2005), similar to those found in the overlying Aul, Grava and Tomül nappes.

The *Aul Nappe* structurally overlies the Vals Slices and consists of an ophiolitic mélange complex at its base, including serpentinite and pillow basalts, overlain by a marble of age not younger than Jurassic (STEINMANN 1994).

The *Grava Nappe* overlies the Aul Nappe with a basal mélange zone, which contains Early Jurassic Gryphaea-bearing limestones (NABHOLZ 1945), metabasalts and dark shales. The rest of the nappe consists of Cretaceous "Bündnerschiefer" (STEINMANN 1994). This nappe is folded around the front of the Adula Nappe and the Lunschania Antiform. In an overturned tectonic position, it can be followed all the way into a synform located between the Simano and Leventina-Lucomagno nappes (WIEDERKEHR et al. 2008). Westward it is found as a klippe in the core of the Molare Syncline (see §5.7). Further west, an outcrop of "Bündnerschiefer" pinched in the Piora-Peiden Slice Complex (located between Lago Ritom and Airolo) is attributed to the Grava Nappe based on lithological and structural analogy. This latter occurence closes the nappe to the southwest above Airolo. However, the Quaternary cover hides this possible closure and it could instead connect with the Sion-Courmayeur Nappe that passes just south of this locality and contains similar rocks (PROBST 1980).

The *Tomül Nappe*, the highest of the "Bündnerschiefer" nappes rooting in the "Misox Zone", locally has an ophiolite-bearing mélange at its base, overlain by an over 2 km-thick series of probably Cretaceous–Paleogene age (STEINMANN 1994). In contrast with the Grava Nappe, the Tomül Nappe is not wrapped downwards around the front of the Adula Nappe. It can be followed eastward, below the Middle Penninic Schams Nappe Complex, and is then backfolded, together with the latter, around the front of the Suretta Nappe in order to come to lie in an overturned position on top of the Schams Nappe Complex in the upper limb of the Niemet-Beverin Backfold (SCHREURS 1995, SCHMID et al. 1997). This backfolded part of the Tomül Nappe is also referred to as "Arblatsch Flysch" (ZIEGLER 1956). East of Lenzerheide, the Tomül Nappe can be followed even further to the east and into the Prättigau Half-Window that exposes a very thick and multiply folded Cretaceous–Paleogene "Bündnerschiefer" and flysch sequence underlying the Middle Penninic Falknis and Sulzfluh nappes (NÄNNY 1948, WEH & FROITZHEIM 2001).

6.3.1.3. Chiavenna Nappe

The Chiavenna Nappe is a voluminous ophiolitic complex consisting of metaperidotites, amphibolites, metagabbros and rare carbonate rocks. To the south it lies tectonically "above" the Gruf Complex along a subvertical contact, to the north it is overlain by the Tambo Nappe (SCHMUTZ 1976). The position of the Chiavenna Nappe below the Tambo Nappe, as is the case for the Tomül and Grava nappes, leads to the interpretation of this ophiolitic complex as originating from the ocean floor of the Valaisan Basin (SCHMUTZ 1976, SCHMID et al. 1996a). This is supported by the Cretaceous age of the magmatic protoliths (LIATI et al. 2003).

6.3.1.4. Pfunds Nappe

The Pfunds Nappe constitutes the lowest and the largest part of the Lower Engadine Window. It consists of kilometer-thick Mesozoic shaly-calcareous-sandy marine sedimentary rocks of Cretaceous age ("Bündnerschiefer"), which contain some metabasalt bodies. The large body of metabasalts at Piz Mundin crops out in the center of the window and forms the stratigraphic basis of the "Bündnerschiefer" that were deposited in the Valaisan Basin (BOUSQUET et al. 1998). Similar "Bündnerschiefer" rocks constitute part of the Tomül Nappe in the nearby Prättigau Half-Window.

6.3.1.5. Roz-Champatsch Mélange and Ramosch Zone

The *Roz-Champatsch Mélange* defined by KLÄY (1957) directly overlies the Pfunds Nappe in the Lower Engadine Window and is dominated by flysch-type sedimentary rocks. Although having formerly been considered an equivalent of the "North Penninic flysch" of the Prättigau (Tomül Nappe), it differs from this nappe in that it includes slivers of various rocks, such as crystalline basement, Triassic sediments and occasional serpentinite (FLORINETH & FROITZHEIM 1994). Hence this unit must be considered as a mélange zone. Its equivalent in Austria is called the Pezid Zone (GRUBER et al. 2010). The sediments of the isolated Stammerspitz Slice (§8.1.5) have a Lower Austroalpine affinity (KLÄY 1957) but its present-day structural position much lower than the rest of the Austroalpine units is enigmatic. Because it directly overlies the Roz-Champatsch Mélange, this slice could possibly be interpreted as a mega-block in this mélange, or even in the Fimber Zone (§6.3.2.4).

The *Ramosch Zone* is largely dominated by mafic and ultramafic rocks, including metabasalts; but near Ramosch it also has the character of a mélange. It forms a discontinuous band, and its occurrence is restricted to the western and southwestern rim of the Lower Engadine Window. This highest Lower Penninic ophiolite-bearing unit directly underlies the Middle Penninic Tasna Nappe. In the Piz Tasna area, the Ramosch Zone lies below the serpentinites that form the base of the Tasna Nappe along an Alpine thrust fault. The Ramosch Zone is interpreted as the most oceanward part of the ocean-continent transition visible in the Tasna Nappe (FLORINETH & FROITZHEIM 1994), and could be considered as the lower subunit of the Tasna Nappe (RIBES et al. 2019).

6.3.2. Middle Penninic

In eastern Switzerland, the Middle Penninic is represented by the Tambo and Suretta basement-cover nappes and, additionally, by detached sedimentary nappes. Structurally, the Suretta Nappe occupies the core of the very large-scale north facing Niemet-Beverin Backfold that postdates nappe stacking and can be followed all the way into the Prättigau Half-Window (e.g., SCHMID et al. 1990, SCHREURS 1995, WEH & FROITZHEIM 2001). The sedimentary Schams Nappe Complex and the upper part of the Lower Penninic Tomül Nappe are wrapped around the Suretta Nappe in this mega-fold and backthrust to the southeast in an overturned position over the top of the Suretta Nappe and of the Upper Penninic Avers Nappe (see Pl. II, eastern cross-section).

In the Prättigau Half-Window, the nappe stack is upright again in that the two Middle Penninic Falknis and Sulzfluh nappes overlie the Lower Penninic Tomül Nappe and are overlain by the Upper Penninic Arosa Zone and the Austroalpine domain. The Falknis and Sulzfluh nappes and the Arosa Zone are discontinuous and often very thin. The sedimentary facies of the Falknis Nappe have close similarities with the Tasna Nappe exposed in the Lower Engadine Window (GRUNER 1981). The Mesozoic strata in all these Middle Penninic units can definitely be attributed to the Briançonnais paleogeographic realm.

6.3.2.1. Tambo and Suretta nappes

The crystalline basement of the *Tambo Nappe* is made up of polymetamorphic paragneisses intruded by the Permian Truzzo Granite that escaped Paleozoic deformation and metamorphism. This basement is unconformably overlain by a Permian–Mesozoic cover roughly comparable to the Briançonnais facies of the Barrhorn (Siviez-Mischabel Nappe) and Vanoise series (BAUDIN et al. 1993).

The *Suretta Nappe* also has a Paleozoic basement of para- and orthogneisses intruded by the Permian Rofna Porphyry Complex, which consists of granitoids and effusive-type magmatites (MARQUER et al. 1998). Its Permian–Mesozoic cover, again in Briançonnais facies, is largely of Triassic age. Locally the Triassic is overlain by Jurassic breccias. This cover crops out as thin layers; in one instance it follows a Suretta-internal thrust fault, in other instances they are infolded into narrow synclines that were subsequently backfolded in the upper limb of the north facing Niemet-Beverin Backfold, whose axial trace runs across the Suretta Nappe (SCHEIBER et al. 2012).

Two small windows (Lanzada Windows), dominated by sedimentary rocks typical for the Suretta Nappe, are located in the Val Malenco and surrounded by the Malenco-Forno-Lizun Nappe (MONTRASIO 1984, MONTRASIO et al. 2005). These windows also expose some small occurrences of metagabbro and ultramafics that are correlated with the Avers Nappe.

6.3.2.2. Schams Nappe Complex

The Schams Nappe Complex comprises a set of small nappes, composed of sedimentary sequences exhibiting large facies variations and rich in sedimentary syn-rift breccias of Middle Jurassic to Early Cretaceous age, indicating contemporaneous extension and sinistral strike-slip (RÜCK 1995). The mid-Cretaceous to Cenozoic post-rift sediments are very similar to those found in the Falknis Nappe.

After its emplacement, this nappe complex was folded around the Tambo-Suretta pair during the Niemet-Beverin post-nappe folding (SCHREURS 1995). The fact that the Schams nappes are folded around a locally near-isoclinal fold has long raised the question about the origin of this nappe complex either below the Tambo Nappe or on top of the Suretta Nappe (SCHMID et al. 1990). Structural criteria clearly show that the Schams Nappe Complex has to be rooted below the Tambo Nappe (SCHREURS et al. 1995). Retrodeformation suggests that the Schams nappes formerly occupied an area north of the depositional area of the Tambo and Suretta Mesozoic (SCHMID et al. 1997). This is supported by facies arguments indicating that sediments in the originally northernmost paleogeographical position (now forming the Gelbhorn Nappe) suggest N-directed shedding of syn-rift breccias, and by the Subbriançonnais-type facies of the Triassic strata (RÜCK 1995). The Schams Nappe Complex also contains different mélanges: to the west, in the lower limb of the Niemet-Beverin Backfold, the Knorren Mélange is in contact with the Tambo Nappe, while the Areua-Bruschghorn Mélange marks the boundary with the Tomül Nappe; to the east, in the upper (overturned) limb of the Niemet-Beverin Backfold, the Martegnas Mélange is in contact with the Arblatsch Flysch belonging to the Tomül Nappe (MAYERAT DEMARNE 1994, SCHREURS 1995).

6.3.2.3. Falknis and Sulzfluh nappes

The Falknis and Sulzfluh nappes discontinuously overlie thick Lower Penninic “Bündnerschiefer” and flysch of the Tomül Nappe in the Prättigau Half-Window. They consist of a series of Early Jurassic to Paleogene sediments of Briançonnais origin. The tectonically lower *Falknis Nappe* is characterized by a more than 200 m thick Kimmeridgian–Tithonian Breccia overlain by Tithonian–Barremian marly limestones, Barremian–Aptian sandy limestones and fine grained breccias (GRUNER 1981). The tectonically higher *Sulzfluh Nappe* differs from the Falknis Nappe in that only massive limestone instead of breccia represents the Late Jurassic sediments. In a few places, crystalline basement lenses occur at the base of the Sulzfluh Nappe. The mid-Cretaceous to Cenozoic quartz-bearing sandstone and Couches Rouges are the same in both these nappes. The Falknis Nappe is particularly well developed in the area of the eponymous summit where it is subdivided into several slices. In places, one or the other of these two nappes becomes thinner; in these cases, only the thicker nappe is indicated on the map.

6.3.2.4. Tasna Nappe, Fimber Zone

In the western (Swiss) part of the Lower Engadine Window, the continental basement of the Tasna Nappe is stratigraphically overlain by Triassic to Jurassic sediments that have close similarities to those found in the Falknis Nappe (GÜR-

LER 1995). North of Ardez, the Early Cretaceous sequence contains black shales that could not yet be precisely dated. These shales are followed by Barremian breccias, mid-Cretaceous quartz-rich sediments and Couches Rouges, i.e., a sequence that is again similar to that of the Briançonnais-derived Falknis Nappe. The Cretaceous series is topped by Paleogene flysch. The Cretaceous–Paleogene sequence unconformably cover a former ocean-continent transition characterized by a detachment fault that exhumed subcontinental mantle (FLORINETH & FROITZHEIM 1994, RIBES et al. 2019).

In the northeastern (mostly Austrian) sector of the window, the Tasna Nappe ends and gives way to the *Fimber Zone*, which consists of a mélange formation dominated by Late Cretaceous to Paleogene flysch-type sediments. These contain tectonic slices and olistoliths of highly variable size and lithological composition; many of them are lithologically identical with basement and Mesozoic cover typical for the Tasna Nappe (GRUBER et al. 2010). As this mélange contains quite a lot of ophiolitic bodies, the Fimber Zone – or at least a part of it – could also be correlated with the Arosa Zone.

6.3.3. Upper Penninic

The Upper Penninic subdomain of eastern Switzerland (Graubünden) is represented by oceanic rock associations: mostly sedimentary in the case of the Avers Nappe, largely magmatic in the Platta and Malenco-Forno-Lizun nappes and mainly with the character of a mélange zone for the Arosa Zone.

6.3.3.1. Avers Nappe

The Avers Nappe is made up of shaly-calcareous-sandy marine sediments and ophiolitic rocks originating from the Piemonte-Liguria Ocean. This nappe represents an accretionary wedge at the base of an upper plate consisting of the other Upper Penninic and overlying Austroalpine nappes. This wedge directly overlies the Mesozoic cover of the Middle Penninic Suretta Nappe and probably formed in the Early Paleocene (SCHMID et al. 1996b). The basal thrust of the Avers Nappe was deformed congruently with the Suretta Nappe, and both units were later back-folded together in the upper limb of the huge Niemet-Beverin Backfold (MILNES & SCHMUTZ 1978, SCHMID et al. 1996b, SCHEIBER et al. 2012). A backthrust that formed during this same phase brought part of the Middle Penninic Schams Nappe Complex back towards SE over the Avers Nappe. In its southernmost part, a large normal fault (Turba Mylonite Zone) separates the Avers Nappe and the backthrust Schams and Tomül nappes in the footwall from the Platta and Malenco-Forno-Lizun nappes in the hangingwall (NIEVERGELT et al. 1996).

Next to the sediments of the Suretta Nappe, the larger of the two Lanzada Windows in Val Malenco (§6.3.2.1) exposes some small occurrences of metagabbro and ultramafics that are correlated with the Avers Nappe, hosting a recently detected eclogite (DROOP & CHAVRIT 2014). This, together with the occurrence of blueschists in the Avers Nappe (OBERHÄNSLI 1978), documents the existence of a probably Paleocene major subduction zone at the base of the other Upper Penninic units (SCHMID et al. 1997b). Note, however, that the accretion of these other Upper Penninic nappes (described hereafter) below the Austroalpine nappe pile occurred earlier, i.e., during the Late Cretaceous (HANDY et al. 1996).

6.3.3.2. Malenco-Forno-Lizun Nappe

Three units with distinct lithological assemblages of oceanic origin, situated in adjacent areas, form the Malenco-Forno-Lizun Nappe. The *Malenco unit* (MONTRASIO et al. 2005) consists of large volumes of serpentinite that represent exhumed subcontinental mantle formerly exposed at the ocean floor, and, in a small area adjacent to the Margna Nappe, a transition into continental lower crust in Permian granulite facies, associated with a Permian gabbroic intrusion (MÜNTENER & HERMANN 1996). Further north, the *Forno unit* consists of metabasalts and metagabbros of oceanic origin covered by metasedimentary rocks of Jurassic to Early Cretaceous age, which are in direct contact with the roof of the Bregaglia Intrusion (PUSCHNIG 1998, FROITZHEIM et al. 1996a). The *Lizun unit,* located around the Piz Lizun, northwest of the Engadine Fault and sinistrally offset from the Forno unit (SCHMID & FROITZHEIM 1993), exposes same rocks of oceanic origin as in this latter unit (LINIGER & NIEVERGELT 1990). The Malenco-Forno-Lizun Nappe, together with the Platta Nappe, is located in the hangingwall of the Turba Normal Fault (NIEVERGELT et al. 1996).

6.3.3.3. Platta Nappe

The Platta Nappe consists mainly of an ophiolitic basement, including metabasalts, serpentinites and some metagabbros, covered by a thin Late Jurassic to Cretaceous oceanic sedimentary cover, beginning with radiolarian cherts. The mafic rocks have undergone an Alpine greenschist-facies metamorphism. In contrast to the Arosa Zone, the Platta Nappe does not have the character of a mélange (DIETRICH 1970); however, its upper part contains slivers of continental lithologies and shows characteristics of an ocean-continent transition (HANDY et al. 1996, MANATSCHAL & NIEVERGELT 1997, EPIN et al. 2019). In the south (Upper Engadine), it is separated from the underlying Malenco-Forno-Lizun Nappe by the insertion of the Margna and Sella nappes that are considered part of the Salassic domain (see chapter 6).

6.3.3.4. Arosa Zone

The Arosa Zone is of heterogeneous composition and represents a mélange zone (RING et al. 1990) composed of slivers of ophiolites (e.g., Totalp Ophiolite Complex between Klosters and Davos; BERNOULLI & WEISSERT 1985), pelagic sediments and flysch sequences in a shaly matrix. Slivers of rocks with Austroalpine affinity (crystalline basement, Triassic sediments) are also embedded in the Arosa Zone; they are considered either as allochthons detached from the Adriatic margin during the spreading of the Piemonte-Liguria Ocean (SIGNER et al. 2018), as slices incorporated into the mélange zone during the subduction of the Piemonte-Liguria oceanic plate beneath the Adriatic plate (RING et al. 1990) or as slices belonging to the Lower Austroalpine subdomain (§ 8.1.4).

The Arosa Zone is always located at the base of the Austroalpine units to which it was accreted in Late Cretaceous times. It is best developed in the Arosa–Klosters area and, further north, forms a thin discontinuous band for more than 100 km, first along the Austrian border and then through Vorarlberg and Allgäu. In the Lower Engadine Window, such a thin band is discontinuously preserved between the Middle Penninic Tasna Nappe or Fimber Zone and the Austroalpine Silvretta Nappe. However, an almost complete and well-preserved ophiolitic sequence is found south of Ischgl, adjacent to the Samnaun Valley (KRAINER & TROPPER 2017).

7. SALASSIC

S.M. Schmid & Y. Gouffon

The Dent Blanche, Mont Mary and Sesia nappes in western Switzerland and adjacent Italy, together with the Margna and Sella nappes in southeastern Switzerland and partly in Italy, have an Adriatic paleogeographic affinity, as demonstrated by STAUB (1917). However, their tectono-metamorphic history is quite different from those of the other Adriatic-derived units (Austroalpine and South Alpine domains). They show signs of high-pressure metamorphism as evidence of their subduction below the Austroalpine and South Alpine units (FROITZHEIM et al. 1996b, SCHMID et al. 2004, HANDY et al. 2010) in Late Cretaceous times. High-pressure metamorphism in some of the Austroalpine nappes in Austria is older; the South Alpine units lack such an Alpine metamorphic overprint. On the other hand, the high-pressure metamorphism of the Upper Penninic units, derived from the Piemonte-Liguria Ocean, is Cenozoic (see § 6.2.3), and therefore younger than that of the nappes mentioned above.

These particular continent-derived basement units are interpreted as originating from a continental fragment that split off from the most distal part of the Adriatic margin during the Middle Jurassic opening of the Piemonte-Liguria Ocean. This extensional allochthon is referred to as the Cervinia Terrane (PLEUGER et al. 2007, FROITZHEIM et al. 2008; see Pl. III) or the Margna-Sesia fragment (SCHMID et al. 2004).

Because of their Adriatic affinity, these tectonic units are classically attributed to the Austroalpine. The Dent Blanche, Mont Mary and Sesia nappes, situated in the Western Alps, are sometimes grouped together under the term of "Austroalpine tectonic system of the Western Alps" (DAL PIAZ & ERNST 1978, BIGI et al. 1990). As they occupy a transitional position between the Austroalpine and the Penninic, they have also been attributed to the Upper Penninic (FROITZHEIM et al. 2008) or to a subdomain called "Ultrapenninic" (TRÜMPY 1992).

Given the ambivalence regarding their attribution and the specificity of their tectono-metamorphic history, it seems appropriate to group the tectonic units derived from this extensional allochthon into a new domain (1st order, see § 1.1.1) called "Salassic". This term stems from a Celtic tribe, the Salasses, who settled in the Valle d'Aosta and the Sesia region, at the same time as the Helvetians north of the Alps and the Lepontians between Val d'Ossola and Leventina.

The boundary between the Salassic and the Austroalpine domains occurs in the region of the Upper Engadine (Engiadin'Ota on the map, Switzerland) and the Val Malenco (Italy), represented by the Cretaceous westward frontal thrust of the Corvatsch Slice (Err Nappe Complex) and the Bernina Nappe. This frontal thrust of the Austroalpine nappe stack over the Margna and Sella nappes is observed all the way from the Upper Engadine to the lower Val Poschiavo, where it represents the first movement along a part of the polyphase Lunghin-Mortirolo Movement Zone of MOHN et al. (2011). In the lower Val Poschiavo, the frontal thrust is backfolded around the Pass d'Ur Antiform that formed during Cenozoic N–S shortening (SIDLER & BENNING 1992, MONTRASIO et al. 2005, TROMMSDORFF et al. 2005). The Pass d'Ur Antiform brings the Margna and Sella nappes into contact with the steeply N-dipping root zone of the Austroalpine nappes (Bernina Nappe and the southerly adjacent Tonale Nappe), which follow the Tonale Fault (eastern segment of the Insubric Fault; see § 10.1) westward towards the Mera River. In this area, the Tonale Fault defines the tectonic contact between the Salassic and Austroalpine root zone and the South Alpine domain.

To the west, the Canavese Fault (western segment of the Insubric Fault) forms the direct contact between the Salassic and the South Alpine domains, underlining the fact that the Austroalpine nappe stack did not reach the Western Alps.

7.1. Dent Blanche, Mont Mary and Sesia nappes, Roisan-Cignana Shear Zone

The Dent Blanche and Mont Mary nappes form a large klippe on top of the Upper Penninic Tsaté Nappe. They are separated from each other by the Roisan-Cignana Shear Zone. Erosion isolated this group of units geographically from the Sesia Nappe and left the Pillonet Klippe between them, some 15 km south of the Matterhorn. They are sometimes grouped together in the Dent Blanche Tectonic System (MANZOTTI et al. 2014a, b).

The *Dent Blanche Nappe* comprises two crystalline basement units. The lower Arolla Unit is essentially composed of metagranitoids and some metagabbro bodies, all of Permian age and more or less deformed. The upper Valpelline Unit consists of paragneisses with mafic and carbonate rocks, characterized by a pre-Alpine amphibolite to granulite-facies metamorphism. A Triassic–Jurassic sedimentary cover (Mont Dolin series) overlies the Arolla Unit in a small area of the Val d'Hérens, west of Arolla.

The *Mont Mary Nappe* also includes two crystalline basement units. The so-called Lower Unit mainly comprises pre-Alpine amphibolite-facies paragneisses and minor amphibolites and orthogneisses. The Upper Unit is similar to the Valpelline Unit of the Dent Blanche Nappe.

The *Roisan-Cignana Shear Zone* consists of slices of Mesozoic sediments and crystalline basement in a mylonitic matrix derived from the adjacent Dent Blanche Nappe (Arolla Unit) and of the Mont Mary Nappe (Lower and Upper units) (MANZOTTI et al. 2014a). The high-pressure mineral assemblages along the contact between these tectonic slices indicates that their emplacement occurred in an early deformation stage, before or during the subduction.

The *Sesia Nappe* is located between the Canavese Fault to the east and the Upper Penninic units to the west. It is composed of three units of crystalline basement characterized by different lithological associations. The *Gneiss Minuti Unit* consists mainly of orthogneisses, derived from granitoid of probable Permian age and interbedded with more mafic layers. High-pressure metamorphism of this unit was largely obliterated by the later greenschist-facies metamorphism. The *Eclogitic Micaschist Unit* comprises mostly paragneisses with minor mafic rocks, orthogneisses and calcitic marbles. Eclogitic mineral assemblages are well preserved, rarely overprinted by the subsequent greenschist-facies metamorphism. The unit referred to as *Second Dioritic-Kinzigitic Zone* (2DK) consists of kilometer-scale slices of micaschists, characterized by well-preserved pre-Alpine amphibolite to granulite-facies mineral assemblages as well as minor amphibolites and marbles, locally overprinted by the early Alpine high-pressure metamorphism.

The Dent Blanche, Mont Mary and Sesia nappes are structurally similar, with an upper continental crust unit at the base (Arolla Unit, Lower Unit and Gneiss Minuti Unit) and a lower crustal unit at the top (Valpelline Unit, Upper Unit and 2DK Zone). In the Sesia Nappe, the intermediate Eclogitic Micaschist Unit appears to be derived from a relatively deep part of the upper crust. The high-pressure metamorphism lasted from the Late Cretaceous to the Early Paleogene (VHO et al. 2020 and ref. therein), mainly in the lower and intermediate units; later only, the lower units were significantly re-equilibrated under greenschist-facies conditions. This peculiar situation may be explained by the following succession of events (MANZOTTI et al. 2014b): 1) Jurassic opening of the Piemonte-Liguria Ocean and detachment of exotic blocks of Adriatic upper crust as well as lower crust further back, 2) Late Cretaceous to Early Paleogene closure of the ocean and subduction of the exotic blocks below the Adriatic margin, with the most distal blocks (upper crust) moving under the most proximal blocks (lower crust), then of the oceanic crust and sediments under this preformed assemblage, and 3) Paleogene continental collision with folding to create the present-day structure of the nappes.

7.2. Margna and Sella nappes

The *Margna Nappe* is thrust over the ophiolitic Malenco-Forno-Lizun Nappe and is divided into two W-facing flat-lying antiformal basement cores separated by a thrust fault highlighted by a thin Triassic sedimentary band (LINIGER & GUNTLI 1988, SPILLMANN 1993, SPILLMANN & TROMMSDORFF 2007). The nappe reached epidote-amphibolite-facies conditions during Late Cretaceous deformation (GUNTLI & LINIGER 1989). The basement cores include upper crustal granitoids and paragneisses, as well as lower crustal pelitic pre-Alpine granulites and Permian gabbros. The exhumation of the lower crustal parts of the basement is due to hyperextension at an ocean-continent transition between the ophiolites of the Malenco-Forno-Lizun Nappe and the continental basement of the future Margna Nappe (HERMANN & MÜNTENER 1996). The Mesozoic cover of the Margna Nappe is mainly developed at the top of the nappe, where it forms a syncline that is believed to link the Margna Nappe to the overlying Sella Nappe. However, the contact between the sediments of the overturned limb and the basement of the Sella Nappe is marked by a thrust fault.

The overlying *Sella Nappe* contains only upper crustal granitoids and paragneisses, very similar to that of the overlying Err and Bernina nappe complexes. A thin Mesozoic cover is present mainly at the front of the nappe in the northwest and from there over a few kilometers of its upper limb. As these sediments are missing further southeast, SPILLMANN (1993) considers the Sella Nappe as the intensely deformed lower extension of the Bernina Nappe, while MONTRASIO et al. (2005) treat the Sella Nappe as a separate nappe. The ophiolites of the Platta Nappe not only tectonically overlie the Margna Nappe but also the northernmost parts of the Sella Nappe. This justifies the attribution of the Sella Nappe to the Salassic domain. The rapid wedging out of the Platta Nappe towards the southeast between the Sella Nappe and the overlying Err and Bernina nappe complexes south of the Upper Engadine is attributed to top-E extension that affected the Cretaceous nappe stack after its formation during the latest Cretaceous and before Cenozoic N–S shortening (Ducan-Ela extension phase of FROITZHEIM et al. 1994). MOHN et al. (2011) see a prominent tectonic contact on the top of the Sella Nappe, the so-called "Lunghin-Mortirolo Movement Zone", with contrasting degrees of deformation and metamorphism between the hangingwall and the footwall.

8. AUSTROALPINE

S.M. Schmid

The Austroalpine nappes of eastern Switzerland represent the westernmost part of the much larger area of the Austroalpine domain exposed in Austria (SCHMID et al. 2004, FROITZHEIM et al. 2008, SCHUSTER 2015). The Austroalpine nappes represent allochthons derived from the Adriatic plate. Their initial paleogeographical position was to the southeast of the Piemonte-Liguria Ocean (SCHMID et al. 2008). The main episode of W- to NW-directed transport of nappe stacking is of Cretaceous age ("Eoalpine" orogeny). Later, all these units became thrusted over the Penninic nappes towards the north during the Cenozoic, along a thrust that defines the outer limits of the Lower Engadine and the Tauern windows (see overview by FROITZHEIM et al. 1994 regarding the Swiss part). Moreover, thermochronometric studies postulate significant top-S or top-SE normal fault reactivations near the base of the Austroalpine nappe stack postdating top-N thrusting (PRICE et al. 2018).

The Austroalpine domain comprises two types of nappes. One type consists mainly of pre-Triassic crystalline basement rocks including their Permian–Mesozoic cover rocks ("basement-cover nappe"). The other type consists of detached allochthonous sedimentary cover rocks. Because of the superposition of two orogenic cycles in the Austroalpine domain, its subdivision has always been difficult and controversial.

A first Cretaceous cycle ("Eoalpine") led to eclogitization within the Austroalpine domain along an intracontinental suture (STÜWE & SCHUSTER 2010) preserved in Austria, Slovenia and South Tyrol. There, Eoalpine shortening began already in the Early Cretaceous and culminated between 101 Ma and 90 Ma (Cenomanian– Turonian) with eclogitization (MILADINOVA 2022). In eastern Switzerland, this first orogeny that progressed from east to west started around 90 Ma (Coniacian) and was associated with top-W thrusting (FROITZHEIM et al. 1994, HANDY et al. 1996). After an intermediate phase of extensional deformation (FROITZHEIM et al. 1994), a second orogenic event begun in the Early Cenozoic, associated with top-N thrusting in eastern Switzerland.

In view of the difficulty to devise a structural subdivision that accounts for the 2-stage evolution of the orogeny, the subdivision of the Austroalpine has often been based on paleogeographic interpretations. Historically, the subdivision varied from one author to another depending on the criteria used (see SCHUSTER 2015 for an historical review). Following the interpretation of SCHMID et al. (2004, see also FROITZHEIM et al. 2008, PFIFFNER 2015, SCHUSTER 2015), the Austroalpine domain is subdivided into a Lower and an Upper Austroalpine subdomain. The term “Middle Austroalpine”, variably defined (e.g., TOLLMANN 1959, 1977, NEUBAUER et al. 2000, MOHN et al. 2011), was not retained. The sedimentary nappes forming the Northern Calcareous Alps are considered Upper Austroalpine by all authors and their relationship with the basement-cover nappes will be discussed later.

In eastern Switzerland, the boundary between the Lower and Upper Austroalpine is largely based on paleogeographic considerations. The Upper Austroalpine units are derived from relatively more proximal parts of the Jurassic passive Adriatic continental margin in respect to the distal continental margin units preserved in the Lower Austroalpine, in particular in the Err Nappe characterized by the presence of rift-related polymict breccias of Early and Middle Jurassic age (e.g., FROITZHEIM & MANATSCHAL 1996). Some units formerly assigned to the Austroalpine – originating from the most distal parts of the Adriatic continental plate or from a continental fragment that broke away from it during the opening of the Piemonte-Liguria Ocean – are here grouped together into a new tectonic domain called Salassic (see chap. 7). These are the Sesia, Dent Blanche and Mont Mary nappes in the west and the Margna and Sella nappes in the east.

In the area of the Tectonic Map of Switzerland, besides the thrust between the Lower and Upper Austroalpine nappes, the Schlinig Thrust also represents an important tectonic contact, located within the Upper Austroalpine subdomain, that emplaced the tectonically higher Ötztal Nappe Complex over the underlying S-charl-Sesvenna Nappe and the Campo Nappe Complex. This major WNW-directed thrust is located near the Switzerland-Austria-Italy triple point and can be followed as an intra-basement shear zone all along the Etsch Valley (Vinschgau) eastwards for some 40 km (SCHMID & HAAS 1989). East of the area of the map, a high-pressure nappe complex is situated at the level of this contact (Koralpe-Wölz Nappe Complex; SCHMID et al. 2004, SCHUSTER 2015). The other tectonic boundaries between the Upper Austroalpine nappes in the footwall of the Ötztal Nappe are of relatively minor importance. The boundary between the sedimentary Lechtal Nappe of the Northern Calcareous Alps and the basement of the southerly adjacent Silvretta Nappe represents a heavily tectonized stratigraphic contact (ROCKENSCHAUB 1990, NAGEL 2006). The Tonale Fault, part of the Periadriatic Fault System, separates the Austroalpine units in the north from the South Alpine units in the south.

8.1. Lower Austroalpine

The Lower Austroalpine comprises tectonic units that are derived from the former distal continental margin of the Adriatic plate (see § 1.3, Tab. 2), bordering the Piemonte-Liguria Ocean during the Jurassic–Cretaceous. The facies of syn- and post-rift sediments has remarkable similarities with those found in the Canavese area around the town of Ivrea, located outside our map (FERRANDO et al. 2004), which is a part of the South Alpine derived of the western part of the Adria (see § 1.3, Tab. 2, Pl. III). In the case of the Lower Austroalpine, the strongly deformed pre- and syn-rift strata later became intensely reshaped and reworked during the closure of the Piemonte-Liguria Ocean and subsequent Alpine continental collision. Jurassic extensional detachment faults are occasionally well preserved, and in other cases strongly overprinted by collision-related Alpine deformation and metamorphism (e.g., FROITZHEIM et al. 1994, FROITZHEIM & MANATSCHAL 1996, EPIN et al. 2017).

8.1.1. Err Nappe Complex

The Err Nappe Complex embraces a number of tectonic subunits that, from a paleogeographical point of view, are derived from the most distal Adriatic passive margin which was linked to the adjacent oceanic realm of the Platta Nappe (EPIN et al. 2017).

The Err Nappe (s. str.) is confined to an area northwest of the Engadine Fault (see § 10.5) between Albulapass and Julierpass where it overlies the Carungas Slice (STÖCKLIN 1949), both traditionally being referred to as “Err-Carungas Nappe”. The Bardella-Roccabella Slices are also located northwest of the Engadine Fault. It is convenient to group the equivalents of similar slices southeast of the Engadine Fault (Corvatsch, Chastelets and Murtiröl slices) together into the Err Nappe Complex. The latter slices are substantially displaced in respect to the “Err-Carungas Nappe” and the Bardella-Roccabella Slices by a sinistral strike-slip motion along the Engadine Fault, combined with relative uplift of the southeastern block (SCHMID & FROITZHEIM 1993).

The *Err Nappe* (STÖCKLIN 1949) is a basement-cover nappe located north of a multiply deformed synclinorium, the so-called “Samedan Zone”, that separates the Err Nappe from the southerly adjacent basement of the Julier Nappe that is part of the Bernina Nappe Complex (HANDY et al. 1996, HANDY 1996, MANATSCHAL & NIEVERGELT 1997).

The *Carungas Slice*, consisting of a band of predominantly overturned Mesozoic sediments and its associated crystalline basement, forms the hangingwall of the Platta Nappe and the footwall of the Err Nappe. This slice extends from east of Savognin all the way to the Julierpass road above Bivio, along the western margin of the Err Nappe (MANATSCHAL & NIEVERGELT 1997, their “lower Err Nappe”). The small portion of crystalline rock wedged between the two branches of the Engadine Fault near Sils Maria is also related to the Carungas Slice. This slice is derived from the most distal part of the former Adriatic continental margin.

The *Bardella-Roccabella Slices*, also located northwest of the Engadine Fault, are sedimentary slices detached from their former crystalline substrate. The Bardella Slice is located in the footwall of the Julier Nappe and overthrusts the sedimentary cover of the Err Nappe, being pinched in along the multiply deformed synclinorium of the “Samedan Zone”, all the way between the Julierpass road and St. Moritz. The Roccabella Slice, in contrast, is found in the immediate footwall of a klippe of the Err Nappe and is in direct contact with the Platta Nappe in the area east of Septimerpass. Small occurrences of sedimentary slices belonging to the Err Nappe Complex are also found north of Sils Maria, pinched in between the overlying basement of the Err Nappe and the Platta Nappe (HANDY et al. 1996, HANDY 1996).

The *Corvatsch Slice* (SPILLMANN & TROMMSDORFF 2007) can be seen as the equivalent of the Err Nappe located southeast of the Engadine Fault. It is predominantly made up of intensely deformed pre-Mesozoic basement. Its Mesozoic cover is only rarely preserved just below the overlying Bernina Nappe (e.g., at Fuorcla Surlej).

The *Chastelets Slice* is a small slice of basement and cover in the footwall of the Corvatsch Slice (SPILLMANN & TROMMSDORFF 2007). It directly overlies the Platta Nappe and hence occupies a similar position to that of the Roccabella Slice northwest of the Engadine Fault.

The *Murtiröl Slice*, consisting of basement and cover, forms a dome-like feature in the footwall of an important extensional detachment. This detachment fault and the adjacent Engadine Fault separate the Murtiröl Slice from all the surrounding units belonging to either the Bernina Nappe Complex (in the northwest and southwest) or to the Upper Austroalpine Languard and Ortler nappes (in the east and northeast). This detachment fault is referred to as the Mezzaun Detachment Fault in the southwestern rim of the dome (see FURRER et al. 2015, Fig. 12) but can be followed further to the north, swinging around into a NW–SE strike in the lower Val Trupchun, where the extensional offset becomes more substantial. This is one of the most spectacular normal faults attributed to the Late Cretaceous phase of extension that postdates Cretaceous shortening but predates Cenozoic collision (FROITZHEIM et al. 1994).

8.1.2. Bernina Nappe Complex

As is the case for the Err Nappe Complex, the Bernina Nappe Complex also includes a series of subunits. However, paleogeographically they occupied a somewhat more proximal position in which E-dipping former normal faults are thought to have been in a favourable orientation for reactivation during W-directed Alpine shortening according to FROITZHEIM et al. (1994). Structurally, the Bernina Nappe Complex occupies a higher tectonic position compared to the Err Nappe Complex. The Julier and Bernina Nappes are considered as a single tectonic unit, but carry different names only because of their different location in relation to the Engadine Fault (see § 10.5). The Ela Nappe and underlying Madulain Slices are also considered to be part of the Bernina Nappe Complex. The Mezzaun Slice is a rather isolated piece of this nappe complex located southeast of the Engadine Fault directly underlying the Upper Austroalpine units, which justifies its attribution to the Bernina Nappe Complex on structural grounds.

The *Bernina Nappe* is a basement-dominated nappe that occupies a very large area southeast of the Engadine Fault. The basement is dominated by Late to Post-Variscan magmatic rocks, which intrude an older basement of presumably Precambrian age with Variscan overprint that is mainly preserved in the northern part of the nappe (SPILLMANN 1993, BÜCHI 1994, SPILLMANN & TROMMSDORFF 2007). Its Mesozoic cover is rather sparsely preserved, except for two important and famous occurrences, one around Piz Alv, north of the Bernina Pass, in the footwall of the Languard Nappe, and the other at the Sassalb, east of Poschiavo, in the footwall of the Campo Nappe (MOHN et al. 2012). The Bernina Nappe lacks a clear separation from the underlying Sella Nappe (SPILLMANN 1993), which is attributed to the Salassic (see chap. 7). South of Poschiavo, the Bernina Nappe is folded around the E-plunging Pass d'Ur Antiform and can be followed westward along the Southern Steep Belt north of the Tonale Fault, until being cut off by the Bregaglia Intrusion.

The *Julier Nappe* represents the equivalent of the Bernina Nappe northwest of the Engadine Fault. This fault sinistrally offsets the two basement-dominated nappes, combined with relative uplift of the Bernina Nappe in respect to the Julier Nappe (SCHMID & FROITZHEIM 1993). The lithological characteristics of the basement are identical to those of the Bernina Nappe (PETERS & DIETRICH 2008). An undisturbed contact between basement and cover of the Julier Nappe is not preserved. Parts of its former cover became detached and form klippen preserved in the core of the multiphase synclinorium of the "Samedan Zone" (Schlattain-Clavadatsch-Padella Slices, HANDY 1996). In the area of Piz Nair near St. Moritz, however, the base of the Julier Nappe appears to have overthrust its own cover.

The *Schlattain-Clavadatsch-Padella Slices* form small isolated klippen, located in the core of the synclinorium of the "Samedan Zone" and composed of Triassic to Late Cretaceous sediments (ROESLI 1945, EBERLI 1988, FURRER et al. 1985). They were thrust onto the cover of the Err Nappe and attributed to the Bernina Nappe Complex.

The *Mezzaun Slice* crops out southeast of the Engadine Fault around the Piz Mezzaun. It is composed of a Mesozoic sequence considered as part of the Bernina Nappe Complex (FROITZHEIM et al. 1994, FURRER et al. 2015). This slice is downfaulted by the Late Cretaceous Mezzaun Normal Fault in respect to the domal structure of the Murtiröl Slice (Err Nappe Complex) forming the footwall of this fault. It is overthrust by the Müsella Slice.

The *Müsella Slice* is composed of the Müsella basement and an overlying band of strongly tectonized Mesozoic sediments ("Corn element", FURRER et al. 2015). According to SCHMID & FROITZHEIM (1993) and FROITZHEIM et al. (1994), this slice is considered part of the Bernina Nappe Complex mainly for structural reasons. Thereby the Müsella basement is correlated with the basement of the Julier Nappe while the Mesozoic sediments are correlated with the Ela Nappe (FURRER et al. 2015) on the north-western side of the Engadine Fault. The Mesozoic sediments of the Müsella Slice are overthrust by the Upper Austroalpine Languard Nappe. However, PETERS (2005) and MOHN et al. (2011) consider this slice to be part of the Upper Austroalpine Languard Nappe.

The *Madulain Slices* ("Albula Steilzone", FURRER et al. 2015) are located on the northwestern side of the Engadine Fault, where they lie to the north of the underlying Err Nappe and represent the base of the overlying Ela Nappe. This group is made up of slices of sediments, attributed to the Bernina Nappe Complex by facies, in which are inserted thin and intensely folded slices of Err basement and sediments. This slice complex extends from west of the Pass d'Alvra (Albulapass) all the way to Madulain in the Engadine Valley.

The *Ela Nappe*, which forms the hangingwall of the Madulain Slices and the footwall of the Upper Austroalpine Silvretta Nappe, consists of a sedimentary sequence that was completely detached from its former crystalline substrate during Cretaceous top-W thrusting along Carnian evaporites. Large parts of it were affected by sinistrally transpressive deformation during Cretaceous shortening, followed by an extensional overprint in the latest Cretaceous (FROITZHEIM 1992) and the N-directed thrusting of the Silvretta Nappe during the Cenozoic orogeny (FROITZHEIM et al. 1994, FURRER et al. 2015). Hence, the internal structure of the Ela Nappe is highly complex due to its polyphase deformation.

East of Piz Kesch, below the Silvretta basement, a band of Triassic sediments, ending against the Engadin Fault, overthrusts the rest of the Ela Nappe which is dominated by Jurassic deposits. This band is interpreted as representing a thin uppermost slice of the Ela Nappe dragged along the base of the Upper Austroalpine Silvretta Nappe.

The Ela Nappe is assigned to the Lower Austroalpine Bernina Nappe Complex (FURRER et al. 2015) based firstly on the close similarity of its lithofacies to those of the Middle Jurrassic sediments of the Mezzaun Slice (see above; EBERLI 1988), secondly on its offset by the Engadine Fault and the difference in structural position between the Ela Nappe and the Ortler Nappe (SCHMID & FROITZHEIM 1993, FROITZHEIM et al. 1994) and thirdly on the difference in metamorphic grade of these two nappes (CONTI 1997). As in the earlier literature, MOHN et al. (2011) instead attribute it to the Upper Austroalpine nappes, based on sedimentological and paleogeographical considerations in comparison with the Upper Austroalpine Ortler Nappe.

8.1.3. Rothorn-Schwarzhorn Nappe Complex

South and northeast of the Prättigau Half-Window, comparatively small units separate the Upper Penninic Arosa Zone from the Upper Austroalpine Schiahorn and Silvretta nappes. The lithofacies of the sediments preserved in these units have a Lower Austroalpine affinity, i.e., an Adriatic distal margin origin.

In the southwestern part, between Tiefencastel and Arosa, the Lower Austroalpine is represented by two small nappes, namely from top to bottom: the *Rothorn Nappe* with a basement-cover sequence, directly underlying the Upper Austroalpine Schiahorn Nappe (see §8.2.2), and the sedimentary *Tschirpen Nappe* overlying the Arosa Zone.

Further to the northeast, up to the Klosters area, the Arosa Zone is overlain by the crystalline *Dorfberg Nappe,* which is itself overlain by the Schiahorn Nappe as far as the Davoser See and by the Silvretta Nappe further to Klosters. The thin, discontinuous sedimentary *Schafläger Nappe,* locally overlain by crystalline rocks of the Rothorn Nappe, separates the Dorfberg Nappe from the overlying Schiahorn Nappe and Silvretta Nappe respectively (SIGNER et al. 2018). The Schafläger Nappe can be correlated with the Tschirpen Nappe (STRECKEISEN 1986). FROITZHEIM et al. (1994) correlated the Dorfberg and Tschirpen nappes with the Err Nappe Complex and the Rothorn Nappe with the Bernina Nappe Complex.

In the Rätikon area (northeastern corner of the Prättigau Half-Window), NAGEL (2006) correlated the Lower Austroalpine slices to the following units defined south of the Prättigau Half-Window: the “Walser Slice” with the Rothorn Nappe (Bernina Nappe Complex) and the “Schwarzhorn Slice” with the Dorfberg Nappe (Err Nappe Complex). The “Schwarzhorn Slice” consists mainly of a metamorphosed diorite body of Cambrian age (NILIUS et al. 2016) and is interpreted to represent the continuation of the “Gabbrozug” in the Dorfberg Nappe (STRECKEISEN 1948).

8.1.4. Grüenhorn-Casanna Slice Complex

The *Grüenhorn Slice* and the *Casanna Slice* are both small superimposed thrust sheets which were repeatedly sliced. They comprise a sedimentary series of Lower Austroalpine affinity and tectonically overlie the Arosa Zone (WEISSERT 1975). The Arosa Zone near Davos contains slices consisting of Mesozoic strata of Lower Austroalpine affinity, such as the Weissfluh Slice, which are considered a part of the mélange (see §6.3.3.4; SIGNER et al. 2018). However, the Grüenhorn-Casanna Slice Complex is here considered as a tectonic klippe correlated with the Err Nappe Complex, emplaced over the Arosa Zone as a separate tectonic entity (SIGNER et al. 2018).

8.1.5. Stammerspitz Slice

At the rim of the Lower Engadine Window, the Stammerspitz Slice is made up of a sedimentary series with a Lower Austroalpine affinity (KLÄY 1957). Due to its location as a klippe directly above the Roz-Champatsch Mélange, this slice can be interpreted either as the lowermost unit of the Lower Austroalpine or as a sliver within this mélange (§ 6.3.3.4) or even within the Fimber Zone (§ 6.3.2.4).

8.2. Upper Austroalpine

The Upper Austroalpine tectonically overlies the Lower Austroalpine. At the same time, it embraces those units originating from the Adriatic continental plate (HANDY et al. 2010) that are interpreted to originally have been relatively more proximal in respect to the distal continental margin units preserved in the Lower Austroalpine. The Upper Austroalpine units underwent less deformation during the opening of the Piemonte-Liguria Ocean and generally appear less intensely deformed during the Alpine orogeny. Many of them are basement-cover nappes, except for the small Roggenstock-Mördergruebi Nappe, the nappes of the Northern Calcareous Alps (§ 8.2.2) and the Quattervals Nappe, which are made up entirely of sedimentary rocks.

The term "Middle Austroalpine" used by TOLLMANN (1977), embracing many of these units, was abandoned by more recent studies and is not used here. In Austria, tectonic units are generally grouped into nappe systems; this is not the case in this map. This effects the following nappes: 1) The Silvretta-Seckau Nappe System comprises the Languard, S-charl-Sesvenna and Silvretta nappes as well as the Campo Nappe Complex, 2) the tectonically higher Ötztal-Bundschuh Nappe System is represented only by the Ötztal Nappe Complex, 3) although the Tonale Nappe lacks a Mesozoic cover, it is attributed to the still higher Drauzug-Gurktal Nappe System which is not affected by the Alpine metamorphic overprint (SCHMID et al. 2004). Note that the Silvretta Nappe, the S-charl-Sesvenna Nappe and the Campo Nappe Complex, all being part of the Silvretta-Seckau Nappe System, essentially occupy the same position within the Upper Austroalpine nappe stack (FROITZHEIM et al. 1994). Other units, consisting predominantly of cover sequences detached from the S-charl-Sesvenna Nappe and the Campo Nappe Complex (Ortler and Quattervals nappes, Umbrail-Terza Slice Complex), are transported towards the WNW, below the advancing Ötztal Nappe Complex (FROITZHEIM et al. 1994, CONTI 1997, TRÜMPY et al. 1997).

8.2.1. Roggenstock-Mördergruebi Nappe

A pair of isolated klippen found in central Switzerland (Iberg Klippen) are testimony that Austroalpine cover nappes must have formerly extended as continuous thrust sheets westwards to the meridian of the Vierwaldstättersee. These klippen only expose Late Triassic to Early Jurassic sediments. TRÜMPY (2006) excluded that they belong to the Lower Austroalpine or Salassic nappes. The Roggenstock-Mördergruebi Nappe forms the highest unit of the Iberg Klippen and is in direct tectonic contact with the underlying Arosa Zone that in turn overthrusts Middle Penninic units. Since the Lower Austroalpine is missing, these klippen are best correlated with the nappes of the Northern Calcareous Alps, which also directly overlie the Arosa Zone west of the Rätikon mountain range.

8.2.2. Northern Calcareous Alps: Allgäu, Lechtal, Inntal and Krabachjoch nappes, Cenoman-Randschuppe; Schiahorn Nappe

A nappe stack consisting exclusively of sedimentary rocks, ranging from the Permian to the Late Cretaceous, occupies the entire northern part of the Austroalpine in the Northern Calcareous Alps. These were detached from their crystalline basement during the Late Cretaceous, as inferred from synorogenic Cretaceous deposits (ORTNER & KILIAN 2022). They were affected by top-NW thrusting in the Cretaceous (Hauterivian to Turonian, ORTNER & KILIAN 2022), followed by top-N thrusting in the Cenozoic. This led to a complicated internal structure. From bottom to top these nappes were classically grouped into Bajuvaric, Tirolic-Noric and Juvavic nappe systems, a concept that is presently under discussion (ORTNER & KILIAN 2022). In the area of the Tectonic Map of Switzerland, from bottom to top, the Cenoman-Randschuppe, the Allgäu Nappe and the Lechtal Nappe belong to the Bajuvaric Nappe System, the Inntal Nappe and the Krabachjoch Nappe to the Tirolic-Noric Nappe System.

The Cenoman-Randschuppe consists of an imbricate zone of slivers formed at the active margin between the Adriatic continental plate and the Piemonte-Liguria Ocean (GAUPP 1983), while the other units are composed of continuous sedimentary series. In the Rätikon mountain range, the base of the Lechtal Nappe contains locally Permian metasediments that are adjacent to the northern boundary of the "Phyllitgneiszone" that represents the northern, strongly retrogressed and phyllonitic part of the Silvretta Nappe (GRUBER et al. 2010). This has led some authors to propose that parts of the Mesozoic of the Lechtal Nappe originally represented the cover of the Silvretta Nappe (e.g., EISBACHER et al. 1990). However, the majority of the sedimentary nappes of the Bajuvaric Nappe System originated from south of the Silvretta and Ötztal nappes (e.g., AUER & EISBACHER 2003). Where the Tirolic-Noric Nappe System is concerned, stratigraphic contacts with some Paleozoic sediments ("Grauwackenzone") do exist in an area east and outside the map sheet (PLÖCHINGER 1980).

In the northern Rätikon mountain range, between Austria, Liechtenstein and Switzerland, the Lechtal Nappe is intersected by out-of-sequence thrust faults, which in places lead to the exposure of isolated lenses of the Arosa Zone. Such thrust faults divide the westernmost Lechtal Nappe into several slices (the Schesaplana, Gorfion, Augstenberg, Ochsenkopf, Heubühl and Drei Schwestern slices; ALLEMANN 2002). The "Northern Mittagspitz Zone", in the eastern Rätikon (NAGEL 2006), and the Madrisa Slice, which is isolated north of Klosters between the Silvretta Nappe above and the Upper Penninic Arosa Zone below, are considered to be inverted slivers derived from the Lechtal Nappe.

The *Schiahorn Nappe* (formerly "Arosa Dolomites") is a small unit underlying the Silvretta Nappe between Tiefencastel and Davos. It consists of Triassic to Early Jurassic sediments with lithofacies similar to that of the Upper Austroalpine Ortler Nappe (see §8.2.7; FURRER 1993, EBERLI 1988, FROITZHEIM et al. 1994). In the Rätikon area (northeast corner of the Prättigau Half-Window), NAGEL (2006) correlates the sedimentary "Southern Mittagspitz Zone" with the Schiahorn Nappe, both having a similar stratigraphic sequence with respect to the Allgäu Nappe, as well as a structurally comparable position with it.

8.2.3. Languard Nappe

The basement-dominated Languard Nappe covers a relatively small area. It is surrounded by the Engadine Fault in the northwest and lacks an equivalent on the northwestern side of this fault. It overthrusts the Bernina Nappe in the south, while in the north it overlies the Mezzaun Slice of the Bernina Nappe Complex and the Murtiröl Slice of the Err Nappe Complex; the thrust contacts being overprinted by normal faults (e.g., the Mezzaun Normal Fault; see §8.1.1 and 8.1.2) over large distances. To the east and northeast the Languard Nappe is overthrust by the basement of the Campo Nappe Complex and by the Ortler Nappe, which both occupy a higher tectonic position (CONTI 1997).

8.2.4. Silvretta Nappe

The Silvretta Nappe is the northernmost Upper Austroalpine basement-cover nappe extending over a large area located between the southern rim of the Northern Calcareous Alps in the north and the Engadine Fault in the south. Most of its area is occupied by high-grade metamorphic basement that was multiply deformed since the Precambrian, ending with an amphibolite-facies Variscan tectono-metamorphic event in the Carboniferous (MAGETTI & FLISCH 1993). A top-N Alpine thrust of secondary importance separates this high-grade basement from a narrow belt of low-grade basement referred to as the *"Phyllitgneiszone"* (including the Landeck Quartzphyllites) that is nowadays also considered to be a part of the Silvretta Nappe (GRUBER et al. 2010). It has a lower grade of pre-Alpine metamorphism and has been intensely sheared during the Alpine orogeny (ROCKENSCHAUB 1990).

The Triassic cover of the Silvretta Nappe is preserved in two SW–NE striking synclines located at the western edge of the Silvretta Nappe, known as the Landwasser and Ducan synclines (FROITZHEIM et al. 1994). They formed during top-NW thrusting in the Cretaceous, and then were overprinted by normal faulting still in the latest Cretaceous. This was followed by top-N thrusting of the entire Silvretta Nappe over the Penninic units during Cenozoic times. Only very small lenses of Permo-Carboniferous and Early Triassic slivers ("Puschlin Zone") are preserved within the Landeck Quarzphyllites (GRUBER et al. 2010).

8.2.5. S-charl - Sesvenna Nappe

The basement of the S-charl - Sesvenna Nappe is commonly referred to as the Sesvenna basement and its cover as "S-charl - Unterbau" and "S-charl - Oberbau" (DÖSSEGGER 1987, TRÜMPY et al. 1997). The "S-charl - Unterbau" forms a series of NE–SW trending series of synclines and anticlines that affect both basement and cover without major detachments within the sedimentary sequence (KARAGOUNIS 1962). In contrast, the "S-charl - Oberbau", referred to as *Tavrü Slice*, straddling the northeastern rim of the S-charl - Sesvenna Nappe neighbouring the Engadine Fault (see § 10.5), consists entirely of a Norian to Cretaceous succession, volumetrically dominated by an over 2 km thick Hauptdolomit. The Tavrü Slice is completely detached from the Carnian Raibl Group. This slice, separated from the tectonically higher Ötztal Nappe by the Schlinig Thrust, suffered substantial internal extension in a domino-style (see cross-sections in TRÜMPY et al. 1997); the cause of this extension, either by stretching below the basal thrust of the Ötztal Nappe (SCHMID & HAAS 1989) or by deformation during the Late Cretaceous extensional phase (FROITZHEIM et al. 1997), being a matter of debate.

Nowadays most authors agree that the S-charl - Sesvenna Nappe, including the Tavrü Slice, basically occupies the same tectonic position as the Silvretta Nappe, the two being only separated from each other by the Engadine Fault. In the area between Zernez and Scuol, the steeply SE-dipping Engadine Fault appears as a normal fault in cross-section (TRÜMPY et al. 1997) that shows more than 5 km vertical downthrow of the southeastern compartment (S-charl - Sesvenna Nappe) relative to the northwestern compartment (Silvretta Nappe). This extension was associated with sinistral strike-slip motion along the – in this area – sinistrally transtensive Engadine Fault (SCHMID & FROITZHEIM 1993). As a consequence of this faulting, the Silvretta Nappe located north of this fault wedges out in a triangular area northeast of Zernez, only to reappear again in the form of the so-called "Oberer Gneiszug" (EUGSTER 1985) in map view. The latter is a narrow band of Sesvenna basement that rims the southeastern part of the Lower Engadine Window between Scuol and Nauders (TRÜMPY et al. 1997).

8.2.6. Campo Nappe Complex

The Campo Nappe Complex (formerly Campo Nappe s.l.), dominated largely by Variscan basement, forms the third largest basement-cover unit that occupied the same tectonic position as the Silvretta and S-charl-Sesvenna nappes during the Cretaceous orogeny (Silvretta-Seckau Nappe System of SCHMID et al. 2004). This nappe complex is composed of different nappes which have substantial petrological and structural differences. Note that contrary to STAUB (1964) and many Italian authors (e.g., CHIESA et al. 2012), the Ortler Nappe is here not regarded as a part of the Campo Nappe Complex. The individual nappes are described below, from southwest to northeast.

The *Masuccio Nappe* is the lowermost nappe, consisting exclusively of amphibolite-facies Variscan basement. This basement nappe overthrusts the Bernina Nappe and is located in the footwall of the Late Cretaceous Mortirolo Normal Fault (MEIER 2003), a transtensional top-E directed extensional fault that became folded around the Pass d'Ur Antiform during Cenozoic folding. In the south, the Masuccio Nappe is in a subvertical orientation and part of the Southern Steep Belt (or root zone) located north of the Tonale Fault. There it is juxtaposed with the structurally much higher Tonale Nappe, located further south and directly adjacent to the Tonale Fault. East of Lago di Poschiavo, the Mortirolo Normal Fault, defining the top of the Masuccio Nappe, abuts the basal thrust of the Campo Nappe Complex that overlies the Lower Austroalpine Bernina Nappe.

The *Campo Nappe* is the largest unit of the Campo Nappe Complex and predominantly consists of Variscan basement, locally intruded by Permian magmatites (e.g., Sondalo Gabbro, Martell Granite; BOCKEMÜHL 1988, PETRI et al. 2017). This nappe tectonically overlies the Masuccio Nappe in the southwest and the Languard Nappe in the northeast and extends all along the base of the tectonically higher Ortler Nappe. Its former Permian-Mesozoic cover has been almost completely detached very early during WNW-directed Late Cretaceous thrusting (CONTI 1992) and is not present nowadays due to erosion. However, small occurrences of Permian-Mesozoic sedimentary rocks remain more or less attached to the basement of the Campo Nappe. A thin slice of Mesozoic cover of the Campo Nappe located at the footwall of the overlying Grosina Nappe is preserved west of Piz Sena in Val Poschiavo (SCHUDEL 1965). Very small outcrops of Permian Verrucano located east of Bormio are found in the footwall of the basal thrust of the Ortler Nappe, here formed by the Carnian Raibl Group (MONTRASIO et al. 2012). Carnian deposits of the Raibl Group also accompany an E–W striking thrust within the basement of the Campo Nappe south of Sulden (within Variscan phyllites of the "Scaglia dello Zebrù", MONTRASIO et al. 2012).

Lithologically, the Variscan basement of the Campo Nappe is dominated by metasedimentary sequences of variable pre-Alpine metamorphic grade, ranging from amphibolite facies in the south (e.g., around the Permian Sondalo Gabbro; MOHN et al. 2011, PETRI et al. 2017) to greenschist facies in the north (e.g., "Filladi di Bormio" and phyllites of the "Scaglia dello Zebrù"). The Alpine metamorphism grade ranges from lower to upper greenschist facies, defined by mineral assemblages and microstructures in the southern Campo Nappe (WERLING 1992, MEIER

2003, VIOLA et al. 2003), to lower greenschist-facies conditions in the north. Widespread penetrative greenschist-facies deformation within the Campo Nappe of Alpine age has also been documented for the above-mentioned Variscan phyllites found along the northern rim of the Campo Nappe.

The *Grosina Nappe* forms a series of tectonic klippen on the southwestern parts of the Campo Nappe along a distinct mylonitic zone associated with top-NW to top-N senses of shear of Cretaceous age (KOENIG 1964, SCHUDEL 1965, MEIER 2003) that possibly reworked a Jurassic decollement zone (MOHN et al. 2012). Only in the west does this mylonitic zone incorporate Mesozoic cover of the Campo Nappe (SCHUDEL 1965). The greenschist-facies carbonates, that often accompany the mylonites along the basal thrust of the Grosina Nappe further to the east (KOENIG 1964), are probably derived from pre-Mesozoic marbles. The amphibolite-facies Variscan basement of the Grosina Nappe is in parts similar to that of the underlying Campo Nappe. However, the basement of the Grosina Nappe differs from that of the Campo Nappe in that orthogneisses are much more frequent, and, additionally, in that there is often a pervasive greenschist-facies metamorphic overprint of the older high-grade fabrics. The root zone of the Grosina Nappe most probably occurs at the southern margin of the Campo Nappe Complex and in the immediate footwall of the tectonically higher Tonale Nappe.

The *Laas Nappe* ("Laaser Einheit" of MAIR et al. 2007) exposes a series of often subvertically northward inclined garnet and staurolite bearing paragneisses, marbles and amphibolites metamorphosed under amphibolite-facies conditions during the Variscan orogeny (MARTIN et al. 2009). Cretaceous metamorphic overprint varies from greenschist facies in the west to lower amphibolite facies in the east (SCHMID & HAAS 1989). This nappe occupies a much-debated and still unclear position in the Upper Austroalpine nappe pile. It is considered a part of the so-called "Ortler-Campo basement" by MAIR et al. (2007), who suggest that there is no Alpine tectonic separation between the Ortler and Campo nappes. However, as described below, the Ortler Nappe overlies the Campo and the Laas nappes along the Zebrù Thrust (CONTI et al. 1994, CONTI 1997) and thus occupies a tectonically higher position. On the other hand, the Laas Nappe is also separated from the Campo Nappe (the "Pejo-Einheit" of MAIR et al. 2007) by a sliver of Mesozoic cover of the Laas Nappe along a steeply S-dipping thrust ("Laaser Linie" of MAIR et al. 2007). Additionally, the distinctly different lithological composition of the basement of the Laas Nappe in respect to that of the Campo Nappe justifies its separation as a distinct nappe. In view of the considerations above, the Laas Nappe is here considered a distinct part of the Campo Nappe Complex. The steeply S-dipping basal E–W striking thrust of the Laas Nappe, oriented perpendicular to the Cretaceous-age Alpine metamorphic zonation, very probably represents a top-N out-of-sequence thrust of Cenozoic age that brings the Campo Nappe over the Laas Nappe. To the north, the Laas Nappe is overlain by the very shallowly N-dipping Cretaceous Vinschgau Shear Zone, located just below the tectonically higher

Ötztal Nappe. This indicates that the Laas Nappe was previously in a tectonically higher structural position within the Campo Nappe Complex during the Late Cretaceous top-WNW thrusting.

The *Vinschgau Shear Zone* represents the structurally highest unit of the Campo Nappe Complex and constitutes a greenschist-facies Alpine mylonitic belt with a thickness of up to 2–3 km that accommodates W-directed thrusting of the Ötztal Nappe Complex in the area north of the Vinschgau Valley floor (SCHMID & HAAS 1989). South of the valley floor and in the lowermost Val Müstair, the same mylonitic belt accommodates WNW-directed thrusting of the easternmost part of the Umbrail-Terza Slice Complex over the S-charl-Sesvenna Nappe (CONTI 1997). The protoliths of this mylonitic belt include pre-Permian basement, sericite-rich Permo-Triassic siliciclastic metasediments and rare occurrences of mid-Triassic carbonates that are part of the Campo Nappe Complex. The fact that the Vinschgau Shear Zone directly overlies both the rest of the Campo Nappe Complex and the easternmost parts of the S-charl-Sesvenna Nappe shows that, at a large scale, the Campo Nappe Complex and the S-charl-Sesvenna Nappe occupy about the same tectonic position within the Upper Austroalpine nappe stack.

8.2.7. Ortler Nappe

The Ortler Nappe overthrusts the Campo Nappe along the WNW–ESE striking Zebrù Thrust, which curves eastward to a NNW–SSE orientation. This thrust formed during an early stage of Late Cretaceous WNW-directed thrusting (CONTI et al. 1994). Over most of its strike, the Zebrù Thrust follows the incompetent sediments of the Raibl Group, which serve as the dominant basal decollement horizon for the Mesozoic sequence of the Ortler Nappe dominated by massive Late Triassic sediments. The youngest sediments are of Turonian age (CARON et al. 1982), thus providing an important constraint regarding the timing of Cretaceous orogeny in eastern Switzerland. Only small occurrences of basement and pre-Carnian sediments are preserved locally, where the decollement horizon in the Carnian sediments encountered a syn-rift normal fault of Jurassic age (CONTI et al. 1994). According to a paleogeographic reconstruction by CONTI (1997), the former basement of the predominantly Mesozoic sequence of the Ortler Nappe most probably occurred east of the present Campo Nappe Complex outcrops and west of the future Ötztal Nappe Complex that nowadays occupies a higher structural position. The transport distance during top-WNW thrusting amounts to well over 100 km.

The hangingwall of the Ortler Nappe is defined by the Trupchun-Braulio Thrust that formed during a later stage of the Cretaceous orogeny. This thrust juxtaposes the Quattervals Nappe (in the west) and the Umbrail-Terza Slice Complex (in the east) over the Ortler Nappe. The thrust is marked by calcite mylonites derived from the footwall and exhibits numerous top-WNW sense-of-shear indicators (CONTI 1997).

8.2.8. Quattervals Nappe

The Quattervals Nappe comprises almost exclusively Late Triassic sediments, mostly dolomitic and calcareous formations of the Norian Hauptdolomit Group of considerable thickness overlain by Rhaetian deposits, which became detached from their former substratum along the Carnian Raibl Group during the Cretaceous orogeny (SOMM 1965, DÖSSEGGER 1987, TRÜMPY et al. 1997). The nappe consists of a series of NNE-dipping slices that overthrust the Ortler Nappe along the western part of the Trupchun-Braulio Thrust. These slices discordantly abut against the gently SSE-dipping cover of the "S-charl-Unterbau" located to the northwest along what is referred to as the "Gallo Line" in the literature (KARAGOUNIS 1962, TRÜMPY et al. 1997, see their cross-sections 2 and 3). This Gallo Fault was originally the basal thrust of the Quattervals Nappe and the Umbrail-Terza Slice Complex which were both thrust over the S-charl-Sesvenna Nappe (SCHMID 1973, CONTI 1997). In its present-day orientation, the Gallo Fault represents a late-stage top-WSW normal fault that defines the southeastern limit of a large-scale anticlinorium centered in Val Müstair and the lower Spöl Valley and formed within the S-charl-Sesvenna Nappe to the WSW. Due to this normal faulting overprint, the Quattervals Nappe and Umbrail-Terza Slice Complex in the hangingwall, together with the underling Ortler Nappe became downthrown towards the south by a fault-perpendicular displacement of at least 3 km. According to CONTI (1997), this normal fault is of Late Cretaceous age and reactivated a former WNW-directed Late Cretaceous thrust of the Quattervals Nappe over the S-charl-Sesvenna Nappe. According to this author, the provenance of the Quattervals Nappe most probably occurs east-southeast of its present-day outcrop area, having been transported to the WNW together with the Ortler Nappe along the Zebrù Thrust and then over the latter nappe along the Trupchun-Braulio Thrust (see discussion of alternative views in TRÜMPY et al. 1997). Hence, both the Ortler and Quattervals nappes represent considerably WNW-wards displaced (>100 km) allochthons in the hangingwall of the Campo Nappe Complex and the S-charl-Sesvenna Nappe.

8.2.9. Umbrail-Terza Slice Complex

This slice complex consists of two geographically separated parts. The smaller *Terza Slice* forms a simple klippe overlying the westernmost part of the Quattervals Nappe, comprising a slice of Norian to Rhaetian sediments detached from the incompetent Raibl Group (SOMM 1965). The larger *Umbrail-Chavalatsch Slices* further to the east consist of a very complicated zone of imbrication (SCHMID 1973), composed of two lithologically and tectonically separate units: firstly, of slices of Late Triassic sediments of the Raibl and Hauptdolomit groups, which were sheared off their original stratigraphical underpinnings, i.e., the S-charl-Sesvenna Nappe, and secondly, of pre-Mesozoic basement slices that are correlated with the tectonically higher basement of the Ötztal Nappe Complex that tectonically overlies the

S-charl-Sesvenna nappe. Hence, these WNW-facing Umbrail-Chavalatsch Slices are interpreted as a basal imbrication underneath the Ötztal Nappe Complex, which overrode the sediments of the S-charl-Sesvenna Nappe, shearing them from their former stratigraphical base and imbricating them with basement slice pulled out of its base (SCHMID 1973). In the east, this zone of imbrication with the Trupchun-Braulio Thrust at its base completely replaces the Quattervals Nappe and bends around into a NE–SW strike south of Sta. Maria. In the area of Piz Chavalatsch, the zone of imbrication directly overlies the Vinschgau Shear Zone of the Campo Nappe Complex and hence occupies a tectonic position identical to that of the Ötztal Nappe Complex (CONTI 1997).

8.2.10. Ötztal Nappe Complex

In the area of the Tectonic Map of Switzerland, only the western part of the Ötztal Nappe Complex is present. It consists of two lithologically and tectonically distinct units: the Ötztal Nappe forms the main part, and the smaller, overlying Matsch Nappe occurs in the Vinschgau area within the southern area of the nappe complex (SCHMID & HAAS 1989, HABLER et al. 2009). The *Ötztal Nappe* consists mainly of polymetamorphic paragneisses with minor orthogneisses and amphibolites. At its western front, here lacking an Alpine metamorphic overprint, it overthrusts the S-charl-Sesvenna Nappe along the Schlinig Thrust, a discrete fault formed under brittle conditions. FROITZHEIM et al. (1997) claimed extensional overprint during the Late Cretaceous Ducan-Ela phase of what was originally a thrust contact, whereas STUTZ & WALTER (1983) see only compression, and SCHMID & HAAS (1989) interpret the extension leading to spectacular domino structures beneath the Schlinig Thrust as a secondary structure of the Ötztal Nappe overthrust. Southeast of Mals, the base of the Ötztal Nappe Complex is no longer a basal thrust fault, but changes to a broad shear zone (Vinschgau Shear Zone, §8.2.6), due to the eastward increasing grade of metamorphism reaching higher greenschist-facies conditions (SCHMID & HAAS 1989). The Vinschgau Shear Zone consists mainly of rocks of the Campo Nappe Complex, but in its upper part the occurrence and thickness of the Variscan basement belonging to the Ötztal Nappe Complex cannot be defined, because of the close lithological similarities between the basements of the two nappe complexes in the immediate vicinity of the shear zone. The Ötztal Nappe Complex was thrust towards the WNW over the S-charl-Sesvenna Nappe far beyond the present-day location of the Schlinig Thrust and the Vinschgau Shear Zone, as indicated by isolated klippen of Ötztal basement overlying the S-charl-Sesvenna Nappe and the presence of Ötztal basement as part of the Umbrail-Chavalatsch Slices. Peak temperatures of Cretaceous metamorphism, associated with the top-WNW thrusting of the Ötztal Nappe Complex, were reached around 90 Ma ago (THÖNI 1981).

The *Matsch Nappe* differs from the underlying Ötztal Nappe in that it is built up of a characteristic polymetamorphic (Variscan, Permian and Alpine) association of interlayered metapelites, amphibolites and pegmatites (HABLER et al. 2009). Manifestations of Permian metamorphism, associated with the intrusion of pegmatites, are absent in the Ötztal Nappe, and hence thrusting of the Matsch Nappe over the Ötztal Nappe must be of early Alpine age, predating emplacement and metamorphism within the Ötztal Nappe Complex at around 90 Ma.

8.2.11. Tonale Nappe

The largest part of the Tonale Nappe is characterized by a very distinct and lithologically variable association of predominantly sillimanite-bearing paragneisses, marbles, quartzites and amphibolites metamorphosed during the Variscan cycle, referred to as the Tonale Gneiss Complex (formerly "series"). The Tonale Gneiss Complex systematically follows the E–W striking part of the Tonale Fault (Insubric Fault) all the way from Giubiasco (Ticino) beyond the eastern margin of the map area over a distance of 150 km (CORNELIUS & FURLANI-CORNELIUS 1930). In the west, the Tonale Nappe forms a steeply N-dipping narrow strip of mylonitic series that are part of the Southern Steep Belt (or "root zone" north of the Tonale Fault), bounded by the tonalites of the Bregaglia Intrusion to the north and Alpine mylonites and cataclasites of the Tonale Fault in the south (LARDELLI 1981). The mylonitic series of the Tonale Nappe was strongly affected by dextral shearing under ductile and later brittle conditions along the Tonale Fault (FUMASOLI 1974). Between Sondrio and Tirano, the Tonale Nappe represents the hangingwall of the Late Cretaceous Mortirolo Normal Fault (MEIER 2003). Further east, a second Late Cretaceous normal fault, the SE-dipping Pejo Normal Fault, accommodates top-E extension combined with a sinistral strike-slip component in the present-day map view (WERLING 1992, VIOLA et al. 2003). The amount of displacement across the Pejo Normal Fault seems to be substantial since this fault juxtaposes the Tonale Nappe that lacks Alpine metamorphic overprint with the southernmost Campo Nappe Complex that was at least locally metamorphosed under upper greenschist-facies conditions during the Alpine cycle (WERLING 1992).

Near the eastern margin of the map area, the Tonale Nappe additionally comprises a rock association that is lithologically distinct from the Tonale Gneiss Complex; it is referred to as the Ulten (or Ultimo) Unit in the literature (MARTIN et al. 2009). It overlies the Tonale Gneiss Complex along a pre-Alpine tectonic contact. The Ulten Unit is characterized by kyanite-bearing paragneisses and migmatites, containing boudins of amphibolitized eclogites, metagabbros and peridotites. After a high-pressure event of unknown age, the Ulten Unit was exhumed to a lower crustal depth of around 30 km between Devonian and Carboniferous times, associated with trondhjemitic intrusions and related migmatization; it then slowly cooled during Permian to Jurassic times (DEL MORO et al. 1999). Its thermal history, as well as its original location in the lower crust within the Variscan orogen, are reminiscent of the Ivrea Zone of the South Alpine domain. A direct correlation of the Ivrea Zone located south of the Tonale Fault with the Ulten Unit north of this fault suggests a dextral offset across the Tonale Fault by some 150 km (LAUBSCHER 1991) that largely occurred during the Oligocene (STIPP et al. 2004). This dextral offset is compatible with the kinematic analysis of mylonites accompanying the Tonale Fault east of the Bregaglia Intrusion, characterized by a subhorizontal stretching lineation and indicating dextral shear (SCHMID et al. 1989, WERLING 1992, STIPP et al. 2004).

9. SOUTH ALPINE

D. Bernoulli, V. Picotti & R. Fantoni

Deep seismic surveys by the Swiss National Science Foundation (NRP 20, PFIFFNER et al. 1997a) show, along a transect through the Central Alps, that a wedge of Adriatic lower and upper crust is indented into the European crust. South of the Tonale Fault, which divides the Southern from the Central Alps, the top of the Adriatic crust appears to occur at a depth of 14 km near Chiasso, plunging with a shallow dip towards the Alps. A horizontal layered interval between 12 and 14 km is interpreted as the autochthonous sedimentary cover of the basement. This interval underlies a package of less reflective strata interpreted as detached and folded South Alpine basement and sediments, which form a number of thrust sheets filling the large volume between the autochthonous sedimentary cover and the surface.

The South Alpine tectonic domain exposes a complete section of the Adriatic continental crust from ultramafic (slices of uppermost continental mantle lithosphere), mafic and felsic granulite-facies rocks (lower continental crust: Ivrea Zone) through medium- and low-grade basement rocks (middle – upper continental crust: Strona-Ceneri and Val Colla zones, basement of the Orobic units) to unconformably overlying non-metamorphic Late Carboniferous sediments that were involved in post-Variscan folding (GRAETER 1951, REINHARD 1964).

The South Alpine continental crust is a polymetamorphic collage preserving the signatures of different Precambrian and Paleozoic orogenic events (HANDY et al. 1999, ZURBRIGGEN et al. 1997, FRANZ & ROMER 2007 and ref. therein) and of post-Variscan, Early Permian extension (BRODIE & RUTTER 1987), magmatic underplating in the lower crust accompanied by high-temperature metamorphism and anatexis in the lower crust (RIVALENTI et al. 1975, 1984, QUICK et al. 1994), magmatism in the upper crust and subaerial volcanism (QUICK et al. 2009).

The metamorphic grade of the rocks underlying the Late Carboniferous unconformity increases from deep burial diagenesis in the Carnic Alps in the east, to amphibolite facies west of Lugano (SCHALTEGGER & BRACK 2007 and ref. therein). Exhumation of the amphibolite-facies Variscan metamorphic rocks to the surface must therefore predate the Permian magmatic and metamorphic events. After the Variscan collision, the middle to upper crust cooled below 500–350 °C (MCDOUGALL & HARRISON 1999) in the Late Carboniferous (BORIANI & VILLA 1997, FEIJT 2002), before being affected by the Permian igneous activity and granulite-facies metamorphism in the lower crust of the Ivrea Zone (e.g., VAVRA et al. 1996).

At the end of the Variscan orogeny, the crustal thickness appears to have equilibrated to normal crustal thickness (ca. 30 km; SCHMID 1993) before crustal thinning during the Mesozoic continental margin evolution. The combined effects of Permian transtension, Triassic extension and Jurassic rifting reduced the thickness of the crust to about 15 km before the onset of the Alpine orogeny.

The detached Variscan continental crust and its overlying Permian to Miocene sedimentary cover form a fold-and-thrust belt, the southern back-chain of the Alps defined as the South Alpine tectonic domain. This S-vergent back-chain is separated from the other domains of the Western and Central Alps to the west by the Canavese Fault and to the north by the Tonale Fault (see § 10.1). Both faults are part of an Oligocene–Miocene post-collisional system of transpressive transfer faults along the northwestern boundary of the Adriatic indenter. In the Ticino transect, the Central Alps have been uplifted by some 15 km with respect to the Southern Alps along this fault system (HURFORD 1986). In the east, the western sector of the South Alpine domain (Piemonte and Lombardia) is separated from the eastern one (Trentino–Veneto) by the southern branch of the Giudicarie Fault.

To the south, the Late Miocene (Messinian) to Quaternary deposits of the Po Plain unconformably cover the most external and youngest South Alpine thrust sheets (Milan Belt). During Mesozoic extension and Alpine orogeny, the rocks of the Variscan basement underwent high anchizone (sub-greenschist) to lower greenschist-facies metamorphism (CRESPI et al. 1982, SPALLA & GOSSO 1999, SPALLA et al. 1999), and the deformation occurred mainly under brittle conditions.

During the Early Mesozoic continental rifting, preceding the opening of the Middle–Late Jurassic Alpine Tethys, the crust of the evolving Adriatic continental margin was segmented by N–S trending extensional faults with throws of up to several kilometers (BERNOULLI 1964, BERTOTTI et al. 1993, BERRA et al. 2009). During the Alpine orogeny, the extensional faults evolved into transfer zones between the different segments, defining blocks with different depths to basement and separated by oblique ramps (SCHÖNBORN 1992, PICOTTI et al. 1995, SCHUMACHER et al. 1997). However, the minimum overall Alpine shortening west of the Giudicarie Zone remains more or less constant, estimated at around 60–70 km (based on the interpretation of new subsurface data), in contrast to previous estimates of about 100 km (LAUBSCHER 1988, SCHÖNBORN 1992, SCHUMACHER et al. 1997).

Because transfer zones cut across important decollement levels, the structural evolution changes abruptly across them. The individual thrust systems are defined by different decollement horizons and oblique ramps, both constrained by the geometry of the pre-existing Mesozoic faults and the local stratigraphy. Between the Lago di Como and the Giudicarie Fault, a number of incompetent Triassic and Early Cretaceous formations formed decollement horizons in the evolution of the ramp-flat systems of the major thrust sheets (LAUBSCHER 1985, ROEDER 1992, SCHÖNBORN 1992, PICOTTI et al. 1995, SCHUMACHER et al. 1997, FANTONI & FRANCIOSI 2010, ZANCHETTA et al. 2015). In contrast, west of the Lugano Fault, the sediments are in general autochthonous with respect to their original crustal basement.

To the west, the thin-skinned Orobic thrust units of the Bergamasc Alps laterally give way to thick-skinned allochthonous units in the western South Alpine domain, including the Ivrea-Ceneri Complex. This fundamental change from thin- to thick-skinned deformation is likely associated with the greater depth of the basement east of the Lugano – Monte Grona – Val Grande fault system. This major Mesozoic normal fault is subdivided into three segments: 1) the N–S trending Lugano Fault extends at least from Mendrisio northwards to northeast of Lugano, 2) the W–E oriented Monte Grona Fault extends from northeast of Lugano to Lago di Como and was reactivated as an alpine backthrust (N-directed), 3) the SW–NE oriented Val Grande Fault extends from Lago di Como eastwards at least up to M. Legnone. SCARAMUZZO et al. (2022) speculate that the change from thick-skinned to thin-skinned units might coincide with a change from N-directed thrusting in the northwest to S-directed thin-skinned thrusting in the east; however, the evidence for this is rather fragmentary.

A clear definition of the different thrust sheets west of the Lago di Como is difficult, as the thin-skinned thrust sheets of the Bergamasc Alps cannot be extrapolated to the west. West of the Lecco Fault (below the southeastern branch of Lago di Como) the evolution of the thrust systems is strongly influenced by the large difference in the depth of the Variscan basement compared to the Bergamasc Alps. This difference results from the pronounced offsets of pre-existing Mesozoic faults (forerunners of the Lugano and Lago Maggiore faults) with a cumulative throw of several kilometers. In addition, the situation is complicated by the interferences of early structures (Cretaceous or at least pre-Middle Eocene) in the Orobic units with later structures linked to Tonale Fault activity and final exhumation of the Ivrea-Ceneri Complex during Oligocene – Miocene times.

The contrasting structural style west and east of the Lugano – Como sector becomes evident by comparing the western and the eastern cross-sections (Pl. II) that were extended to the Po Plain in order to illustrate the subsurface structures of the tip of the Southern Alps. The western cross-section shows the crust of the Ivrea-Ceneri Complex, obducted along thrusts involving the entire South Alpine crust and part of the subcontinental mantle. The overall geometry could be interpreted as an asymmetric flower structure, related to the transpressive movements along the Tonale-Canavese fault system. Along the basal thrust, the South Alpine basement is overthrusting a reduced Mesozoic to Eocene sequence and the thick clastic Oligocene–Miocene sequence of the Gonfolite Lombarda Group for a distance of about 10 to 12 km. The Miocene southern foreland deposits are onlapping onto the allochthonous basement units above an intra-Burdigalian unconformity (ROURE et al. 1990). To the south, crust and overlying sediments are involved in the most external thrusts of the Apennines (Sali Vercellese and Monferrato) that also involve the unconformable, post-orogenic Messinian to Pleistocene undeformed deposits along the South Alpine border.

The eastern cross-section shows the structural style of the Southern Alps, which is dramatically different from that of the area west of the Lugano Fault. The crust is of normal thickness and is flexed towards the north under the Central Alps (SCHMID et al. 1996). In this sector, the depth of the Moho is at about 40 km below the Tonale Fault (e.g., BRAGATO et al. 2011). Based on geometrical reconstructions derived from the available surface data and scarce subsurface data, LAUBSCHER (1985, 1988) and SCHÖNBORN (1992) constructed balanced cross-sections defining four major thrust sheets (nappes); however, new surface and subsurface data indicate the presence of a complex stack of thrust sheets of limited lateral extent.

Alpine deformation proceeded from north to south. The uppermost and oldest thrust sheets, the Upper Orobic Nappe, consists of an around 5 to 7 km thick basement sheet, arranged in a series of en-échelon anticlines, first interpreted by LAUBSCHER (1985) as ramp anticlines. The thrusts associated with the Upper Orobic Nappe ramped into the sedimentary cover, creating several duplexes that occur in a belt of klippen. The distribution of these erosional remnants reflects the later deformation by the basement ramps of the underlying younger local thrust sheets and imbricates, namely the Lower Orobic Imbricates. The en-échelon arrangement of the ramp anticlines in the Lower Orobic Imbricates is similar to that of the Upper Orobic Nappe with a more diffused deformation in the sedimentary cover. A large part of the Bergamasc Alps and of the Giudicarie region belongs to this unit. The southernmost and lowest thrust system is called the Milan Belt; its basement ramps are hidden below the Po Plain like most of the deformed sedimentary cover (FANTONI et al. 1999). The Milan Belt consists of thrust imbricates, locally inverting Mesozoic high-angle faults, developed as a frontal accretion of the western South Alpine domain during the Miocene. East of Lago di Garda, units equivalent to the Milan Belt crop out extensively along the External Giudicarie Zone.

The age of deformation in the South Alpine units is still not fully understood. Direct evidence for Late Cretaceous deformation in the Upper Orobic Nappe is limited (Ar/Ar ages of pseudotachylites, ZANCHETTA et al. 2011). Flysch sediments, containing lithoclasts of older formations including Variscan basement clasts, could suggest Cretaceous movements in the future South Alpine tectonic domain (e.g., CASTELLARIN 1972). However, the source area of these sediments is uncertain, probably situated within the Cretaceous orogen of the Eastern Alps; it is unclear how Cretaceous orogeny affected the future Lombardian Alps. In the Giudicarie area, a minor Late Cretaceous transpressional reactivation of Jurassic normal faults was suggested by DOGLIONI & BOSELLINI (1987), and documented by PICOTTI et al. (1998). Inversion of Jurassic rift faults could be responsible for the unconformities described in the Upper Cretaceous sediments of the central South Alpine domain by BERSEZIO et al. (1993) and FANTONI et al. (2004) in the subsurface of the Po Plain.

Pre-Middle Eocene deformation is well documented in the Upper Orobic Nappe, near the Tonale Fault, and in the Lower Orobic Imbricates, where the Adamello Batholith clearly cuts across the thrust sheets of both units (BRACK 1981). Volcanic dykes, dated at 50 Ma, also cut across some thrust planes of the Upper Orobic Nappe in the Presolana area, north of the Lago d'Iseo (ZANCHI et al. 1990, ZANCHETTA et al. 2015), as well as of the Lower Orobic Imbricates, west of the Lago d'Iseo (D'ADDA et al. 2011). In the Lower Orobic Imbricates, the Adamello Batholith intruded already deformed sedimentary rocks (BRACK 1981); however, the Adamello Batholith must have been separated from its underpinnings by the thrusts along the Val Trompia and Giudicarie faults (PICOTTI et al. 1995, VERWATER et al. 2021). Consequently, pre- and post-Adamello shortening must have affected these units. Along the Tonale Fault, transpressive movements of Late Oligocene to Early Miocene overprinted the older structures (SCHUMACHER et al. 1997, PROSSER 1998, VERWATER et al. 2021).

The Oligocene–Miocene Gonfolite Lombarda Group represents a deep-water clastic wedge deposited during the post-collisional growth of the South Alpine fold-and-thrust belt. In the area south of Como–Chiasso–Varese, these late synorogenic sediments, belonging to the Milan Belt, are thrust to the north over the Lower Orobic Imbricates along the Monte Olimpino Backthrust during the latest phases of deformation of the latter unit (BERNOULLI et al. 1989). Unconformities within the Gonfolite Lombarda Group and reworking of older sediments indicate that the Neogene South Alpine thrust-and-fold belt grew during deposition of the Gonfolite Lombarda Group (BERNOULLI et al. 2018). Apatite fission tracks are completely or partially annealed in detrital apatites in Oligocene sediments, whereas the Miocene sediments show no annealing of the apatite fission tracks (WAGNER 1988, GIGER 1991, BERNOULLI et al. 1993), indicating that the lower part of the Gonfolite Lombarda has been exhumed along the Monte Olimpino Backthrust from a depth of more than 3 km. Sediments as young as Serravallian are involved in folding and thrusting at the foothills of this region (TREMOLADA et al. 2010).

Below the Po Plain, thrusts and folds of the Milan Belt involve the Miocene formations up to the Tortonian (PIERI & GROPPI 1981). Deformation of the External Giudicarie Zone proceeded throughout the Middle to Late Miocene and, in the Lower Orobic Imbricates, out-of-sequence thrusts cut along pre-existing folds and thrusts (e.g., "Flessura frontale"). In the Late Miocene, large-scale thrusting and folding ceased in the western South Alpine domain. The Miocene structures of the Milan Belt are sealed by Messinian to Quaternary continental and marine deposits, the base of which represents the regional Messinian unconformity (FANTONI et al. 2004). These deposits form a wedge that thickens towards the south and represents the tip of the Apennines Foreland Basin.

9.1. Canavese Zone

The Canavese Zone consists of individual slivers of basement and Mesozoic sedimentary cover rocks trapped along the Internal and the External Canavese faults between the Ivrea-Ceneri Complex in the southeast and the Sesia Nappe in the northwest, dismembered by Alpine shear zones and brittle faults. It extends from the area west of Ivrea (south of the map border) to Locarno where it is truncated by a fault that links the Centovalli Fault to the Tonale Fault. It includes migmatitic and leucogranitic basement rocks with inclusions of mafic granulites similar to those of the Ivrea Zone, and amphibolite-facies basement rocks with granitic intrusions similar to those of the Strona-Ceneri Zone. The lower and upper crustal and sparse mantle rocks were presumably juxtaposed along one or more Mesozoic detachment faults. The Mesozoic sedimentary cover can be compared to that of the Lower Austroalpine Err Nappe Complex in Graubünden and is interpreted as part of the distal Adriatic margin (FERRANDO et al. 2004). Alpine metamorphism is of prehnite-pumpellyite-actinolite facies (anchizone to weak epizone). Northeast of the Canavese area, i.e., over a large part of their map extent, basement and sediments of the Canavese Zone are intensely mylonitized and part of the Insubric greenschist-facies mylonite belt separating the Sesia Nappe from the Ivrea-Ceneri Complex.

9.2. Ivrea-Ceneri Complex

In the area west of Lago di Lugano, pre-Alpine depth to basement of the top of the Mesozoic succession was much smaller than to the east in the Bergamasc Alps, and no major decollement horizons were present in the Mesozoic sedimentary succession leading to Alpine ramp-flat thrust geometries as observed in the Bergamasc Alps. West of Lago Maggiore, the pre-Alpine basement forms one thick-skinned, allochthonous unit (see Pl. II, western cross-section; ROURE et al. 1990), that was involved in Alpine thrusting and folding. In addition, the Mesozoic faults largely influenced Alpine deformation within the basement and the sedimentary cover. The larger faults soled in the Variscan basement delineate different compartments within the thick-skinned Ivrea-Ceneri basement.

The Alpine-tectonic Ivrea-Ceneri Complex includes the lower crustal rocks of the Ivrea Zone and the WNW part of the middle–upper crustal Strona-Ceneri Zone. In the northwest, the Ivrea-Ceneri Complex is separated from the Canavese Zone by the Internal Canavese Fault, east of Locarno from the Central Alps by the Tonale Fault. In the east and southeast, the transition to the Upper Orobic Nappe is not clearly defined. The boundary can be traced along the Tamaro Thrust (BÄCHLIN 1937) and the Lago Maggiore Fault. In the south, west of Lago Maggiore, the Ivrea-Ceneri Complex with its Mesozoic cover is overlain by the post-orogenic deposits of the Po Plain.

The rocks of the Ivrea Zone are characterized by a steeply dipping main foliation and compositional banding, deformed during the Alpine orogeny by flexural slip-folding, which produced major antiforms south of the Canavese Fault. Alpine deformation occurred under greenschist-facies conditions, presumably synchronous with transpressional movements along the Tonale Fault in the Oligocene–Miocene (SCHMID 1993).

The middle to upper crust of the Variscan Strona-Ceneri Zone includes: 1) a complex of para- and orthogneisses including high-grade metasediments, banded amphibolites and eclogites interpreted as the relics of a Neoproterozoic or Early Paleozoic accretionary complex (SCHMID 1993, ZURBRIGGEN et al. 1997, HANDY et al. 1999), 2) the overprinted remains of an Ordovician orogeny (462–450 Ma), including a magmatic arc or fore-arc (FRANZ & ROMER 2007, ZURBRIGGEN 2020), 3) a younger, Variscan (Early Carboniferous?) accretionary complex containing metasediments and relics of oceanic crust. The Variscan Strona-Ceneri Zone is intruded by Permian granites and overlain by Permian volcanics and a thin sequence of Triassic to Early Jurassic sediments (BERRA et al. 2009). Adjacent to the Ivrea Zone, the rocks of the Strona-Ceneri Zone are overprinted by the Permian high-temperature metamorphism. During Mesozoic rifting, low-angle detachment along the Pogallo Fault separated the lower crustal Ivrea rocks from the middle–upper crustal Strona-Ceneri basement (HANDY 1987).

The Ivrea Zone is separated from the Strona-Ceneri Zone by the Cossato-Mergozzo-Brissago Fault (CMB) that is interpreted as a Permian fault zone due to its association with Permian granites (BORIANI et al. 2016). This fault is cut by the Pogallo Fault.

South of the Lago d'Orta, the major WSW–ENE trending Cremosina Fault cuts the Ivrea-Ceneri Complex. Early Jurassic sediments are trapped along it. This fault is most probably cut by the Lago Maggiore Fault. There is an apparent sinistral horizontal offset along the Cremosina Fault, displacing the lower crustal rocks of the Ivrea Zone by about 15 km. A vertical component is suggested by different crustal sections of the Strona-Ceneri Zone, yielding granitic intrusions to the north and the Permian surface overlain by volcanics to the south.

The Lago Maggiore Fault was originally an Early Mesozoic rift fault that separated the Early Jurassic Monte Nudo Basin in the east from the Gozzano High in the west. The Lago Maggiore Fault extends largely below the lake, but in the south, it runs onshore between the Permian volcanics of the Ivrea-Ceneri Complex, overlain by Middle Triassic dolomites, and the Cretaceous – Cenozoic sediments of the Varesotto Imbricates. To the north, the Lago Maggiore Fault probably follows the lake towards the northeast, possibly reflecting the original listric geometry of the Mesozoic precursor fault.

9.3. Upper Orobic Nappe

The Upper Orobic Nappe can be followed from the Bergamasc Alps across Lago di Como to the area north of Lugano (BERTOTTI 1991, REAL et al. 2018). However, there is no clear-cut Alpine-tectonic boundary in the basement northwest and west of Lugano. Indications suggest that the change from thin-skinned thrust sheets in the east (see Pl. II, eastern cross-section) to thick-skinned ones to the west (see western cross-section) occurs over a broad zone, probably defined by pre-Alpine faults. Because the surface of the Variscan basement was much higher in the area west of the Mesozoic Lugano Fault, the basement involved in thrusting appears to be much thicker west of Lugano than in the east and the tectonic style changes drastically.

To the north, the Upper Orobic Nappe is limited by the Tonale Fault, along which slivers of Triassic dolomites occur, possibly relics of Mesozoic extensional allochthons (REAL et al. 2018). East of Lugano, backthrust sediments of the Lower Orobic Imbricates mark the southern boundary of the nappe (BERTOTTI 1991). West of Lugano, the steeply dipping Permian volcanics and Triassic dolomites along the Tresa Valley mark the boundary with the Varesotto Imbricates (BERNOULLI et al. 1976). The contact may be tentatively interpreted as a verticalized thrust or, along a segment northwest of M. Caslano, as a transfer fault. The steeply dipping “Schlingen”-structures of the basement are dissected by a network of S-vergent thrusts connected by transfer faults (REINHARD 1964, SCHUMACHER 1997). The occurrence of small relics of non-metamorphic Permian cover rocks along these faults indicates a post-Variscan age for these structures.

West of Lago di Como, the basement of the Upper Orobic Nappe consists of the Variscan Val Colla Zone and the part of the Variscan Strona-Ceneri Zone that would not belong to the Alpine Ivrea-Ceneri Complex (see §9.2). The Strona-Ceneri and Val Colla zones are separated by the Late Variscan Val Colla Fault (REINHARD 1964), a mylonitic fault zone sealed at M. Caslano, west of Lugano, by unconformably overlying Permian volcanics (GRAETER 1951). In the northeast, the Val Colla Fault is cut by Alpine faults and interrupted by the Tonale Fault (REINHARD 1964). East of Lago di Como, the Val Colla Zone passes laterally into the basement of the Upper Orobic Nappe (REAL et al. 2018). The Val Colla Zone consists mainly of paragneisses, hornblende-epidote schists and metagranites. These Variscan, originally amphibolite-facies metamorphic rocks, were retrogressed to the greenschist facies, possibly during Mesozoic rifting and associated exhumation of the basement rocks (REAL et al. 2018 and ref. therein).

East of Lago di Como, the Upper Orobic Nappe forms the roof of the present-day structural edifice of the South Alpine units. The widely outcropping basement consists of a metasedimentary Paleozoic succession including phyllites, micaschists and paragneisses, intruded by Ordovician granitoids, at present orthogneisses. These Variscan metamorphic rocks are intruded by Late Variscan diorites and tonalites. Alpine deformation of this basement is recorded by crenulation of the Variscan foliation, whereas, in the core of basement synclines, folds of meters to hundreds of meters in width involve locally the Early Permian sediments (northern Valle Seriana). This structural belt consists of an array of regionally complex anticlines, with a dextral en-échelon arrangement, including fold systems associated with kilometer-scale thrusts (DE SITTER & DE SITTER-KOOMANS 1949). These structures were presumably controlled by the original geometry of the Early Permian Collio Basin. The main axial-plane Alpine foliation is regionally persistent and steeply NNW-dipping; it is postdated by a less pronounced foliation, which is linked to the development of shear planes with a top-S sense of shear. The southern limbs of the anticlines show an almost regular southward dip of the Permian to Early Triassic formations, which plunge below the Middle–Late Triassic succession. This thrust contact is generally hidden by Quaternary deposits; in limited exposures it is highlighted by some stretched Anisian dolomitic-evaporitic rocks and/or by tectonic elision of part of the stratigraphic succession. This contact between the basement anticlines and the deformed Triassic units has been interpreted as the expression of wedging of the Permian sediments – which were extruded during Alpine inversion of the Collio Basin – within the Early Triassic fine-grained clastics and evaporites. South of this wedging structure, large duplications in the Triassic carbonates are typical for the Upper Orobic Nappe. They are preserved from erosion in a large synform, created by the underlying basement ramp anticline of the Lower Orobic Imbricates.

The eastern Upper Orobic main thrust, called Gallinera Thrust (DE SITTER & DE SITTER-KOOMANS 1949) marks a change in the regional strike of the thrust, from E–W to NE–SW, likely due to the presence of a sinistral transfer zone towards the Giudicarie Fault. Since the Gallinera Thrust is clearly cut off by the Adamello Batholith, this sinistral transfer zone could, at least in part, be pre-Adamello in age.

9.4. Varesotto Imbricates

The Mesozoic Lugano – Monte Grona – Val Grande fault system coincides with the change from thin-skinned to thick-skinned deformation in the South Alpine domain. In the absence of sedimentary decollement horizons, no ramp-flat geometries developed within the sedimentary formations; the Permian volcanics and Mesozoic sediments are autochthonous with respect to their crystalline basement. No plausible correlation with the tectonic units of the central South Alpine domain across the Lugano Fault is possible. The tectonic units below and in front of the Upper Orobic Nappe are called Varesotto Imbricates, in analogy to the Lower Orobic Imbricates. Between the Lago Maggiore and the Lugano Fault, Permian WSW–ENE trending transtensional and Early Mesozoic N–S trending extensional structures are reflected by rapid lateral changes in thickness and facies of cover successions (Bernoulli 1964, Kälin & Trümpy 1977). The Variscan basement of the Varesotto Imbricates is unconformably overlain by Permian volcanics and Mesozoic sediments.

The WSW–ENE trending Arbostora Anticline occupies the southern part of the Varesotto Imbricates and is separated to the north, by the Marzio Fault, from a complex syncline of imbricated Mesozoic sediments. West of a complex transfer zone, thrusts are N-vergent, east of it S-vergent. With the Early Jurassic syn-rift sediments increasing towards the Monte Nudo Basin, the Arbostora Anticline plunges axially to the WSW and the Early Jurassic basinal sediments appear to form a N-vergent drape over the Marzio Fault (Schumacher 1997). The southern flank of the Arbostora Anticline disappears below the Monte Olimpino Backthrust, along which the Gonfolite Lombarda Group of the Milan Belt overthrusts the Varesotto Imbricates, forming a subsurface triangle zone (Bernoulli et al. 1989). The small imbricates of Mesozoic sediments to the south of the Arbostora Anticline, near Stabio, are interpreted as splays at the base of the Milan Belt in this triangle zone (Bernoulli et al. 2017, 2018).

The occurrence of an extensive allochthonous unit below the Arbostora Anticline is confirmed by an unpublished reflection seismic profile across the Monte San Giorgio area. The line shows, below the Arbostora Anticline, between 800 and 1800 m a N-dipping layered sedimentary sequence overlying a zone of indistinct basement reflections (Bernoulli et al. 2018, Pl. III).

9.5. Lower Orobic Imbricates (incl. Internal Giudicarie Zone)

The Lower Orobic Imbricates, underlying the Upper Orobic Nappe, can be followed from the Lago di Garda, in the east, up to the Lugano Fault in the area of Monte Generoso, in the west. The westernmost part of the Lower Orobic Imbricates is separated from the Upper Orobic Nappe by the Lugano – Monte Grona fault system, a reactivated Mesozoic normal fault separating the Lugano High from the Generoso Basin (see p. 102). During the Alpine orogeny, the pre-existing fault acted mainly as a transcurrent fault: sinistral in the north, east of Lugano, and merging with the northward Monte Grona Backthrust (Bertotti 1991), placing the Lower Orobic Imbricates atop the Upper Orobic Nappe; dextral in the south, near Mendrisio (Bernoulli et al. 2018). South of Mendrisio, the continuation of the Lugano Fault is lost within the tightly folded Late Cretaceous flysch. The Lugano Fault does not affect the Monte Olimpino Backthrust of the Milan Belt, and is therefore older. To the east, the sediments of the former Generoso Basin are separated from the Upper Orobic Nappe of the Bergamasc Alps by the NW–SE trending Lecco Fault, probably a reactivated Mesozoic fault (BERTOTTI 1991, SCHUMACHER et al. 1997). However, in the southeast, a link with the Lower Orobic Imbricates of the Bergamasc Alps exists (SCHUMACHER et al. 1997).

To the south, the Mesozoic sediments of the Generoso Basin plunge along a flexure ("Flessura frontale") under the younger sediments of the Late Cretaceous Lombardian Flysch and its Paleogene cover. The morphologically prominent "Flessura frontale" is a blind thrust that appears to be kinematically linked to the younger deformation of the underlying Milan Belt. Internally, the sedimentary rocks of the Generoso Basin are detached along the Carnian evaporites forming a number of folds and S-vergent thrusts (BERNOULLI et al. 2018; Pl. II, eastern cross-section). The younger, Cretaceous and Paleogene sediments, outcropping south of the "Flessura frontale", are tightly folded into S-vergent chevron folds and thrust to the south suggesting decollement in Aptian–Albian layers at depth, probably along a blind thrust.

In the northern Bergamasc Alps, the Lower Orobic Imbricates consists of basement units associated with Early Permian deposits of the Collio Basin, whereas the Middle Triassic and younger deposits are detached along the Anisian cargneule and stacked towards the south. These imbricates form large-wavelength anticlines, interpreted as ramp structures by LAUBSCHER (1985, 1988, SCHÖNBORN 1992). The three anticlines, from west to east named Orobic, Trabuchello and Cedegolo, show a clear en-échelon pattern, suggesting the occurrence of separate thrust imbricates, 20 to 30 km wide, linked at depth with the right-lateral Tonale Fault.

In the southern Bergamasc Alps, the structural style is thin-skinned, with Late Triassic and Jurassic units thrust and deformed to form the "Flessura frontale" against the tightly folded Cretaceous to Paleogene deposits to the South. The original definition of this structure refers to a W–E to WNW–ESE trending alignment of knee-folds and fault-propagation faults that define a morphological border of the higher mountains to the foothills between Lago di Como and Lago d'Iseo (DESIO 1929). The fold belt is accompanied by steeply dipping thrusts, along which the Rhaetian to Jurassic formations are thrust onto the Cretaceous strata, with a regional WNW–ESE trend. Deviations from this trend follow N–S oblique-slip transfer faults controlled by pre-existing normal faults associated with the Jurassic basin margins. In the Lecco area, the structures associated with the "Flessura frontale" cut across older thrusts and folds of the adjacent tectonic units (SCHÖNBORN 1992, FANTONI et al. 1999). The "Flessura frontale" is interpreted as a belt of out-of-sequence deformation cutting across the Neogene structures of the Lower Orobic Imbricates to the south (FANTONI et al. 2004).

South of the "Flessura frontale", and outside the Tectonic Map of Switzerland, a border belt includes, at the surface, mainly syn-orogenic Late Cretaceous flysch successions and Maastrichtian to Late Eocene redeposited deep-water carbonate sediments, detached from their substratum along the incompetent Aptian–Albian layers (FANTONI et al. 2004, FANTONI & FRANCIOSI 2010, SCIUNNACH et al. 2023). The prevailing structures are paired synclines–anticlines, some kilometers along strike, with a WNW–ESE trend and a left en-échelon arrangement.

The *Giudicarie Zone* is a NNE–SSW trending Cenozoic sinistral transfer zone displacing the Tonale Fault to the north (Pustertal Line), kinematically linked with the post-nappe folding of the Tauern Window and the eastward lateral escape of the Eastern Alps (LAUBSCHER 1991). This zone is structurally divided into an internal part, kinematically linked to the Lower Orobic Imbricates, and an external part, linked to the Milan Belt. The Giudicarie Zone is bounded to the west by the Giudicarie Fault (see § 10.1). Along the northern segment of this fault, the Giudicarie Zone is juxtaposed against the Austroalpine nappes (just at the eastern edge and outside the Tectonic Map of Switzerland). The southern segment separates the Internal Giudicarie Zone from the (older) Middle Eocene to Early Oligocene Adamello Batholith and the Val Trompia Unit that is a Lower Orobic imbricate in the Bergamasc Alps. To the southwest, the Internal Giudicarie Zone is kinematically linked to the Val Trompia Thrust. Within the Giudicarie Zone, strain partitioning between strike-slip and thrust faults resulted in around N–S trending transfer faults connecting ESE- and S-directed thrusts involving the crystalline basement (PICOTTI et al. 1995, VERWATER et al. 2021). The N–S trending transfer faults are often reactivated and inverted Mesozoic extensional faults. An important one, north of Lago di Garda (Ballino Fault), coincides with the facies change between the Mesozoic Lombardian Basin and the Trento Plateau (CASTELLARIN 1972). The thrusts in the Internal Giudicarie Zone, west of the Ballino Fault, represent the up-section propagation of the structures forming the ramp anticline of the Val Trompia and south Giudicarie, involving basement, sedimentary cover and, at depth, the underpinnings of the Adamello Batholith. The only fragment of basement east of the Giudicarie Fault in the area of the map occurs along the Sabion Fault, a small ramp anticline probably reactivating a Permian–Mesozoic structural high. The structures in the Internal Giudicarie Zone consist of short NE–SW oriented frontal ramp anticlines, connected by long, N–NE oriented lateral ramps and synclines, often reactivating Mesozoic normal faults (TREVISAN 1938). Some E–W strike-slip faults occur west of Riva del Garda. They appear to be the continuation of the Val Trompia Thrust during its final dextral reactivation in the Late Miocene.

N–S to NW–SE shortening in the southern sector of the Internal Giudicarie Zone is estimated at some 18 km for the Late Oligocene to Early Miocene, and about 12–22 km for the Middle–Late Miocene (VERWATER et al. 2021). Early Miocene sediments are involved in the deformation of the Giudicarie Zone (LUCIANI

1989); thermochronological evidence suggests deformation between 15 and 8 Ma (VERWATER et al. 2021 and ref. therein). Like in the Milan Belt, a Messinian unconformity forms the youngest age bracket for deformation (PICOTTI et al. 1997).

9.6. Milan Belt (incl. External Giudicarie Zone)

Almost the entire subsurface area of the hilly landscape and of the entire Po Plain, south of the Southern Alps (outside of the Tectonic map), is occupied by tectonic units rooted in the Southern Alps or the Northern Apennines. Along the front of the South Alpine units, the buried folds and thrusts are unconformably overlain by post-orogenic Messinian to Quaternary sediments. Along the Apennines, these sediments are involved in N-directed thrusts (see Pl. II, western cross-section) that locally cut across older South Alpine thrusts.

The structural units of the Milan Belt (LAUBSCHER 1985; Lombardic Nappe of SCHÖNBORN 1992), that kinematically links up with the External Giudicarie Zone, occupy large areas in the subsurface of the Po Plain (FANTONI et al. 1999, 2004). In the southwest, the allochthonous sediments of the Oligocene–Miocene Gonfolite Lombarda Group, emplaced during the Late Miocene along the Monte Olimpino Backthrust (BERNOULLI et al. 1989), are interpreted as part of the Milan Belt. To the south, in the subsurface of the Po Plain, the Monte Olimpino Backthrust, together with the S-vergent Villafortuna Thrust, forms a broad syncline (FANTONI & FRANCIOSI 2010). In the east, the Milan Belt connects with the external thrusts between Lago di Garda and Adige; these thrusts are the surface propagation structures of a deep basement ramp, passively folding and uplifting the Internal Giudicarie Zone (PICOTTI et al. 1995).

Below the Milan Belt, in central Lombardia, the top of the Adriatic basement is found at about 10 km depth and plunges gently below the South Alpine units (see Pl. II, eastern cross-section). The overlying, slightly deformed Mesozoic carbonate successions are overlain by a strongly imbricated stack of Cenozoic clastic sediments, soled by a decollement running along the top of the pelagic/hemipelagic Cretaceous to Middle Eocene succession.

In the middle sector of the Po Plain of Lombardia, the Mesozoic carbonates are deformed by regional folds related to the propagation of deep thrust faults ramping up from the Variscan basement (see Pl. II, eastern cross-section). These younger faults deform the sole thrust below the imbricated Cenozoic units. South of this belt, the Cenozoic clastic succession is deformed together with the underlying Mesozoic; the shortening is estimated to be only a few kilometers. Below the central and southern Po Plain, at the tip of thrusts, gentle anticlines formed within the Cenozoic clastic wedges. These folds are offset by the northward propagation of the younger external front of the Apenninic thrusts.

In the southwestern foreland area, structures inverting the syn-rift Mesozoic basins are preserved. Reactivation of the pre-existing normal faults led to the inversion of the throw of the faults and to uplift of the now compressive structures during shortening.

In the Milan Belt beneath the Po Plain, the South Alpine structures became inactive by the end of the Messinian, similar to the adjacent Piemonte area to the west (FANTONI et al. 2002). In the entire western sector of the Po Plain of Piemonte and Lombardia, deformation was essentially synchronous, even if the style of deformation differs from place to place, and came to an end during the Messinian. Since the latest Messinian, the evolution of the South Alpine foreland has been controlled mostly by isostatic uplift of the axial zone and by the flexural response of the foreland to the tectonic load of the Apennines, resulting in a 5–6° southward dip of the Pliocene–Quaternary monocline (PICOTTI et al. 1997).

10. MAJOR FAULTS

S.M. Schmid

This chapter contains a brief description of the most important late Alpine (Oligocene or younger) large-scale faults. Note that these faults, in many cases actually fault zones that can be of km-scale width, were traditionally referred to as "lines" in the literature.

10.1. Periadriatic Fault System: Canavese Fault, Tonale Fault and Giudicarie Fault

The Periadriatic Fault System is a complex lineament stretching from Hungary in the east, through Slovenia, Austria and Italy, to western Piemonte. This fault system marks a major tectonic boundary between the Southern Alps and the main body of the Alps to the north. The deformation style changes fundamentally on both sides: the Southern Alps are characterized by relatively minor Alpine metamorphism and displacement (S-vergent thrusting and folding) of the South Alpine basement and its sedimentary cover, whereas the rest of the Alps is built up by a NW- to N-vergent nappe structure with major displacement and high metamorphism near the fault system and then decreasing to low at the northwest Alpine front.

In the area of the Tectonic Map of Switzerland, the Periadriatic Fault System is represented by its westernmost segments, from east to west: the Giudicarie Fault, the Tonale Fault and the Canavese Fault. The latter two, grouped by many authors under the term of "Insubric Fault", accommodate dextral slip motion and/or backthrusting of the nappe stack north of these faults over the South Alpine domain. The ductile fault rocks (mylonites) found along the Insubric Fault primarily formed during the Oligocene (32–23 Ma; SCHMID et al. 1989), while the brittle component observed along the Tonale Fault is considerably younger (MÜLLER et al. 2002, PLEUGER et al. 2012).

The *Canavese Fault* extends west of Locarno with an ENE–WSW orientation that changes to NNE–SSW south-southwest of the Valle d'Ossola. This fault primarily accommodates backthrusting of the Sesia Nappe across a kilometer-wide belt of mylonites over the Ivrea Zone (SCHMID et al. 1987). On the map, the entire Canavese Zone is included in this mylonitic belt, but not in the southwest near Ivrea. The Canavese Fault is subdivided into two branches, the external one running between the rocks of the Sesia Nappe and those recognized as belonging to the Canavese Zone, and the internal one between the latter and the rocks of the Ivrea Zone. Movements along this mylonitic belt appear to be polyphase, formed however mainly during the Paleogene (ZINGG & HUNZIKER 1990).

The straight *Tonale Fault* runs eastward from Locarno all the way to Dimaro at the eastern margin of the map, where it is offset by the Giudicarie Fault (see below). The westernmost part of the Tonale Fault, between Locarno and Morbegno in Valtellina, still accommodates backthrusting of the amphibolite-facies units of the Central Alps over the non-metamorphic South Alpine across the Insubric mylonite belt. East of Morbegno, the lineations of these mylonites of the Tonale Fault rapidly swing into a subhorizontal orientation, indicating a rapid eastward change from a backthrusting regime to a dextral strike-slip motion (BERGER et al. 1996). East of the eastern end of the Bregaglia Intrusion, the mylonites of the Tonale Fault exclusively exhibit subhorizontal lineations indicating dextral strike-slip with only minor amounts of backthrusting (WERLING 1992, MEIER 2003, STIPP et al. 2004). Dextral strike-slip motion along the Tonale Fault amounts to a total relative displacement estimated at some 100–150 km and is related to the relative westward movement and indentation of the Ivrea Zone leading to the formation of the arc of the Western Alps (LAUBSCHER 1991, SCHMID & KISSLING 2000). In contrast to the Canavese Fault, the southern margin of the mylonite belt is overprinted by a discrete very steeply N-dipping cataclastic fault recording dextral strike-slip motion. This brittle component is geometrically linked to dextral strike-slip motion along the brittle Centovalli Fault (see below) and leaves the Canavese Fault unaffected.

The *Giudicarie Fault* is a Miocene brittle fault, which crops out in the Giudicarie and Rendena valleys, north of Lago di Garda in the southeastern corner of the Tectonic Map of Switzerland. This major fault is a NNE–SSW oriented segment of the Periadriatic Fault System. It separates two E–W segments of this Periadriatic Fault System: the Tonale Fault in the west and the Pustertal-Gailtal Fault in the east, which are offset by about 75 km. The southern part of the Giudicarie Fault is entirely located in the South Alpine, while the northern part separates

Austroalpine units to the west and South Alpine units to the east. Only the southern part occurs in the area of the map (SE border), with a small portion of the northern part occurring at the eastern edge of the map area.

Some authors (e.g., LAUBSCHER 1988, 1991, POMELLA et al. 2012) regard the Periadriatic Fault System as derived from an originally straight E–W striking fault, composed of the Tonale and the Pustertal-Gailtal faults. Both were offset by the Giudicarie Fault related to the N-directed indentation of the South Alpine indenter, located east of our map, that triggered rapid exhumation of orogenic crust within the entire Tauern Window (FRISCH et al. 2000, SCHARF et al. 2013). Other authors (VIOLA et al. 2001, 2003 and ref. therein) interpret the Periadriatic Fault System as already curved in the Giudicarie area before the 15–20 km sinistral displacement absorbed by the Giudicarie Fault Zone. The latter thus developed on a geometric feature inherited from the original passive margin later affected by post-collisional shortening, first characterized by an Oligocene E-directed thrusting of the Austroalpine basement over the South Alpine sediment, then by the sinistral strike-slip Giudicarie Fault.

10.2. Centovalli Fault

The E–W striking Centovalli Fault extends between Locarno and Domodossola and represents a very diffuse and broad zone of intense brittle deformation consisting of mineralized faults, cataclasites, kakirites and fault breccias. This fault zone was active between approximately 14 Ma and recent times according to radiometric dating of clay fractions (ZWINGMANN & MANCKTELOW 2004, SURACE et al. 2011). It overprinted the older Arcegno-Palanzeno Shear Zone (BURRI 2005) in the E–W striking “root zone” of the Penninic and Lepontic nappes (Southern Steep Belt; MILNES 1974b). At its eastern end near Locarno, the Centovalli Fault is kinematically connected by a system of dextral Riedel shears to the brittle component of the Tonale Fault, overprinting earlier formed mylonites of the Canavese Fault (SCHMID 2017). This is consistent with the kinematic indicators indicating dextral shearing along the Centovalli Fault described by SURACE et al. (2011). The western end of the Centovalli Fault east of Domodossola is approximately aligned with the eastern end of the Simplon Fault (see below) associated with dextral shear rather than normal faulting (KELLER et al. 2005). BEARTH (1956) and STECK (2008, Fig. 9), for example, proposed a continuation from the first to the second fault, unlike other authors (e.g., MILNES et al. 1981, MANCKTELOW 1985, KELLER et al. 2005, 2006, CAMPANI et al. 2010, Fig. 1) who excluded the transfer of the major dextral displacement from the Centovalli Fault to the Simplon Fault, because, in their view, the Masera Synform situated north of the Centovalli Fault, on the eastern side of the Valle d’Ossola, continues in a synform south of the Simplon Fault in the western side of this valley; thus, the synform cannot be cut by a connection between the two faults.

10.3. Rhône-Simplon Fault

The two adjoining Rhône and Simplon faults are commonly referred together as the Rhône-Simplon Fault. The Simplon Fault is a normal fault responsible for much of the exhumation of the western Lepontic nappes (MANCKTELOW 1990, STECK 2008 and ref. therein). It extends over the Simplonpass between Visp in the Rhône Valley and Domodossola in the Valle d'Ossola. According to KELLER et al. (2005), the southeastern termination of this normal fault near Domodossola represents a rapid transition to a dextral strike-slip segment, the same as for the Centovalli Fault. A connection between the two faults is considered by some authors but rejected by others (see § 10.2). The western part of the Simplon Normal Fault splits in two branch and links with the seismically still active Rhône Fault associated with dextral strike-slip motion. STECK (1984, 2008) pointed out that a much broader dextral shear zone (his Simplon Ductile Shear Zone) preceded activity along the Rhône-Simplon Fault between 32 and 18 Ma, transforming much of the substantial dextral shearing along the Tonale Fault into thrusting in the frontal part of the Western Alps (e.g., GOUFFON & BURRI 1997, Fig. 7). The Simplon Fault was active during the 19–3 Ma time span (GRASEMANN & MANCKTELOW 1993, CAMPANI et al. 2010, BERGEMANN et al. 2020) and, together with the older Simplon Ductile Shear Zone, kinematically acted as a tensile bridge between the dextral movements along the Rhône Fault and the Tonale Fault, respectively (SCHMID & KISSLING 2000).

10.4. Aosta-Ranzola Fault

The E–W trending Aosta-Ranzola Fault consists of a 1–2 km wide network of closely spaced and predominantly N-dipping normal faults that follow the Valle d'Aosta between Brusson and Aosta. The maximum cumulative vertical throw across this steeply N-dipping central part of the fault system exhuming the footwall located on the southern side of the valley amounts to some 3 km (BISTACCHI et al. 2001). East of Brusson, this normal fault finds a rather abrupt end as it is cut by a SW–NE trending fault, the Ospizio-Sottile Fault, indicating sinistral strike-slip motion of Miocene age (BISTACCHI et al. 2000). The Aosta-Ranzola Fault is of Oligocene age, as documented by the synkinematic emplacement of gold bearing quartz veins and calc-alkaline dykes dated at 29 Ma (DAL PIAZ et al. 1979, DIAMOND & WIEDENBECK 1986). West of Aosta, the Col de Bard Fault can be considered as the continuation of the Aosta-Ranzola Fault progressively flattening towards a more moderate NW-dipping fault as it progressively bends into a NW–SE strike, which offset mainly the Middle Penninic units (GOUFFON 1993, GOUFFON & BURRI 1997). Alternatively, MALUSÀ et al. (2009) consider the Col de Bard Fault as the termination of the Cogne Fault Zone.

10.5. Engadine Fault

The brittle SW–NE striking Engadine Fault accommodated sinistral strike-slip motion, combined with a rotation of the NW block with respect to the SE block. This relative block rotation resulted in a relative uplift of the SE block hosting the Bregaglia Intrusion at Passo del Maloja and in Val Bregaglia, while an opposite vertical throw is observed in the area of the western Lower Engadine Window where the SE block (the S-charl-Sesvenna Nappe) is downthrown and forms the hangingwall of a sinistrally transtensive normal fault (SCHMID & FROITZHEIM 1993, TRÜMPY et al. 1997). The correlation of the nappe units to both sides of the Engadine Fault yields some 2.8 km vertical and horizontal components of displacement near Maloja, 3.1 km pure horizontal strike-slip movement near Samedan and 3.2 km vertical and horizontal components at S-chanf. The vertical throw across the transtensive normal fault at the southeastern margin of the western Lower Engadine Window amounts to some 4 km. The southwestern end of the Engadine Fault in the lower Val Bregaglia very probably coincides with the northern margin of the Gruf Complex while its northeastern end near Nauders is hidden below a late-stage N-directed thrust of the Ötztal Nappe onto the Penninic units of the Lower Engadine Window. Faulting along the Engadine Fault certainly postdates the intrusion of the Val Bregaglia pluton and took place somewhere around the Oligocene-Miocene boundary, when the metamorphosed rocks in Val Bregaglia cooled down below the viscous–brittle transition.

11. CENOZOIC MAGMATIC ROCKS

S.M. Schmid & Y. Gouffon

Several magmatic events occurred during the Alpine orogeny. Two groups of magmatic rocks need to be distinguished: the Hegau Volcanic Suite in the Autochthonous North Alpine Foreland and the extensive Periadriatic province in southern parts of the Alps.

11.1. Hegau Volcanic Suite

The Autochthonous North Alpine Foreland of Germany hosts a Miocene volcanic suite related to intraplate magmatism of alkaline basaltic composition, reaching the region covered by the Tectonic Map of Switzerland in the area of

Singen northwest of the Bodensee. The Hegau volcanism (KELLER 1984) seems to be associated with extension within the NW–SE striking Hegau-Bodensee Graben structure (EGLI et al. 2017) and regional uplift of the Schwarzwald area. Volcanic activity is of Middle to Late Miocene age (LIPPOLDT et al. 1963, SCHREINER 1992). Various episodes succeeded each other between some 14 and 7 Ma: pyroclastics ("Deckentuffe"), including extensive layers of volcanic ash (up to 100 m thick) as well as chimney and crater fills, came first, followed by olivine nephelinites, hornblende tuffs and finally phonolites.

The Upper Freshwater Molasse of northeastern Switzerland contains several levels of bentonite (fossil weathering products of volcanic ash deposits) radiometrically dated between 15.3 and 14.2 Ma (GUBLER 2020 and ref. therein), the ages of which coincide with the onset of Hegau volcanism. A younger bentonite layer near Frauenfeld was dated by RAHN & SELBEKK (2007) at around 11.5 Ma.

11.2. Periadriatic Magmatic Province

Plutons and many dykes of Eocene–Oligocene age straddle the Periadriatic Fault System; the final emplacement of the plutons often coincides temporally with activity along this fault system. As pointed out by ROSENBERG (2004), magmas were channeled from the base of the thickened continental crust into the narrow mylonitic belt of the Periadriatic Fault System, which was used as an ascent pathway with vertical lengths of 20 to 40 km.

As concerns the generation of magma and its ascent across the crust, VON BLANCKENBURG & DAVIES (1995) proposed that rapid lateral migration of slab break-off within the S-dipping European plate resulted in a linear trace of magmatism in local thermally weakened crust. This would explain why most of these magmatic rocks intruded almost synchronously along the Periadriatic Fault System between Biella (Piemonte, Italy) and Slovenia. This hypothesis was recently challenged by MÜNTENER et al. (2021) who proposed that the calc-alkaline magmatism with a lithospheric mantle component, ending at around 28 Ma, reflects deep-seated processes other than slab break-off, e.g., volatile fluxing of the Alpine mantle wedge during the final stages of continental subduction that immediately followed Europe-Adria collision between 43 and 34 Ma.

11.2.1. Biella Volcanic Suite

An Oligocene volcano-sedimentary series covers the most internal portion of the Sesia Nappe along the Canavese Fault in the Biella region. Its northern extremity is just visible at the southern edge of the map. These mostly calc-alkaline andesitic rocks (CALLEGARI et al. 2004) were deposited onto an erosional surface of the Eclogitic Micaschist Unit of the Sesia Nappe 33–32 Ma ago (KAPFERER et al. 2012).

11.2.2. Bregaglia and Novate intrusions

The *Bregaglia (or Bergell) Intrusion* forms a large body between the Val Bregaglia in the north and the Tonale Fault in the south; it extends with a narrow tail of about 40 km westward along the Tonale Fault (Insubric Fault). It comprises mainly calc-alkaline tonalite and granodiorite (SCHMID et al. 1996a), derived from a primitive mantle melt (VON BLANCKENBURG et al. 1998) and channeled from the base of the continental crust into the Periadriatic Fault System (BERGER et al. 1996, ROSENBERG 2004). The base of the pluton overlying the Gruf Complex shows evidence of synmagmatic folding and thrusting indicating contemporaneous late-stage N–S shortening (DAVIDSON et al. 1996). Crystallization and emplacement of the Bregaglia Intrusion took place between 32 and 28 Ma. A smaller body related to the Bregaglia Intrusion crops out northwest of Sondrio (Triangia Pluton), where it intrudes the subvertical Tonale Nappe and its contact with the adjacent root zone of the Campo Nappe Complex.

The main stock of the *Novate Intrusion* partially cuts the Bregaglia Intrusion while smaller ones lie just west of it. The Novate Intrusion is younger in age (24 Ma, LIATI et al. 2000) and consists of a leucogranite. Its peraluminous chemical composition suggests that this granite is not related to the calc-alkaline Bregaglia suite, but was derived from the partial melting of crustal rocks that are widespread in the Southern Steep Belt – or root zone – north of the Tonale Fault (BURRI et al. 2005).

11.2.3. Adamello Batholith

The Adamello Batholith represents the largest Paleogene pluton of the Alps. It is located in the South Alpine domain, adjacent to the Tonale Fault in the north and the Giudicarie Fault in the east. It comprises several intrusions that succeeded each other between 42 and 28 Ma, generally becoming younger in age from south to north. The rocks of this batholith are mainly tonalites accompanied by granodiorites (CALLEGARI & BRACK 2002).

In contrast to the Bregaglia Intrusion and most other Periadriatic plutons, ascent and main emplacement of the different batches of the Adamello Batholith were unrelated to the activity of the neighboring Periadriatic Fault System and occurred by forceful intrusion. The youngest intrusions however, located in the north of the batholith and adjacent to the Tonale Fault (the foliated Avio and Presanella intrusions with ages of 34.6 Ma and 32.0 Ma, respectively), produced a contact metamorphism during which the adjacent mylonites of the Tonale Fault (Southern Mylonite Zone) became deformed under temperatures of up to more than 620 °C. This indicates that dextral strike-slip faulting along the Tonale Fault, recorded in these mylonites within the contact metamorphic aureole, must have started as early as around 34 Ma ago (STIPP et al. 2004).

11.2.4. Colle Gallo and Gandino subvolcanic bodies

Many sills and small magma bodies of andesitic composition intruded the Lower Orobic Imbricates and the Upper Orobic Nappe. Because of their notable size, two of these subvolcanic bodies are depicted on the tectonic map, one near Gandino and the other east of Albino (Colle Gallo), both northeast of Bergamo. They are associated with normal faults and cut earlier thrusts. Intrusion ages around 40 Ma and geochemical analyses suggest a close relationship with the earliest Adamello intrusion stages (D'ADDA et al. 2011).

12. POST-OROGENIC SEDIMENTS

D. Bernoulli, Y. Gouffon, V. Picotti & R. Fantoni

Post-orogenic deposits cover a part of the bedrock throughout the area covered by the Tectonic Map of Switzerland, particularly in areas of smooth morphology such as the Swiss Plateau and the foothills of the Southern Alps. The discontinuity of this cover, often from one to several tens of meters thick, makes it possible to identify the underlying bedrock. Therefore, only the most significant Quaternary deposits, as well as Late Neogene sediments south of the Alps, are shown on the map.

12.1. Alluvial and glacial deposits (Quaternary; incl. Messinian – Pliocene sediments south of the Alps)

On the Swiss Plateau, only areas with a Quaternary sediment thickness of more than about 50 m1) are represented on the Tectonic Map of Switzerland, i.e., mainly the large alluvial plains. In the Alps and beyond the Swiss border, delineation of the major Quaternary fill is based both on morphology and existing geological maps.

In the foothills of the Southern Alps, several isolated outcrops of Messinian continental conglomerates, local late Messinian brackish water deposits (PICOTTI et al. 1997) and Early Pliocene marine deposits occur (WINTERBERG et al. 2020 and ref. therein). Messinian gravel and Pliocene marine deposits also occur below the

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1) See the layer "Thickness of unconsolidated deposits" on https://map.geo.admin.ch

lakes (Cazzini et al. 2020). They fill the deeply buried valleys that resulted from the pronounced sea-level drop associated with the Messinian salinity crisis (Finckh 1978, Bini et al. 1978, Amadori et al. 2018, Cazzini et al. 2020). The Early Pliocene mudstones represent the remnants of the marine ingression in the Late Miocene valleys, which correspond to present-day valleys, documenting the establishment of the drainage network of the Southern Alps in Tortonian times. These Neogene deposits are covered by alluvial and glacial deposits of Early, Middle and Late Pleistocene age (e.g., Monegato et al. 2023). In the adjacent Po Plain, the post-orogenic sediments include Messinian continental conglomerates, late Messinian brackish water deposits, Pliocene marine sediments, Quaternary marine, alluvial and glacial to periglacial deposits (e.g., Muttoni et al. 2003). Collectively, they are arranged in a wedge, thickening towards the south, due to the flexuring of the Northern Apennines foreland (e.g., Picotti et al. 1997; see Pl. II, western and eastern cross-sections).

12.2. Rock avalanche deposits

In the Alps, catastrophic rock avalanches occurred following the glacier retreat after the Last Glacial Maximum. Only the largest deposits are represented on the map: Sierre, Engelberg, Glarus, Flims and Tamins. The Goldau rock avalanche is much more recent as it occurred on the 2nd September 1806.

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ENCLOSURES

Plate Ia	Legend (for the map and the Plate II)
Plate Ib	Legende (zur Karte und Tafel II)
Plate Ic	Légende (de la carte et de la Planche II)
Plate Id	Legenda (della carta e della Tavola II)
Plate II	Tectonic cross-sections through the area covered by the Tectonic Map of Switzerland
Plate III	Paleogeographic sketch maps

Tectonic cross-sections through the area covered by the Tectonic Map of Switzerland

by

Yves Gouffon, Ferdinando Musso Piantelli and Anina Ursprung

South Alpine part of the western and eastern cross-sections:
Daniel Bernoulli, Vincenzo Picotti and Roberto Fantoni

Western and eastern cross-sections, except South Alpine parts: modified after the cross-sections on the 3rd edition of the Tectonic Map of Switzerland

Central cross-section, South Alpine part: modified after SCHMID et al. (2017)

Scale 1:500 000

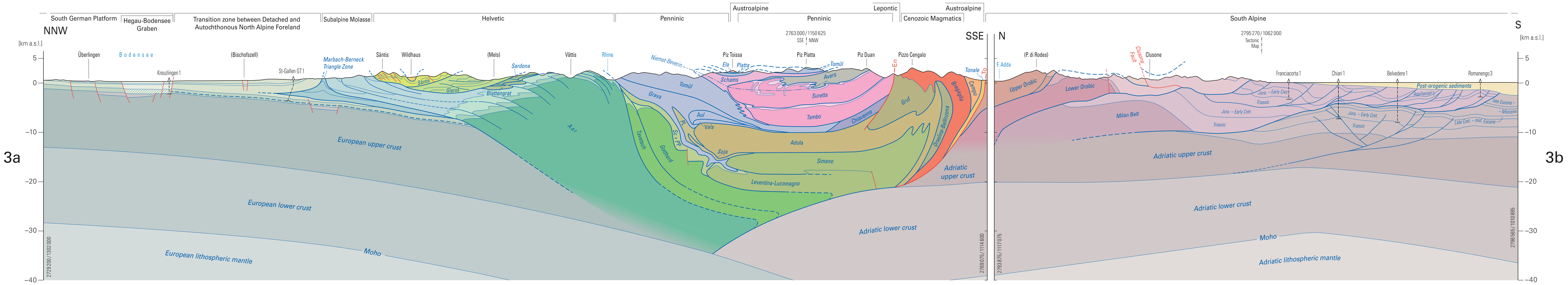
0 10 30 50 km

Legend: see plate Ia–d

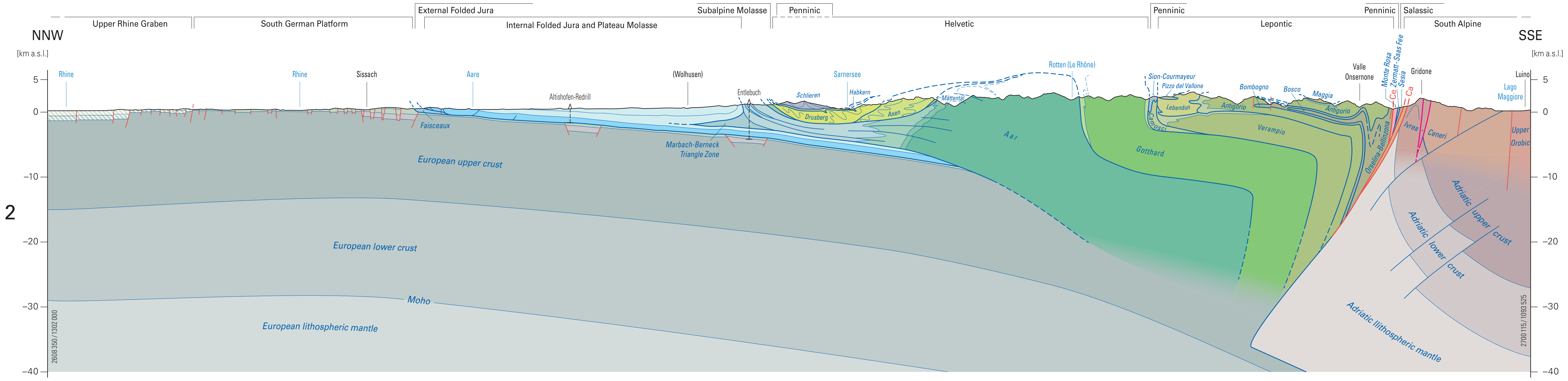
↥ Deep borehole (projected)

-·-·- Axial trace of a major fold

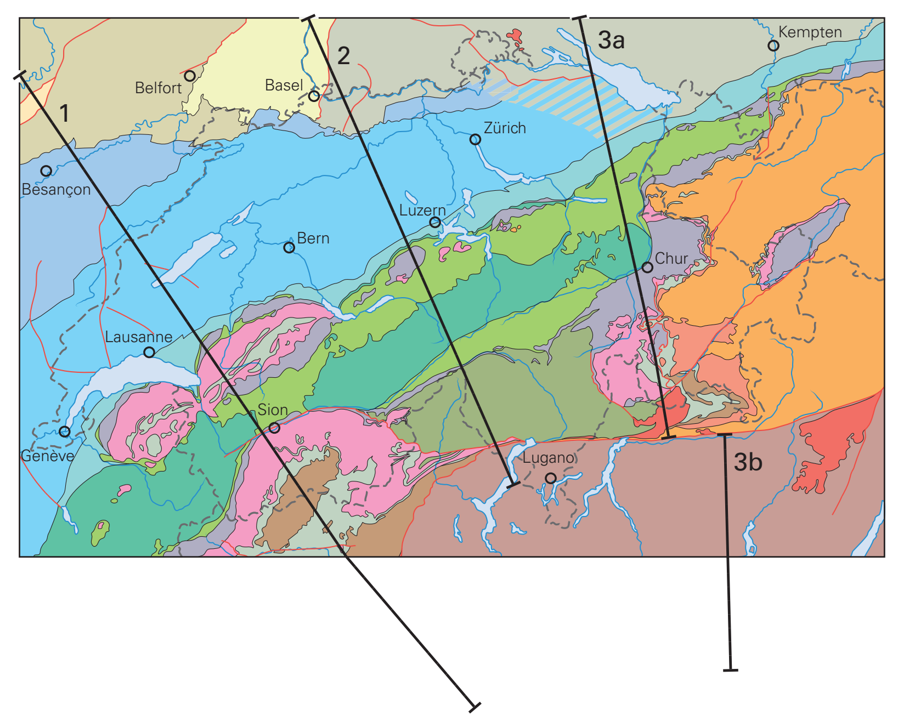
Eastern cross-section



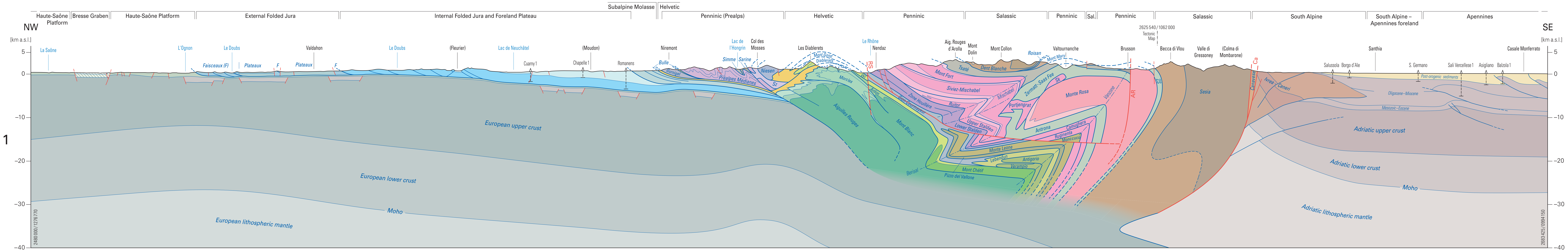
Central cross-section



Traces of the cross-sections



Western cross-section



Paleogeographic sketch maps

Successive paleogeographic position of the tectonic domains
present in Switzerland and surrounding regions

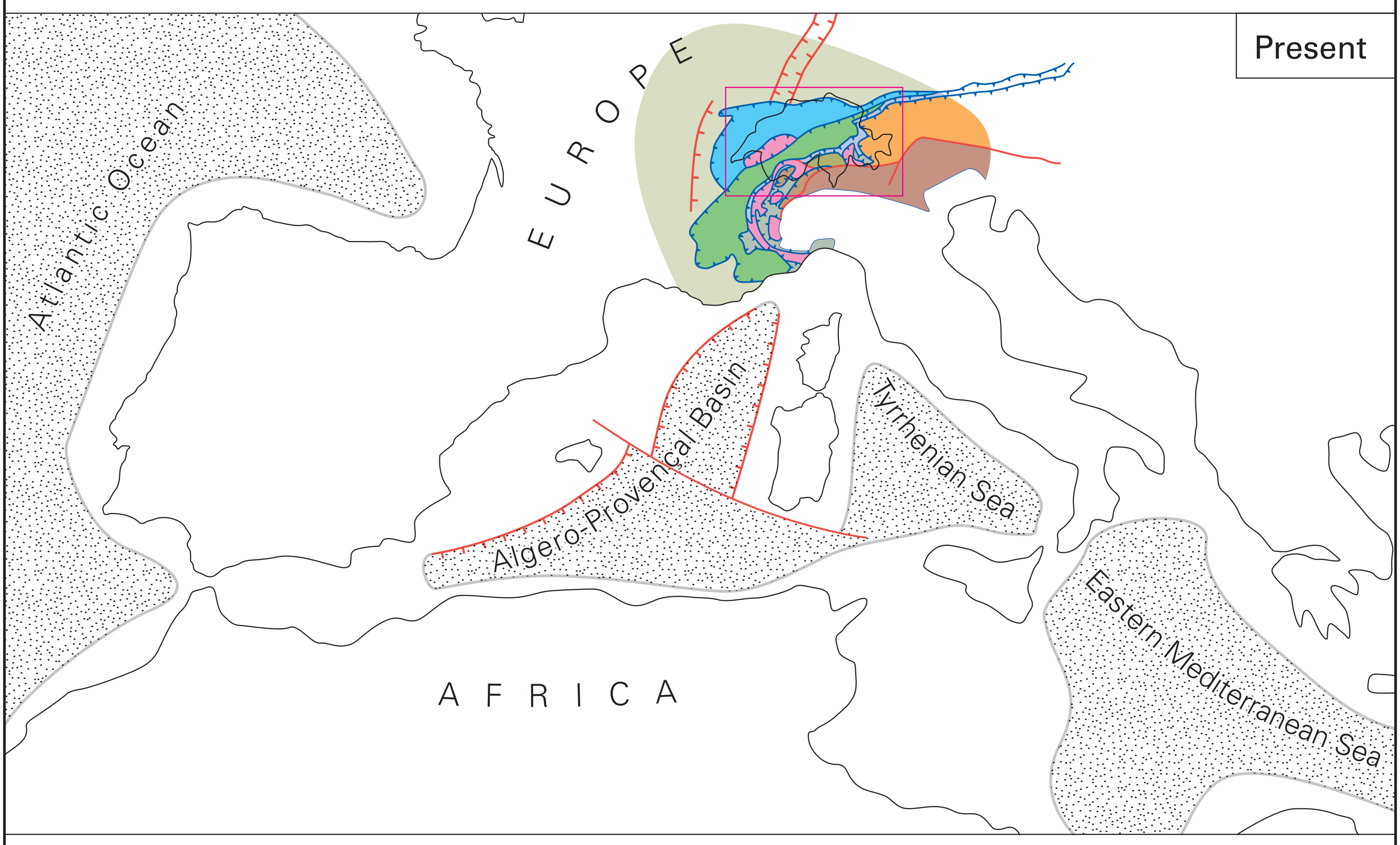
by **Yves Gouffon**, simplified after Handy et al. (2010)

Scale ca. 1:17 500 000

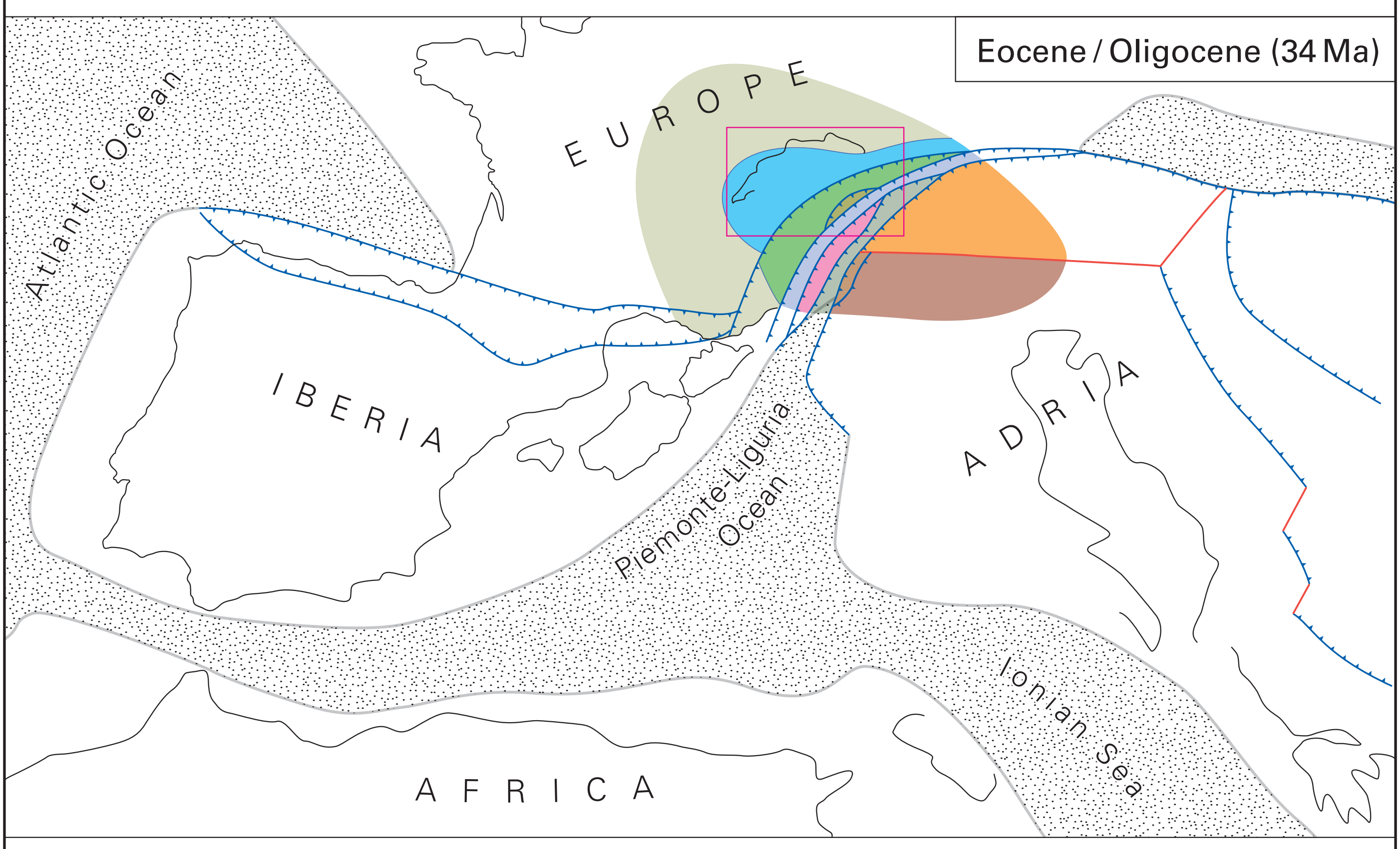
0 500 1000 km

- 🟫 South Alpine
- 🟧 Austroalpine
- 🟫 Salassic
- 🟩 Upper Penninic
- 🟪 Middle Penninic
- 🟦 Lower Penninic
- 🟩 Lepontic
- 🟩 Helvetic
- 🟦 Detached North Alpine Foreland
- ⬜ Autochthonous North Alpine Foreland

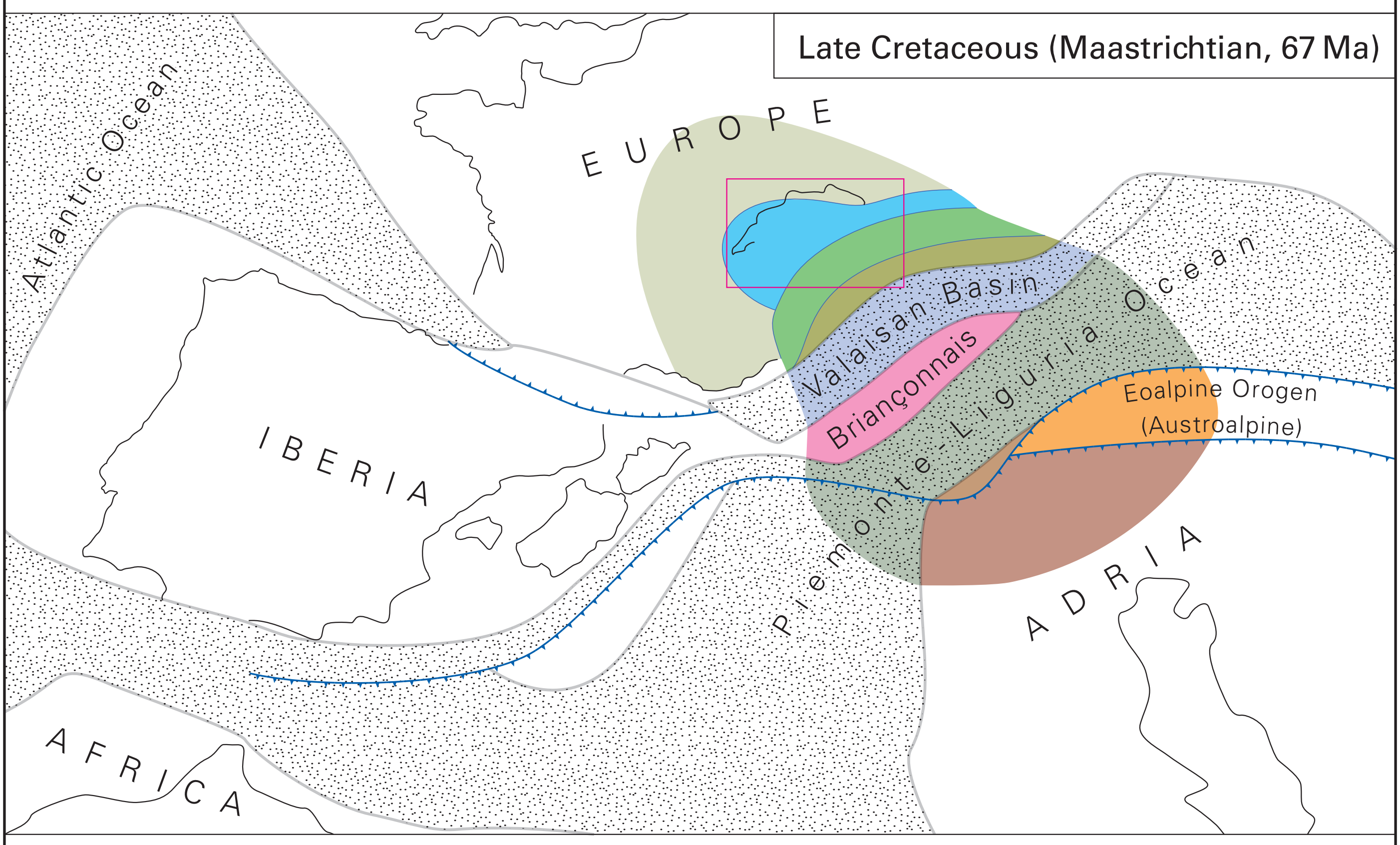
- Fault in general
- Thrust fault
- Normal fault
- ⬜ Continental lithosphere
- ▨ Oceanic lithosphere
- 🟪 Area of the Tectonic Map of Switzerland



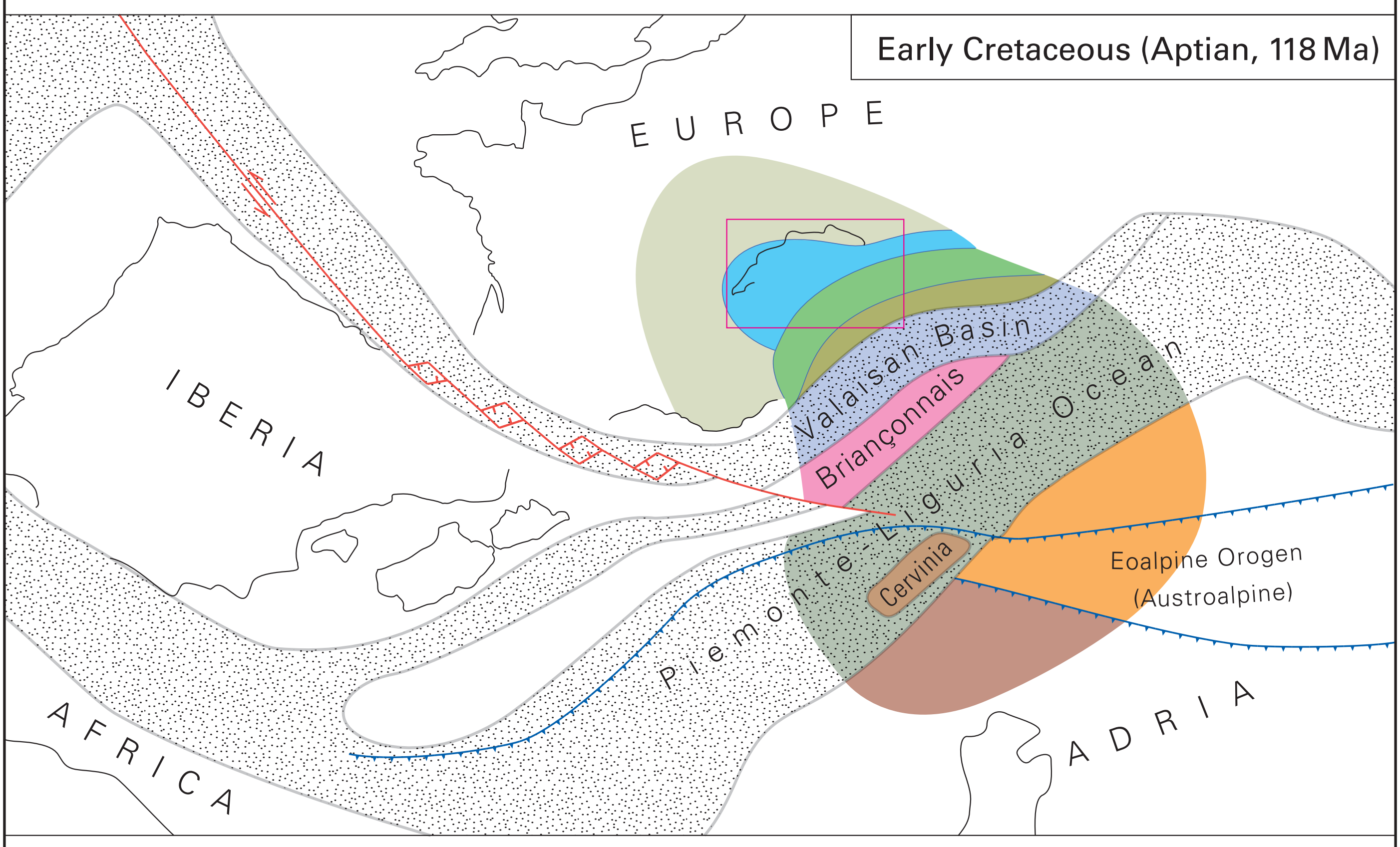
Present



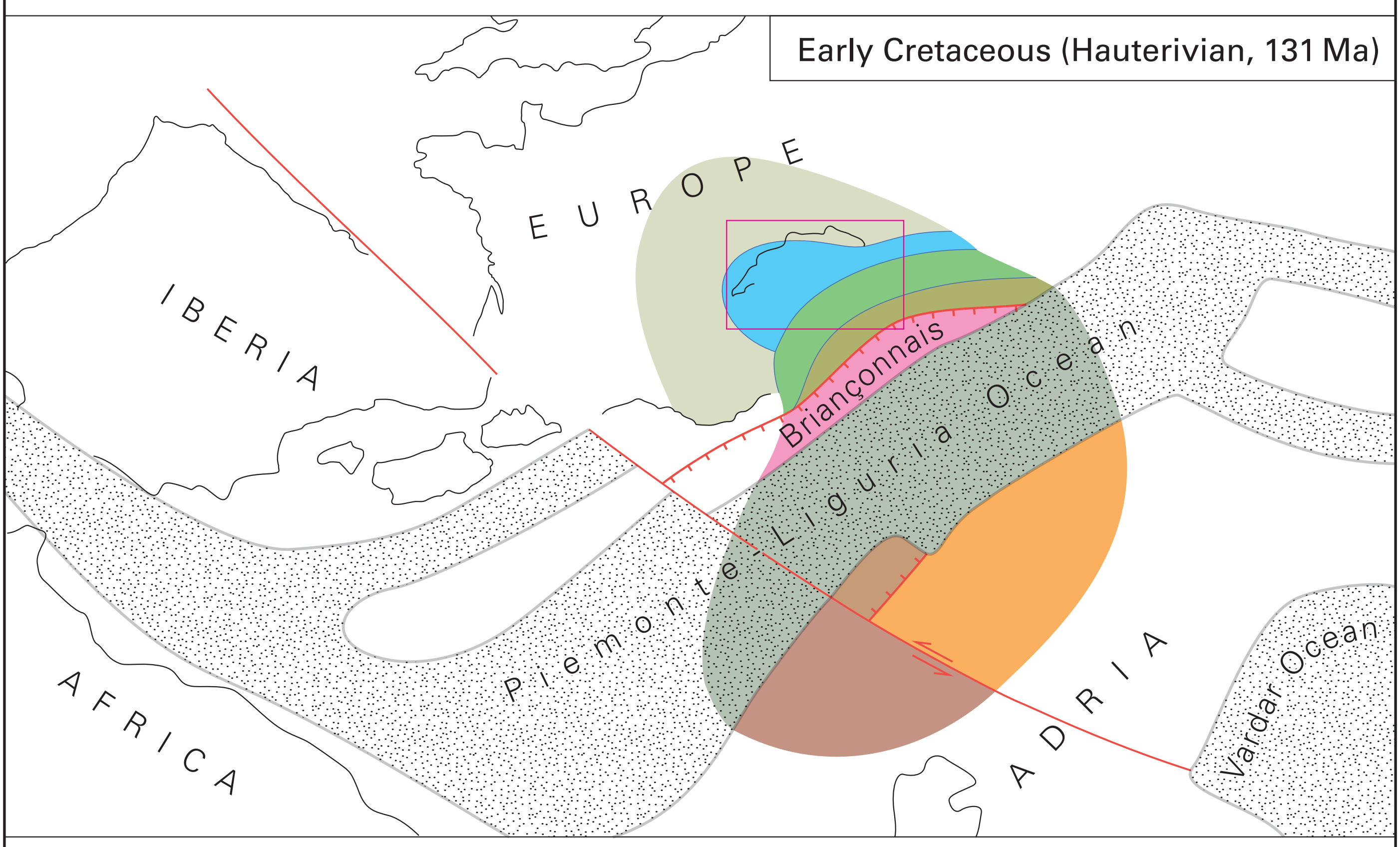
Eocene / Oligocene (34 Ma)



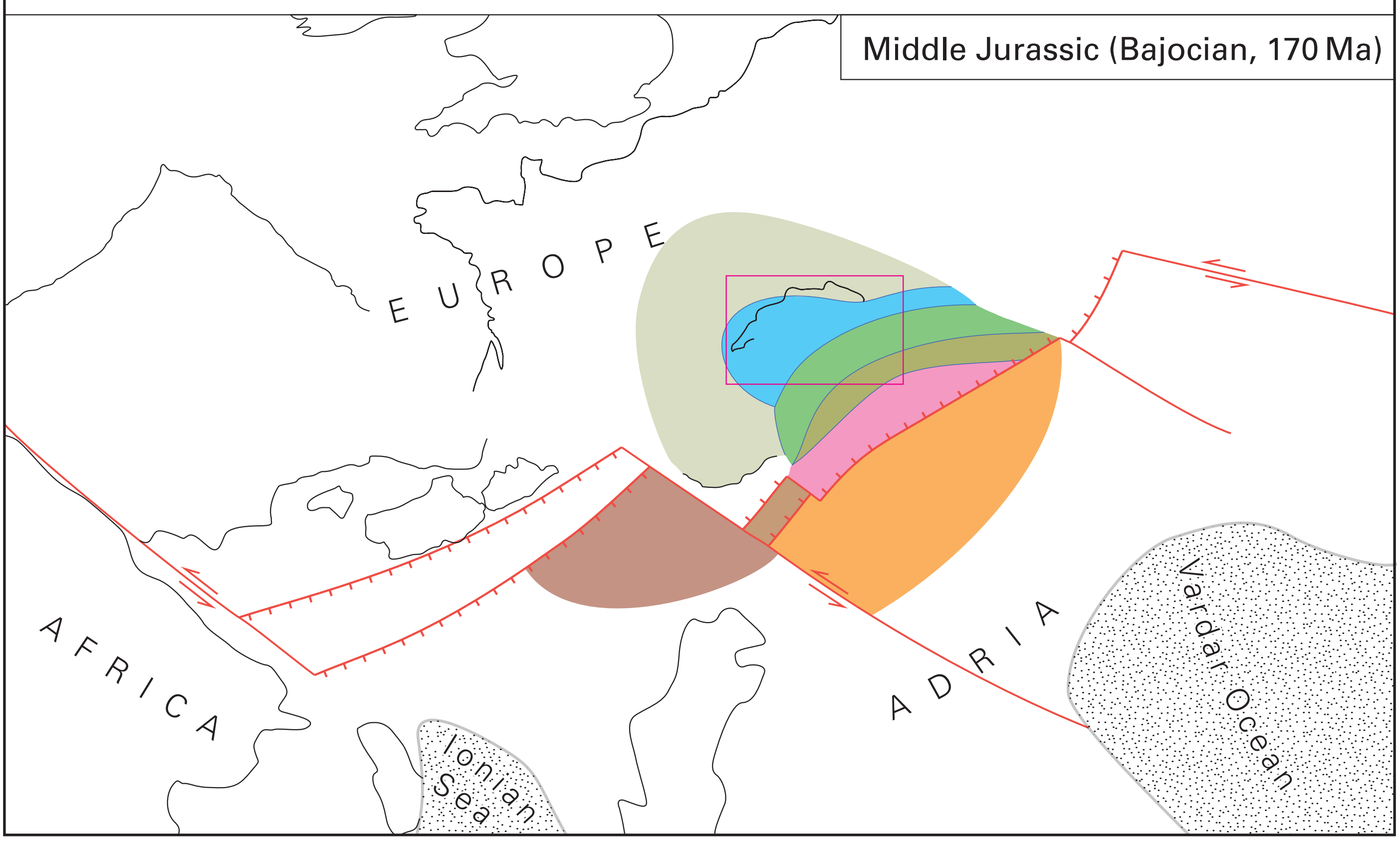
Late Cretaceous (Maastrichtian, 67 Ma)



Early Cretaceous (Aptian, 118 Ma)



Early Cretaceous (Hauterivian, 131 Ma)



Middle Jurassic (Bajocian, 170 Ma)