World Geomorphological Landscapes

Emmanuel Reynard *Editor*

Landscapes and Landforms of Switzerland

Springer

World Geomorphological Landscapes

Series Editor

Piotr Migoń, Institute of Geography and Regional Development, University of Wrocław, Wrocław, Poland

Geomorphology—'the Science of Scenery'—is a part of Earth Sciences that focuses on the scientific study of landforms, their assemblages, and surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of geomorphology. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations. Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us creating shapes which look improbable. Many geomorphological landscapes are so immensely beautiful that they received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for millions of years and include unique events. This international book series will be a scientific library of monographs that present and explain physical landscapes across the globe, focusing on both representative and uniquely spectacular examples. Each book contains details on geomorphology of a particular country (i.e. The Geomorphological Landscapes of France, The Geomorphological Landscapes of Italy, The Geomorphological Landscapes of India) or a geographically coherent region. The content is divided into two parts. Part one contains the necessary background about geology and tectonic framework, past and present climate, geographical regions, and long-term geomorphological history. The core of each book is however succinct presentation of key geomorphological localities (landscapes) and it is envisaged that the number of such studies will generally vary from 20 to 30. There is additional scope for discussing issues of geomorphological heritage and suggesting itineraries to visit the most important sites. The series provides a unique reference source not only for geomorphologists, but all Earth scientists, geographers, and conservationists. It complements the existing reference books in geomorphology which focus on specific themes rather than regions or localities and fills a growing gap between poorly accessible regional studies, often in national languages, and papers in international journals which put major emphasis on understanding processes rather than particular landscapes. The World Geomorphological Landscapes series is a peer-reviewed series which contains single and multi-authored books as well as edited volumes.

World Geomorphological Landscapes—now indexed in Scopus®!

More information about this series at http://www.springer.com/series/10852

Emmanuel Reynard
Editor

Landscapes and Landforms of Switzerland

Springer

Editor
Emmanuel Reynard
Institute of Geography and Sustainability and
Interdisciplinary Centre for Mountain Research
University of Lausanne
Lausanne, Switzerland

ISSN 2213-2090 ISSN 2213-2104 (electronic)
World Geomorphological Landscapes
ISBN 978-3-030-43201-0 ISBN 978-3-030-43203-4 (eBook)
https://doi.org/10.1007/978-3-030-43203-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, nature often surprises us creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they received the highest possible recognition—they hold the status of World Heritage Sites. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique geological events such as meteorite impacts. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. For centuries, and even millennia, they have been shaped by humans who have modified hillslopes, river courses and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by geomorphology—'the Science of Scenery'—a part of Earth Sciences that focuses on landforms, their assemblages, surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

To show the importance of geomorphology in understanding the landscape and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume presents geomorphological history and landscapes of Switzerland—a country, whose image is created by geomorphology more than anywhere else. A popular view equates Switzerland with the Alps and this book contains many examples of superb Alpine landscapes, shaped by uplift and erosion, glaciers of the past and the present, large-scale mass movements such as huge landslides and rapid debris flows, karstic processes and rivers. However, stories told by geomorphic landscapes outside the Alps are no less fascinating, even if these Fore-Alpine regions lack the grandeur of snow-covered peaks and glacier-filled valleys. The authors of many chapters also remind us about an important role of humans in shaping the landscape, perhaps best exemplified by the vineyards of Lavaux, declared a UNESCO World Heritage. Finally, Switzerland is a country where many important discoveries in the field of geomorphology and Quaternary have been made and these aspects have also been covered.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists (IAG)—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union (IGU) and the International Union of Geological Sciences (IUGS). Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which keeps to the scientific rigour, is the most appropriate means to fulfill these aims and to serve the geoscientific community. To this end, my great thanks go to Emmanuel Reynard for adding this book to his busy agenda, successfully coordinating the large, multinational team of authors and delivering such an exciting and lavishly illustrated story to read and enjoy. I also acknowledge the excellent work of all individual authors who share their expert knowledge of Switzerland with the global geomorphological community. I am sure that this book, offering the best sample of Swiss geomorphological sceneries, will become both a most useful reference source about the country and a ready list of destinations to visit on a future geomorphological trip.

Piotr Migoń
Series Editor

Foreword

Emmanuel Reynard's email whether I would like to write the foreword to the book on *Landscapes and Landforms of Switzerland* he has been editing reached me while I was doing fieldwork on wind erosion and dust emissions in the Free State in South Africa. Looking through the impressive list of contributions in the Table of Contents for the book made it very clear to me how special the landscapes and landforms of Switzerland are. Here I was working on a flat high plateau during a windy and somewhat cold winter morning in South Africa, trying to measure small amounts of material driven across the land surface by wind, when all the images of Swiss mountains, glaciers and rivers popped up in my mind, a feast for geomorphologists, at least after a few weeks of studying wind erosion on croplands. So I did not hesitate to agree to contribute this short foreword to *Landscapes and Landforms of Switzerland*.

The 29 chapters of *Landscapes and Landforms of Switzerland* comprise a much wider range of landscapes and geomorphic systems than one could expect from a country which is usually associated with its Alpine landscape. Apart from highlighting the great variety of Swiss geomorphology, to me the great number of chapters and topics of *Landscapes and Landforms of Switzerland* also shows two unique elements of the book: on one hand, the classic description of the landforms; on the other, the deep insights into the processes that have formed these landscapes in the past and which shape them today and in the future. This perspective of *Landscapes and Landforms of Switzerland* also conveys a rather unique role of Swiss Geomorphology. In Switzerland, the proximity of humans and the dynamic and changing environment is closer than in many other countries. Geomorphology is, therefore, one of the most important scientific disciplines making the connection between these two spheres by generating an understanding of the material, forms, processes and history of the Earth surface. The efforts of Emmanuel Reynard and the team of authors who contributed to *Landscapes and Landforms of Switzerland*, therefore, illustrate both the relevance of geomorphology in Switzerland and the excellent research on landscapes and landforms conducted in Switzerland.

Bultfontein, South Africa
August 2019

Nikolaus J. Kuhn
President of the Swiss Geomorphological Society
(2017–2019)

Contents

Editor and Contributors

About the Editor

Emmanuel Reynard is Professor of Physical Geography and Director of the Interdisciplinary Centre for Mountain Research at the University of Lausanne, and a member of the International Association of Geomorphologists (IAG) Executive Committee. He has been Chairman of the IAG Working Group on Geomorphosites (2001–2013) and President of the Working Group on Geotopes of the Swiss Academy of Sciences (2006–2017). His research concerns mountain geomorphology, geomorphological heritage, landscape geohistorical analyses and water management in mountains. He has worked in the Alps, the Romanian Carpathians and in the Maghreb (Tunisia, Morocco).

Contributors

Naki Akçar Institute of Geological Sciences, University of Bern, Bern, Switzerland

Christian Ambrosi Institute of Earth Sciences, University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Canobbio, Switzerland

Nico Bätz Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland;
Department Surface Waters Research and Management, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Kastanienbaum, Switzerland

Luca Bonzanigo Consultant geologist, geolog.ch SA, Bellinzona, Switzerland

Thomas Buckingham UNESCO-World Heritage Swiss Tectonic Arena Sardona, Sargans, Switzerland

Nancy Calhoun Department of Earth Sciences, Simon Fraser University, Burnaby, BC, Canada;
Oregon Department of Geology and Mineral Industries, Portland, Canada

John J. Clague Department of Earth Sciences, Simon Fraser University, Burnaby, BC, Canada

Emmanuel Estoppey eqiilab, Ollon, Switzerland

Jean-Michel Fallot Institute of Geography and Sustainability, University of Lausanne, Lausanne, Switzerland

Isabelle Gärtner-Roer Department of Geography, University of Zurich, Zurich, Switzerland

Ruedi Haller Swiss National Park, Chastè Planta-Wildenberg, Zernez, Switzerland

Philipp Häuselmann Swiss Institute for Speleology and Karst Studies (SISKA), La Chaux-de-Fonds, Switzerland

Peter Heitzmann Geowissenschaftliche Öffentlichkeitsarbeit und Geologische Beratungen, Bern, Switzerland

Kristina Hippe Laboratory for Ion Beam Physics, ETH Zurich, Zurich, Switzerland; Department of Earth Sciences, Freie Universität Berlin, Berlin, Germany

Martin Hoelzle Department of Geosciences, University of Fribourg, Fribourg, Switzerland

Hanspeter Holzhauser Zürich, Switzerland

Ion Iorgulescu Etat de Genève, Département du Territoire, Genève, Switzerland

Susan Ivy-Ochs Laboratory for Ion Beam Physics, ETH Zurich, Zurich, Switzerland

Pierre-Yves Jeannin Swiss Institute of Speleology and Karst Studies (SISKA), La Chaux-de-Fonds, Switzerland

Beat Keller Keller+Lorenz AG, Luzern, Switzerland

Oskar Keller Lüchingen, Switzerland

Robert Kenner WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland

Christophe Lambiel Institute of Earth Surface Dynamics and Interdisciplinary Centre for Mountain Research, University of Lausanne, Lausanne, Switzerland

Stuart N. Lane Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland

Hans Lozza Swiss National Park, Chastè Planta-Wildenberg, Zernez, Switzerland

Michel Marthaler Institute of Geography and Sustainability, University of Lausanne, Lausanne, Switzerland

Simon Martin Bureau Relief, Aigle, Switzerland

Brian W. McArdell Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

Andrea Moscariello Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Samuel U. Nussbaumer Department of Geography, University of Zurich, Zurich, Switzerland

O. Adrian Pfiffner Institute of Geological Sciences, University of Bern, Bern, Switzerland

Marcia Phillips WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland

Andreas von Poschinger Bavarian Environment Agency, Geological Survey, Augsburg, Germany

Géraldine Regolini Bureau Relief, Aigle, Switzerland

Emmanuel Reynard Institute of Geography and Sustainability and Interdisciplinary Centre for Mountain Research, University of Lausanne, Lausanne, Switzerland

Henri Rougier University Lyon 3, Lyon, France

Mario Sartori Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Cristian Scapozza Institute of Earth Sciences, University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Canobbio, Switzerland

Christian Schlüchter Institute of Geological Sciences, University of Bern, Bern, Switzerland

Philippe Schoeneich Institute of Urban Planning and Alpine Geography, University Grenoble Alpes, Grenoble, France

Andreas Wipf Swiss Hiking Association, Bern, Switzerland

Heinz J. Zumbühl Institute of Geography, University of Bern, Bern, Switzerland

1 Introduction

Emmanuel Reynard

Abstract

The variety of Swiss landscapes is due to the combination of varied structural and climatic contexts and a rich geological heritage. The book is divided in three main sections. The first section presents the physical context and details the variety of Swiss geomorphological landscapes. The second section proposes 23 examples of Swiss landscapes, in three main subsections: eight examples of structural landscapes; nine cases of glacial, periglacial and high mountain landscapes; and six examples of river landscapes and landscapes related to gravity-driven processes. The last section deals with geoheritage, geoparks and geotourism.

Keyword

Geomorphological heritage • Landscapes • Switzerland

Switzerland is known not only for its typical products (chocolate, cheese, watches) and services (banking), but also for its landscapes. The latter were at the origin of tourism in Europe in the eighteenth century and landscapes are still among the main tourist attractions in Switzerland today. Their diversity is largely due to the influence of the agricultural development, which has given rise to a multitude of rural sceneries, including typical alternating grasslands, alpine pastures, forests and cultivated fields. Today, however, these rural landscapes are increasingly under pressure from urbanisation, especially on the Swiss Plateau.

The variety of Swiss landscapes is also due to the combination of varied structural and climatic contexts and a rich geological heritage. The aim of this book is to present and discuss the influence of the different structural contexts and current and former climates on landforms, and the importance of the landforms in structuring the landscapes of Switzerland.

The book has three main sections. The first section concerns the physical context and details the variety of Swiss geomorphological landscapes. It includes four texts: The first, by O. Adrian Pfiffner, presents the main features of Swiss geology. The second, by Jean-Michel Fallot, does the same for climate. The following text by Christian Schlüchter et al. gives an overview of the evolution of landscapes during the Quaternary. Finally, Emmanuel Reynard et al. provide an overview of the main geomorphological landscapes in Switzerland.

Section two presents 23 characteristic Swiss reliefs and landscapes. It has three subsections. The first one proposes eight examples of structural landscapes, i.e. cases in which structural conditions have strongly influenced morphology. Andrea Moscariello interprets the geomorphological history of the Geneva basin, which has depended to a great extent on structural conditions and has been shaped by repeated passage of glaciers during the Quaternary. Emmanuel Reynard and Philippe Schoeneich portray a typical Jura landscape, the Joux Valley and its surroundings. Emmanuel Reynard and Emmanuel Estoppey offer a geomorphological analysis of the structural landscape (in the Molasse) of the Lavaux World Heritage vineyard. Using the example of the Diablerets Massif, Philippe Schoeneich and Emmanuel Reynard then present the landscapes of the calcareous massifs of the western “Hautes Alpes Calcaires”. O. Adrian Pfiffner does the same for the landscapes of central Switzerland, around Lake Lucerne, following Philipp Häuselmann’s analysis of the surface and underground landscapes of the Siebenhengste-Hohgant-Schrattenfluh karst system. The following text by Thomas Buckingham and O. Adrian Pfiffner deal with structural landscapes of eastern Switzerland, in the Sardona region, another Swiss World Heritage site. The subsection ends with a geomorphological analysis of one of the most famous peaks in the Alps: the Matterhorn, by Michel Marthaler and Henri Rougier.

E. Reynard (✉)
Institute of Geography and Sustainability and Interdisciplinary Centre for Mountain Research, University of Lausanne, Géopolis, 1015 Lausanne, Switzerland
e-mail: emmanuel.reynard@unil.ch

E. Reynard (ed.), *Landscapes and Landforms of Switzerland*, World Geomorphological Landscapes,
https://doi.org/10.1007/978-3-030-43203-4_1

The second subsection provides nine examples of glacial, periglacial and high mountain landscapes. Switzerland is rich in glaciers. Two examples of regions where glacial processes are still very active were chosen, both of which are part of the Swiss Alps Jungfrau-Aletsch World Heritage site: the Great Aletsch Glacier (text by Hans Holzhauser) and the glaciers on the northern slope of the Bernese Alps in the Jungfrau region (text by Heinz Zumbühl et al.). The next three examples illustrate the rapid evolution of high mountain valleys as a result of global warming, while underlining the importance of the Quaternary heritage: the rockglaciers of the Engadine (text by Isabelle Gärtner-Roer and Martin Hoelzle), the landscapes of the Swiss National Park (text by Christian Schlüchter et al.) and glacial and periglacial landscapes typical of the valleys in the western Alps, such as those of the Hérens Valley (text by Christophe Lambiel). The following two examples deal with Quaternary legacies of two major glaciers on the Swiss Plateau: the Rhone glacier (text by Susan Ivy-Ochs et al.) and the Rhine glacier (text by Oskar Keller). Beat Keller provides a detailed analysis of landscape evolution, highlighting the importance of the Reuss glacier in shaping the lake and the city of Lucerne. Finally, Cristian Scapozza and Christian Ambrosi discuss the importance of glacial, periglacial and fluvial processes in shaping the valleys located in the Southern Alps, emphasising their particularities by comparing them with valleys in the Northern Alps.

The third subsection presents six examples of river landscapes and landscapes related to gravity-driven processes. Peter Heitzmann presents the geomorphological context of the biggest waterfall in Switzerland: the Rhine Falls. Nico Bätz et al. analyse the recent evolution of one of the last braided rivers in Switzerland: the Allondon River in the canton of Geneva. Brian McArdell and Mario Sartori analyse the structural conditions and activity of one of the most active torrential systems in the Alps: the Illgraben. The two following texts concern landslides; the first one, in Campo Vallemaggia (analysed by Luca Bonzanigo) is active, with the most recent major landslide occurring in the 1940s, while the second one in Flims, in the Rhine Valley (studied by Andreas von Poschinger et al.), is an example of a major landslide due to postglacial readjustment of the relief. Here, hillslope landforms caused by gravity combine with fluvial landforms to create an exceptional landscape. The last text (Marcia Phillips, Robert Kenner) concerns the municipality of Pontresina, in Graubünden, and describes the activity of high mountain processes and the new anthropogenic landscapes resulting from measures against natural hazards, very common in the Swiss Alps.

Of course, these examples do not cover all the geomorphological landscapes of Switzerland. Some readers may regret the fact that among the 322 geosites in Switzerland, important sites do not have a chapter to themselves. This is the result of a selection guided not only by scientific criteria (the aim being to present different landscapes influenced by the main structural and climatic contexts throughout the country), but also by practical criteria, including the availability of experts to write a text.

The last section (by Emmanuel Reynard et al.) deals with geoheritage management issues.

This book is a collective work that brings together geomorphologists, geologists and geographers working in different regions of the country. I would like to thank all the colleagues who gave their time to write these summary chapters on their study sites. It may seem easy, but in practice, it is often a time-consuming task searching for research results disseminated in multiple documents, ranging from study reports to scientific articles, student work or geological maps. I would also like to thank Mélanie Clivaz, Research Assistant at the Institute of Geography and Sustainability of the University of Lausanne, who helped produce the figures for some chapters.

The whole book was subject to a review process to ensure the scientific quality of the chapters. I would like to thank the following people who agreed to review one or more chapters: Christian Ambrosi, Philippe Audra, Luca Bonardi, Jean-François Buonchristiani, Dov Corenblit, Philip Deline, Jean-Luc Epard, Monique Fort, Wilfried Haeberli, Peter Heitzmann, Raimund Hipp, Christophe Lambiel, Robin Marchant, Jürg Meyer, O. Adrian Pfiffner, Marcia Phillips, Martine Rebetez, Cristian Scapozza, Philippe Schoeneich, Roberto Seppi and Ronald T. Van Balen.

I also express my warm appreciation to Piotr Migoń, scientific editor of the series “World Geomorphological Landscapes”. His careful proofreading of all the chapters and his rich experience in publishing other books in the series made it possible to clarify certain formulations and uses that may be understandable to Swiss researchers, but not necessarily for foreign readers, and to improve the formal and scientific quality of the chapters. I am grateful to him to have invited me to join the admirable editorial project he is coordinating.

I would also like to acknowledge the precious support of Springer Nature, particularly Robert K. Doe, Senior Publisher, and Rema Devi Viswanathan, Manjula Saravanan, Banu Dhayalan and Madanagopal Deenadayalan who coordinated the publication process with endless patience and dedication.

Without claiming to be exhaustive, I hope that reading the general chapters in sections 1 and 3 will help understand the context and reasons for Switzerland’s rich geomorphological diversity, while the chapters in section 2 give some concrete examples chosen among the country’s many geomorphosites and geomorphological landscapes (Fig. 1.1).

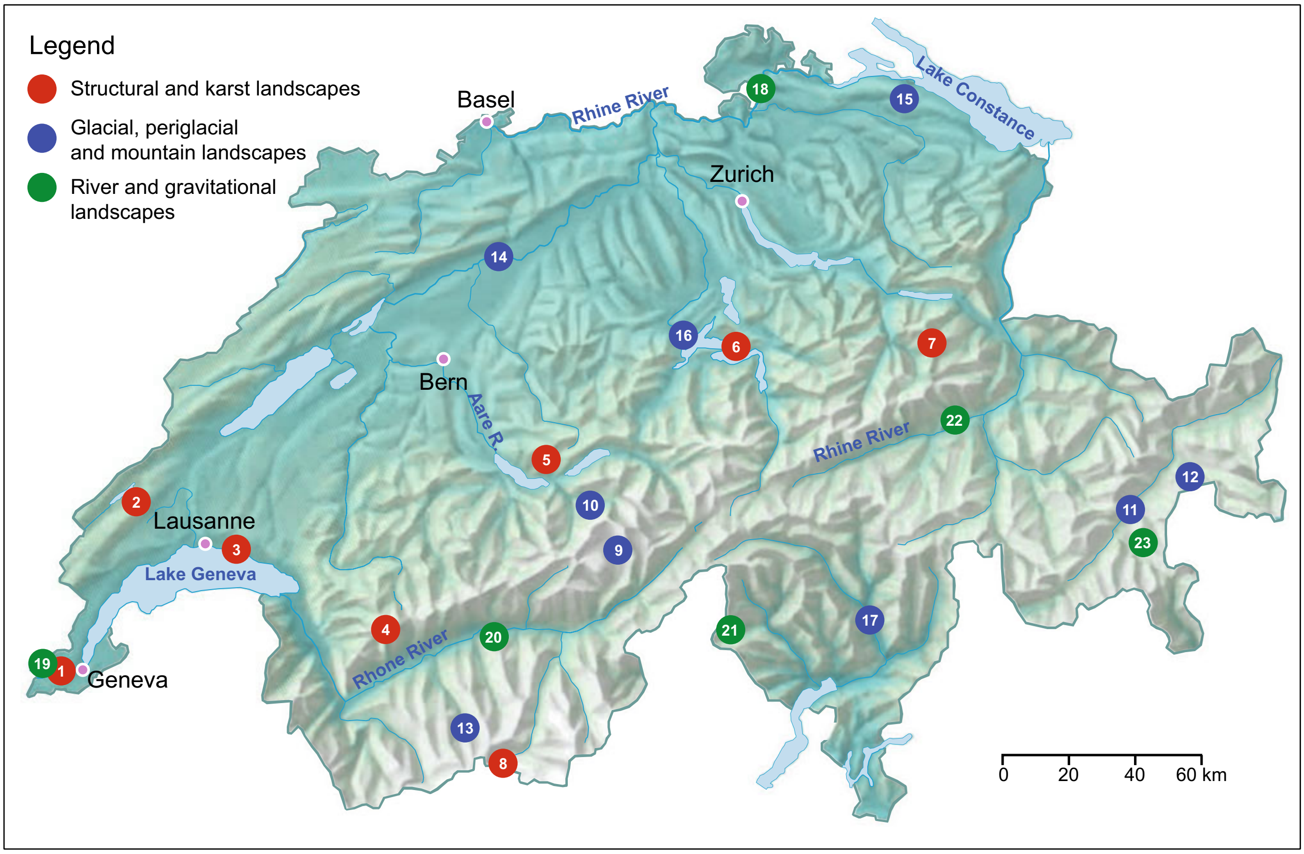

Fig. 1.1 Location of the 23 examples of geomorphological landscapes presented in section 2 of the book. 1. Geneva Basin; 2. Joux Valley; 3. Lavaux terraced vineyard; 4. Diablerets Massif; 5. Siebenhengste-Hohgant-Schrattenfluh karst system; 6. Structural landscapes of Central Switzerland; 7. Tectonic Arena Sardona World Heritage site; 8. Matterhorn; 9. Grosser Aletschgletscher; 10. Finsteraarhorn-Jungfrau glacier landscape; 11. Rockglaciers of the Engadine; 12. Swiss National Park; 13. Hérens Valley; 14. Wangen an der Aare glacier landscape; 15. Lake Constance glacier landscape; 16. Lake Lucerne; 17. Geomorphological landscapes of Ticino; 18. Rhine Falls; 19. Allondon River; 20. Illgraben torrential system; 21. Campo Vallemaggia landslide; 22. Flims and Tamins rockslide landscape; 23. Periglacial landscapes and protection measures above Pontresina. Source of the map: swisstopo

Emmanuel Reynard is Professor of Physical Geography and Director of the Interdisciplinary Centre on Mountain Research at the University of Lausanne, and a member of the International Association of Geomorphologists (IAG) Executive Committee. He has been chairman of the IAG Working Group on Geomorphosites (2001–2013) and president of the Working Group on Geotopes of the Swiss Academy of Sciences (2006–2017). His research concerns mountain geomorphology, geomorphological heritage, landscape geohistorical analyses and water management in mountains. He has worked in the Alps, the Romanian Carpathians and in the Maghreb (Tunisia, Morocco).

Part I

Physical Environment

2 The Geology of Switzerland

O. Adrian Pfiffner

Abstract

The general picture of the physiographic map of Switzerland reflects the tectonic structure rather directly. Local relief in the Jura Mountains is a direct consequence of folding of the detached Mesozoic strata. The Swiss Plateau mimics the Molasse Basin with flat lying sediments while thrusting and tilting of these strata in the Subalpine Molasse amalgamated these units with the Alps. The Alps exhibit nappe stacks of very different origin. Most of them evolved from pre-Triassic crystalline basement rocks and their sedimentary cover. In many cases the cover was detached from its basement and now forms a nappe stack of its own. The Helvetic nappe system derived from the European continental margin contains nappes of cover rocks displaced over 30–50 km; crystalline basement rocks form large-scale domes. The Penninic nappe system is derived from basins that formed in Mesozoic times between the European and Adriatic continents. They contain far travelled nappes of cover rocks, as well as nappes of basement rocks that were transported over considerable distances, too. In addition, nappes of oceanic rocks outcrop as thin slivers at the top. Post-nappe folding within the Penninic nappe stack is reminiscent of their complex formation history. The Austroalpine nappe system was derived from the Adriatic margin and now forms a horizontal layer as the highest unit in eastern and central Switzerland. This nappe system contains crystalline basement as well as Mesozoic cover rocks and was emplaced early in the Alpine history in a ENE direction. The Southalpine nappe system was derived from the Adriatic margin as well. Here thrusting of crystalline basement with its Mesozoic cover was south-directed. The various Alpine nappe piles led to the amalgamation of very different rock types: continental and oceanic basement rocks, shallow marine carbonates, deep marine clastics and radiolarian chert to name the most important. Landforms and landscapes reflect these differences, in addition to the landforms created by fluvial and glacial erosion.

Keywords

Rock types • Tectonic structure • Alpine nappe structure • Jura Mountains • Molasse Basin

2.1 Introduction

The geology of Switzerland covers the Central Alps, a segment of the Alpine chain located between the Western Alps of France and Italy and the Eastern Alps of Italy, Austria and Germany. In this segment the Alpine chain is particularly narrow, yet it contains all the major tectonic units and exhibits landmark landscapes and landforms for which the Alps are known. This chapter aims at giving an overview of the geological structure of Switzerland, the major rock types involved, the geological history related to these rock types and their impact on Alpine landforms and landscapes. An overview of the geology of Switzerland can also be found in Trümpy (1980), Pfiffner (2014, 2019) and geodata are available from the Swiss Geological Survey (https://www.swisstopo.admin.ch).

The digital elevation model in Fig. 2.1 displays the deep valleys carved into the Swiss Alps. The high local relief along the Rhine and Rhone rivers is highlighted by the green color of the low lying valley floors in comparison to the high mountain ranges on either side. Both the Rhine and Rhone rivers follow longitudinal valleys within the Alps but exit the Alps as transverse rivers. The major Alpine rivers drain into various seas: Rhine into the North Sea, Rhone into the Mediterranean Sea, Adda into the Adriatic Sea (via Po River), and Inn into the Black Sea (joining the Danube).

O. A. Pfiffner (✉)
Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland
e-mail: adrian.pfiffner@geo.unibe.ch

E. Reynard (ed.), *Landscapes and Landforms of Switzerland*, World Geomorphological Landscapes,
https://doi.org/10.1007/978-3-030-43203-4_2

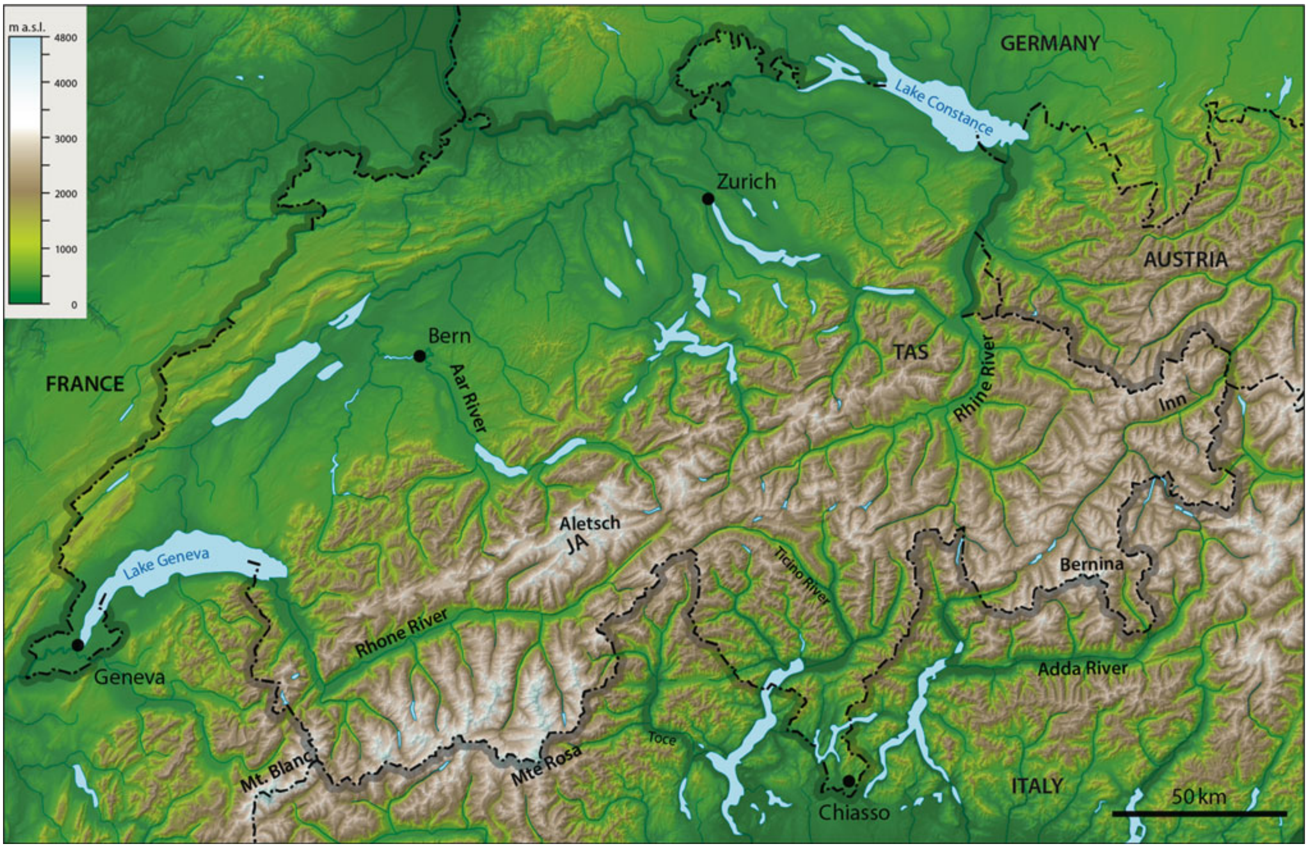

Fig. 2.1 Digital elevation model (DEM) of Switzerland giving the main features pertinent to this chapter. UNESCO World Heritage sites: JA = Swiss Alps Jungfrau-Aletsch, TAS = Swiss Tectonic Arena Sardona

Within the Central Alps three areas of high elevation exceeding 4000 m a.s.l. can be recognized: Mont Blanc—Monte Rosa, Aletsch, and Bernina. These areas are dominated by granitic bedrock. These rocks are resistant to erosion and are therefore worn down more slowly (see Kühni and Pfiffner 2001a) The Po Basin to the south of the Alps (south of Chiasso) lies at around 300 m a.s.l. To the north, the Swiss Plateau extends from Lake Geneva to Bern, Zürich, and Lake Constance tapering off from around 600 to 400 m a.s.l. This plateau corresponds to what is called Molasse Basin discussed later in Sect. 2.2.3. To the NW of this plateau the Jura Mountains straddle along the border between Switzerland and France.

The geological structure of Switzerland is shown as a simplified tectonic map in Fig. 2.2. The nappe systems between the Po Basin and Molasse Basin derive from the continental margins of Europe and Adria (a promontory of Africa) and the ocean basins that once existed between the two margins. These nappe systems consist of two groups of rock types: crystalline basement rocks (granites, gneisses, and schists; stippled in Fig. 2.2) and cover sediments that were deposited on these. The Helvetic nappe system can be attributed to the European margin. Its cover sediments continue in the subsurface of the Molasse Basin and reappear in the Jura Mountains and the Foreland around the basement uplifts of the Vosges and Black Forest. The Penninic nappe system is derived from the marine basins, which formed in Mesozoic times between the two continental margins. The Adriatic margin is found today in three units; the Austroalpine, Southalpine, and Salassic nappe systems. The Insubric Fault is part of the Peri-Adriatic fault system, a major fault zone that marks the northern limit of the Southalpine nappe system. Several magmatic intrusions occurred at 40–30 Ma along this fault system, two of which are shown in red in Fig. 2.2.

The deep geological structure of Switzerland is shown in the simplified cross-section in Fig. 2.3. The MOHO, the crust-mantle boundary, is shown to dip from the ordinary value of 30 km for continental crust to more than 50 km beneath the core of the Alps. As visible in the cross-section the crust is thicker because of thrust faults and folds that affected the entire crust. In case of the Aar massif the top

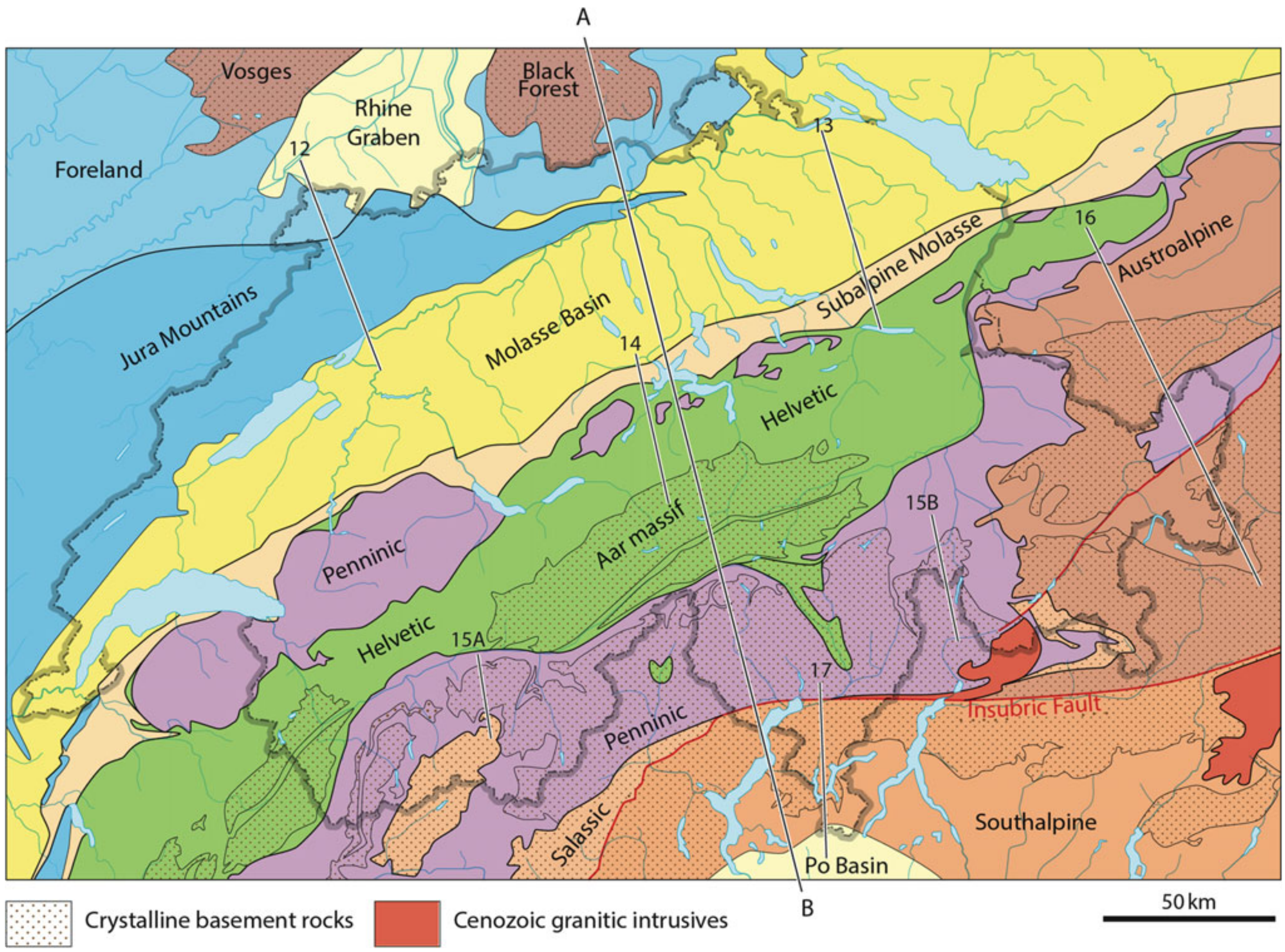

Fig. 2.2 Tectonic map of Switzerland showing the major tectonic units. The line AB is the trace of the cross-section shown in Fig. 2.3, numbers 12–17 denote traces of cross-sections in Figs. 2.12, 2.13, 2.14, 2.15, 2.16 and 2.17

basement was uplifted from 7000 m below sea level to 4000 m above sea level in the process of thickening. The Mesozoic cover sediments are shown to continue from the Aar massif to the NNW beneath the Molasse Basin and link with the Jura Mountains.

The Helvetic and Penninic nappes were transported over distances of 50–200 km as thin sheets of rocks. These sheets, called nappes, are typically 1–3 km thick. It is important to note that most of this nappe pile—a heap of around 30 km—has been eroded in the course of the last 30 million years. The outline of this eroded nappe pile is indicated by the thrust faults shown in the air above the Aar massif (dashed lines in Fig. 2.3). The ancestral rivers, which were responsible for this vast erosion, initiated in the Austroalpine and Penninic nappe systems that once covered the Central Alps. The river network that developed was controlled by the structure and distribution of the different rock types within these nappes. As these rivers incised the bedrock they encountered progressively new rock types and structures which influenced the river network and most likely led to profound changes in the courses of rivers (see also Buckingham and Pfiffner, this volume).

As visible in Fig. 2.3, the Cenozoic sediments of the Molasse Basin extend southward beneath the Helvetic nappe system. The southern part of these sediments was detached, transported northward, and tilted. It now forms the so-called Subalpine Molasse (see Fig. 2.2). The Cenozoic basin fill of the Po Basin to the south of the Alps was also affected by Alpine tectonics. Here thrusting was directed south. Altogether, the Alps form a bivergent mountain belt. The Insubric Fault is a nearly vertical fault that extends deep down into the crust. The units to the north of it were uplifted along this fault and sheared into a large-scale antiformal fold.

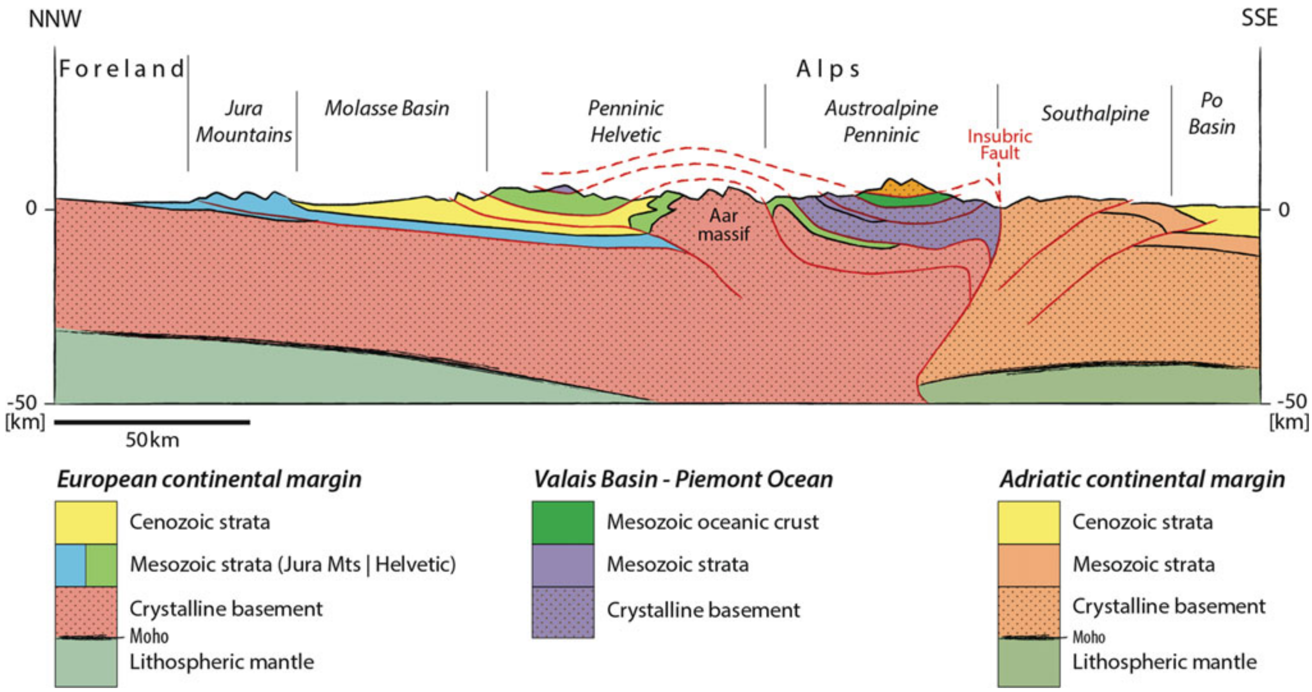

Fig. 2.3 Cross-section from the Northalpine Foreland to the Po Basin. Trace of cross-section is given in Fig. 2.2

2.2 Major Rock Types and Paleogeography

Regarding the geologic structure as well as landforms and landscapes it is useful to distinguish between basement and cover rocks. In the Alpine context basement relates to crystalline basement and cover to its sedimentary cover. In the following the various rock types are discussed in chronological order regarding their age.

2.2.1 Crystalline Basement Rocks

Crystalline basement rocks represent the oldest rock types. They include polymetamorphic gneisses, amphibolites, and granites. Polymetamorphic gneisses are rocks that were heated up to high temperatures (400 °C or more) and deformed. They include granites that intruded the crust more than 400 Ma ago and were transformed (or metamorphosed) to orthogneisses, as well as sediments that were metamorphosed to paragneisses. Amphibolites represent metamorphosed basalts. All these rocks were part of ancient mountain belts that formed 600 and 440 Ma ago and since have been worn down completely. The crystalline basement contains also a rock suite that formed in the course of the Variscan phase of mountain building some 300 Ma ago. They include granites (intruded at 330 and 300 Ma) and late Paleozoic sedimentary and volcanic rocks ranging in age from 300 to 250 Ma. Regarding Switzerland and neighboring areas the crystalline basement was completely worn down by the end of the Paleozoic Era such that shallow seas were able to invade the area subsequently.

In the course of the Alpine cycle of mountain building the crystalline basement was deformed (again), gneisses and granites undergoing another phase of metamorphism. Figure 2.4 shows typical landscapes made of crystalline basement. The photograph in Fig. 2.4a is taken in the UNESCO World Natural Heritage site Swiss Alps Jungfrau-Aletsch (see location in Fig. 2.1). Rugged peaks are at least partly covered with glaciers. The latter were responsible for the development of horns, i.e., peaks with steep flanks created by erosion of cirque glaciers and separated by crests that merge in the summit. Bedrock in this area is predominantly granitic. Figure 2.4b shows the Leventina valley (Ticino River; see location in Fig. 2.1) where the bedrock is made of ortho- and paragneisses. The foliation in these rocks is subhorizontal but does not express itself significantly in the landscape. The strips of agricultural land with the villages of Chironico and Sobrio half way up the mountain flanks are within a homogeneous complex of orthogneisses. The break in slope must be remnant of an ancient valley floor.

2.2.2 Mesozoic Rocks

Mesozoic cover rocks are sediments of variable composition and depositional conditions. The differences arise from the fact that these sediments formed in the course of the breakup

Fig. 2.4 Landscapes in crystalline basement rocks (photos © VBS). **a** Granitic basement in the Swiss Alps region Jungfrau-Aletsch (Bern/Valais) with Bietschhorn, Aletschhorn and Finsteraarhorn. **b** Gneiss basement in the Leventina Valley (Ticino)

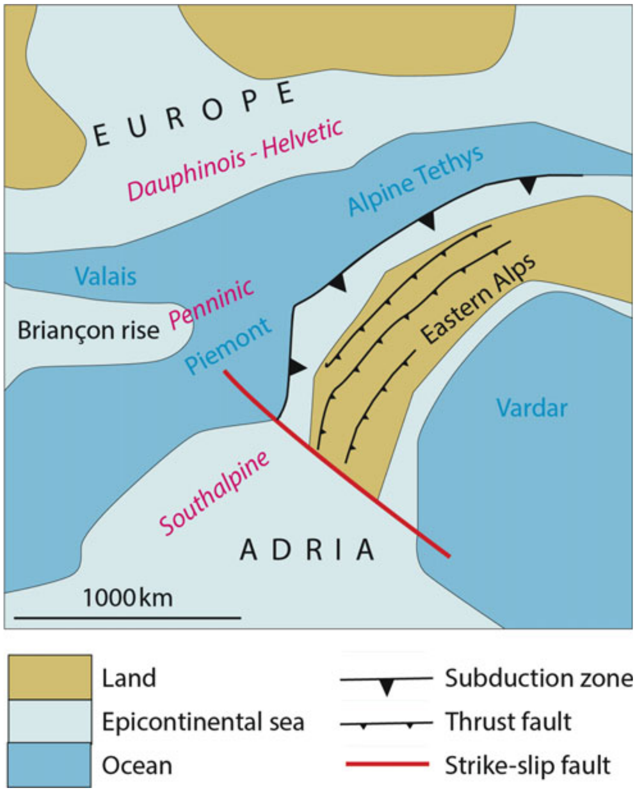

Fig. 2.5 Paleogeographic map in mid-Cretaceous times at around 100 Ma

of Pangea into the continents of Europe, Africa, North, and South America. During this breakup the margins of the continents were first stretched and thinned and as a consequence subsided. Later on complete disintegration of the continents led to the formation of oceanic basins, the Alpine Tethys, between the continental margins. The cover rocks in Switzerland implied the margins of Europe and Adria as well as the Alpine Tethys in between. The paleogeography of the future Alpine region was rather complex as shown in Fig. 2.5, which shows the situation at around 100 Ma. The Alpine Tethys had two branches toward the west: the Piemont Ocean, a true ocean, and the Valais Basin, a deep basin which only locally had true oceanic character. The Briançon rise between the two basins had a continental crust of European affinity. At 100 Ma Adria and Europe converged in a WNW–ESE direction. The Alpine Tethys was subducting beneath Adria and thrusting was going on in the Eastern Alps such that they already rose above sea level. Sedimentation continued in the Southalpine, Penninic, and Helvetic domains.

In the following the most important rock suites are briefly summarized in terms of their importance on landforms and landscapes. Key factors are their thickness and erosional resistance.

Limestone sequences that are 100–500 m thick are widespread, deposited in the shallow epicontinental seas on the European margin and the Briançon rise. Slow subsidence in Late Jurassic and Cretaceous times favored accumulation of a thick sequence of massive limestones, which are resistant to erosion and now form high, laterally continuous cliffs. Figure 2.6 shows the area around Vättis (St. Gallen) in the UNESCO World Heritage site Tectonic Arena Sardona in eastern Switzerland (see Fig. 2.1 for location). Here the gray Jurassic and brownish Cretaceous limestones are stacked on top of each other by thrusting such that cliffs led to a local relief of 2000 m (see also Buckingham and Pfiffner, this volume).

In the Valais basin thick sequences of thin-bedded sandstones and limestone interlayered with shales accumulated. These Late Jurassic–Cretaceous strata (called «Bündnerschiefer» in the local literature) are up to 1000 m thick and are overlain by Cenozoic strata of similar composition that are also a few hundred meters thick. These sequences are also heavily folded and repeated by thrusting such that rivers carved out local relief of more than 1000 m. They appear dark in color in the landscape.

Generally speaking these sandstone-limestone-shale sequences are prone to erosion. Constant dip of these units over larger areas induces asymmetric valleys. The low-angle slopes are parallel to the dip of the beds, including shaly layers. As a consequence, entire slopes slip downhill under the action of gravity, a process that is enhanced by rainfall. An example of such a dip slope is shown in Fig. 2.7a, the western flank of Safiental (Graubünden, eastern Switzerland), which exhibits agricultural activity on the entire flank. Steep slopes on the other hand show gully erosion and large alluvial fans formed at the base of the mountain flanks. Figure 2.7b reveals gully erosion on the northern flank of the Signina Group, including the peaks of Schlüechtli, Tällistock, Piz Riein, and Piz Miezgi.

Oceanic rocks attributed to the Piemont Ocean occur as a sliver of variable thickness that can be traced across the Alps. Their importance lies in the fact that they represent remnants of the subducted ocean floor, which marks the former plate boundary between the Adriatic plate and the Alpine Tethys, which was the leading edge of the European plate. Rock types include serpentinite, gabbro, and basalt. Serpentinite formed by hydration of mantle rocks which appeared at the ocean floor when the ocean opened and the two continents drifted apart. Gabbro and basalts formed from melts within the Earth's mantle, which ascended along fractures that opened in the process of drifting. These oceanic rocks are unfavorable for vegetation owing to their chemical composition (high magnesium content among other) and thus appear as barren rock surfaces even within gentle slopes. They tend to develop reddish-brownish weathering surfaces. Basalts on the other hand can be recognized by their

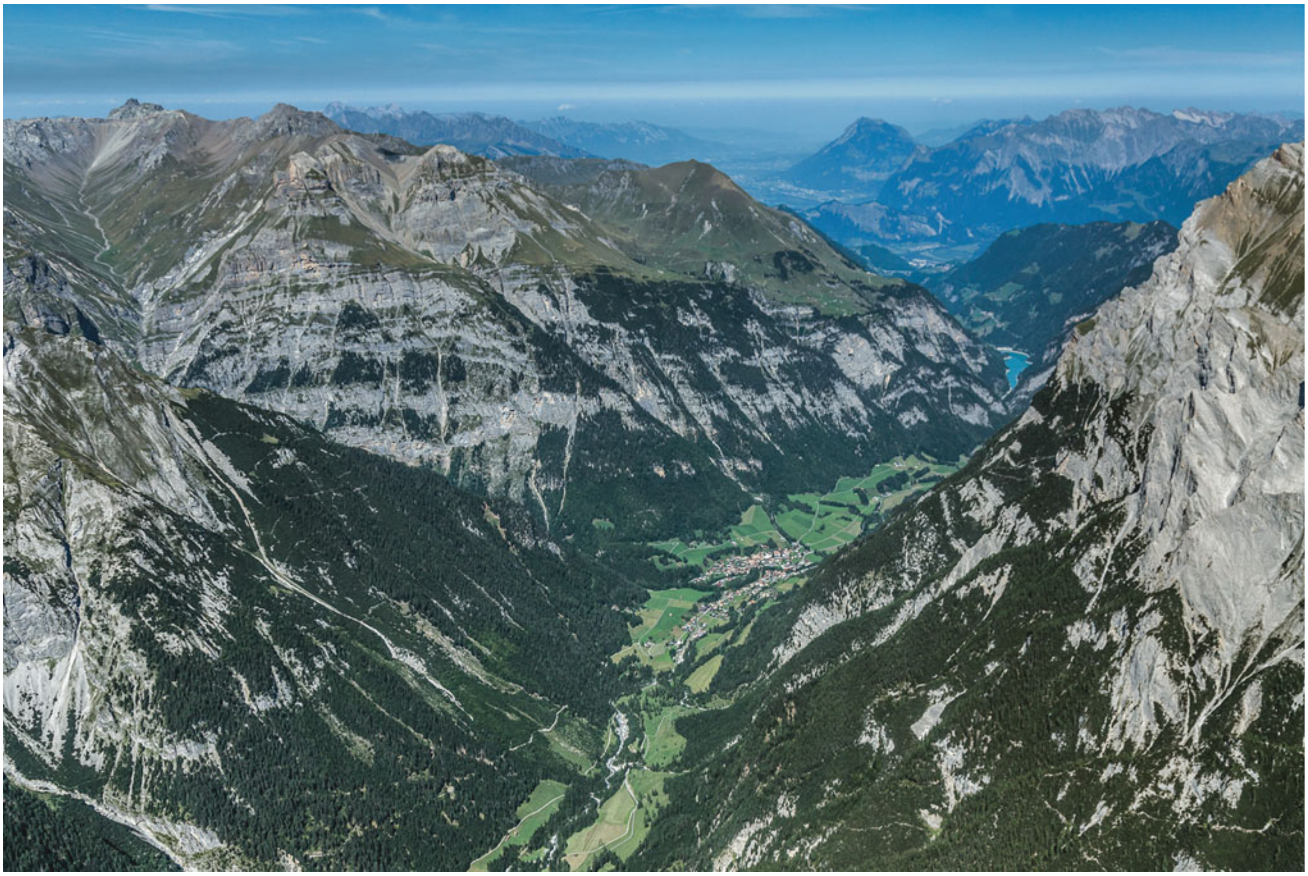

Fig. 2.6 Limestone cliffs around the village of Vättis (St. Gallen) (photo © IG Tektonik Arena Sardona: R. Homberger)

predominantly greenish color in the landscape. The two photographs in Fig. 2.8 illustrate these observations.

2.2.3 Cenozoic Rocks

Cenozoic rocks in Switzerland encompass mainly sedimentary sequences that are known under the name of Flysch and Molasse. Both are synorogenic sediments, that is to say they were deposited as the Alpine chain was emerging. And both Flysch and Molasse accumulated in foreland basins that were adjacent to the front of the growing chain. The basins migrated outward as the chain became wider.

Flysch sediments were deposited in narrow but deep marine troughs by turbidity flows, i.e., submarine mass flows that were possibly triggered by earthquakes on the steep sea bottom. Turbidite deposits are fining upward clastic sediments, with conglomerates or coarse-grained sandstone at the base and shale at the top. Flysch deposits consist of hundreds of turbidites.

Molasse sediments were deposited under conditions changing from marine to continental (Kempf et al. 1999). The oldest unit, the Lower Marine Molasse (*Untere Meeresmolasse* in German, UMM) evolved in time and space from Flysch deposits. As the basin was filled, conditions became continental and gave way to deposition of the Lower Freshwater Molasse (*Untere Süsswassermolasse*, USM). The latter encompasses conglomerates and sandstones deposited by rivers emanating from the early Alpine chain as alluvial fans, as well as mudstones and marls which were deposited on floodplains outside these fans. The incursion of a shallow sea from the east led to the accumulation of sand on tidal flats (Upper Marine Molasse; *Obere Meeresmolasse*, OMM). Once more the basin was filled and a new set of alluvial fans with conglomerates and sandstones were built and accompanied by mudstone and marl deposits in flood plains (Upper Freshwater Molasse; *Obere Süsswassermolasse*, OSM).

The palaeogeographic map in Fig. 2.9a depicts the situation during the deposition of the Lower Freshwater Molasse (UMM) in Oligocene times (25 Ma). The ancestral rivers that drained the Central Alps to the north flowed eastward into the Vienna Basin once they left the mountain chain, while the rivers draining to the south flowed into the persisting Po Basin. The situation changed in the following 10 million years. In Miocene times (15 Ma) the rivers of the

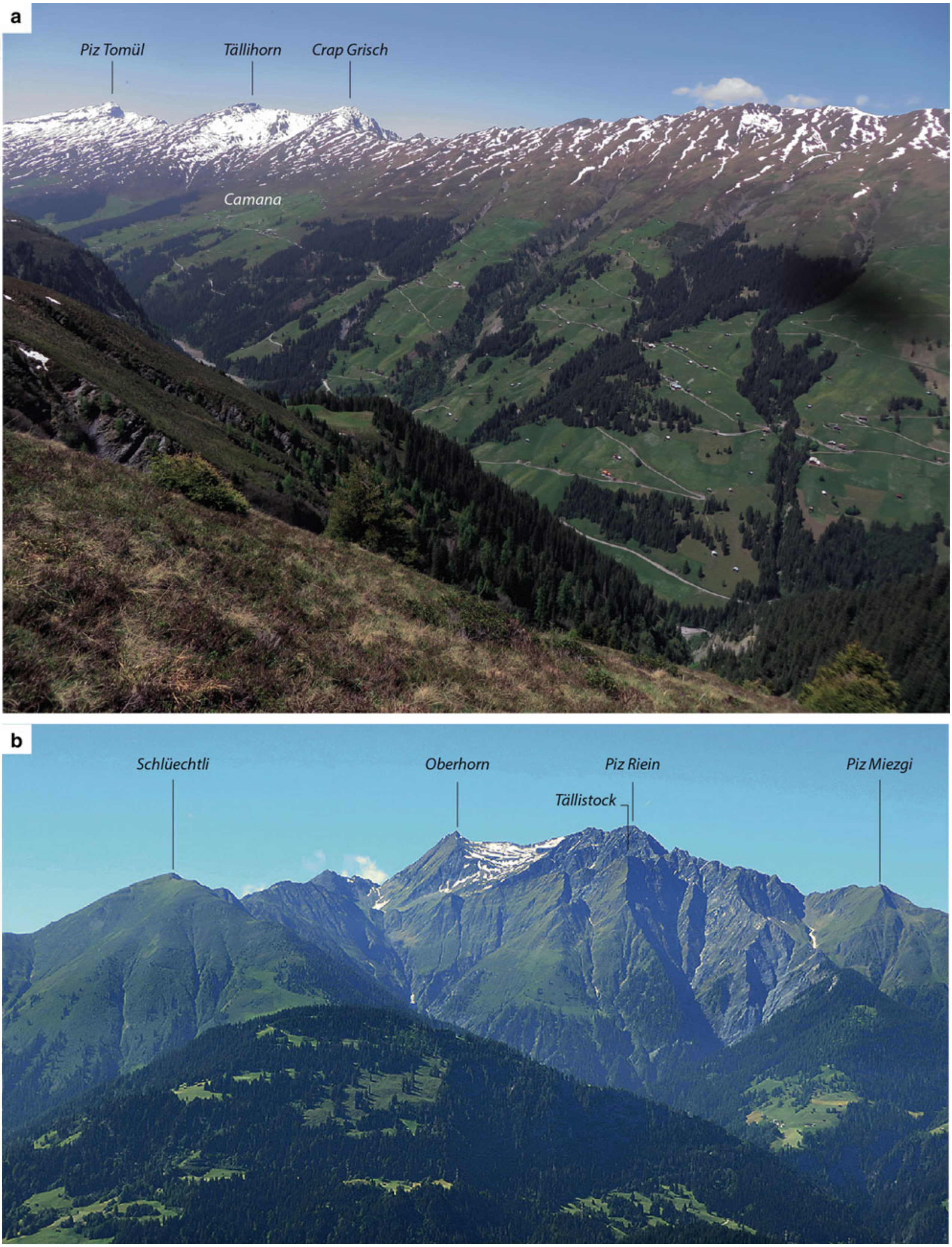

Fig. 2.7 "Bündnerschiefer" landscapes in Graubünden (photos A. Pfiffner). **a** Safiental (Graubünden). The smooth flank is a dip slope gently moving downhill. **b** Signina Group (Graubünden). The steep slopes incised by numerous channels bear witness to gully erosion

Fig. 2.8 Oceanic rocks in the Alps. **a** Avers Valley (Graubünden). The Avers nappe is made of "Bündnerschiefer" beneath the grass covered slope. The Platta nappe contains basalts and, visible in the summit of Mazzaspitz, serpentinite (photo A. Pfiffner). **b** Zermatt area (Valais) with Matterhorn. View is towards the west. The reddish-brownish ridges next to the glaciers are made of serpentinite (photo © VBS)

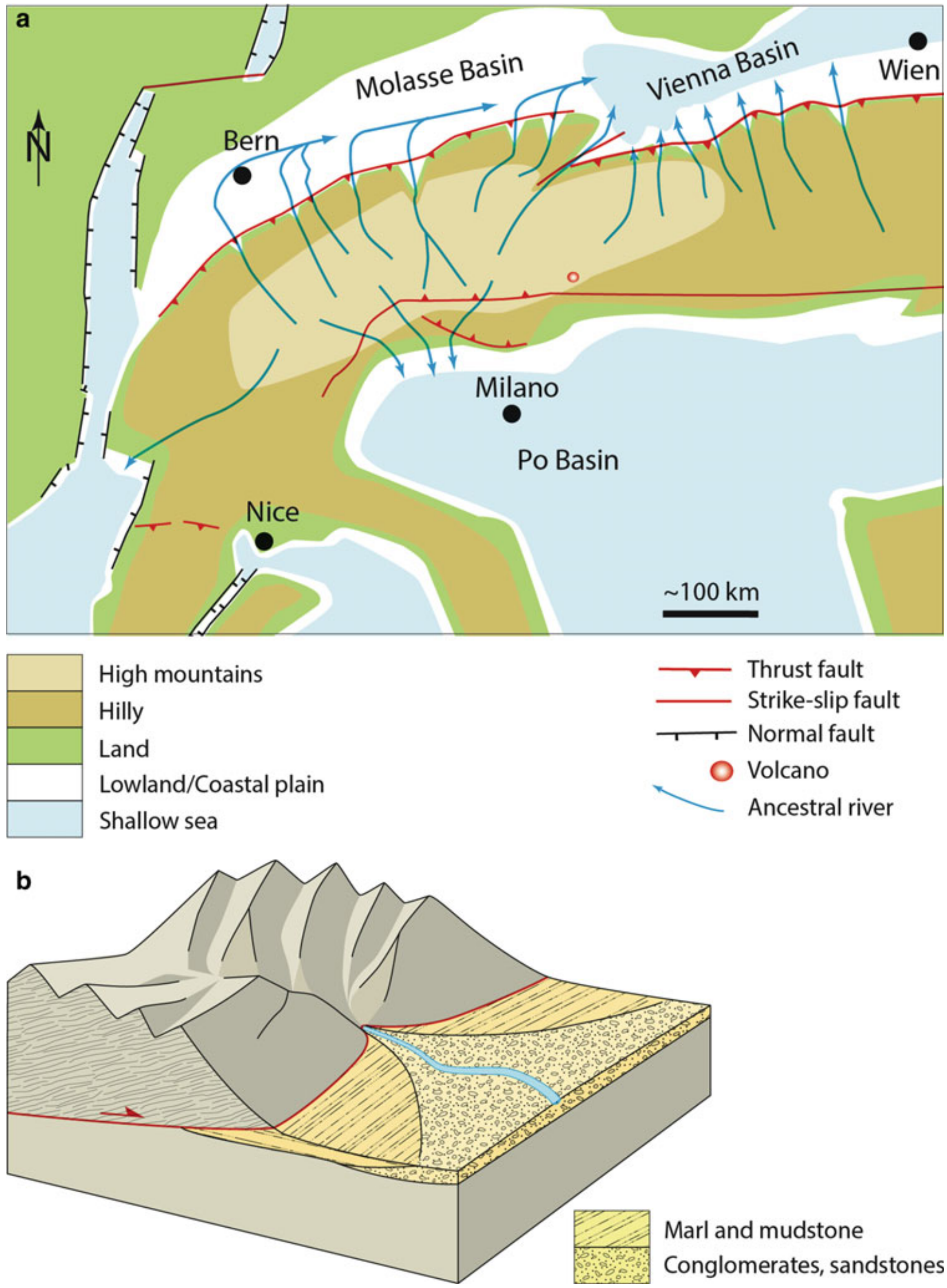

Fig. 2.9 Oligocene paleogeography of the Alps. **a** Paleogeographic map in Oligocene times at 25 Ma. **b** Architecture of an alluvial fan in the Molasse Basin

Upper Freshwater Molasse (OSM) draining to the north took a westward course after leaving the mountain chain. Figure 2.9b illustrates the landscape and depositional environment of an alluvial fan of the Lower or Upper Freshwater Molasse. The mountain chain was incised by the rivers and was contemporaneously uplifted by active thrusting. The observation that some of the alluvial fans kept their position over a long time suggests that the rivers had a constant course at least in their lower reaches. Here it has to be noted that locally the bedrock of the lower reaches was uplifted and eroded simultaneously with incision (Pfiffner 2014). It thus seems that incision was efficient, possibly due to steep channel gradients and/or high discharges. Numerical modeling of tectonic forcing on river network evolution confirms the persistence of rivers in such a dynamic environment (Kühni and Pfiffner 2001b). As reported by Schlunegger and Castelltort (2016), changes in the sedimentary architecture and pebble composition did occur and suggest that in the upper reaches new source rocks were tapped at times suggesting a dynamic landscape evolution.

2.2.4 Quaternary Deposits and Landforms

In the course of the Quaternary the Swiss Alps and their foreland were covered by ice more than a dozen times. Fluvio-glacial gravels deposited in the foreland allowed us to date the sequence of these drastic climatic changes (see Schlüchter et al., this volume). Several times the glaciers advanced way out into the foreland in the north, but barely reached the southern foreland as for example evident on the map showing ice distribution during the Last Glacial Maximum, LGM (see Schlüchter et al., this volume).

Shaping of the landscapes by glaciers was particularly important in the inner Alpine valleys. The glaciers over-deepened and widened the valleys. But after the melt down of the ice running water incised the slopes and existing valleys rather efficiently. The bed load of these rivers accumulated in the over-deepened valleys. As a consequence we find valleys of different type throughout the Alps (see Fig. 2.10a). V-shaped river valleys are the youngest and occur as tributaries of trunk rivers and on the higher areas in the absence of glaciers. In the Illgraben (Valais; see McArdell and Sartori, this volume) shown in Fig. 2.10b incision was aided by a crumbling rock type and high river gradient. A huge fan (Pfyn fan) formed where the river joins the Rhone River. Such fans exist in many other places along the Rhine and Rhone valleys. On the south side of the Alps, a number of V-shaped canyons was carved out by rivers when their base level was lowered in Messinian times (at around 6 Ma) because the Mediterranean had dried out completely (see Scapozza and Ambrosi, this volume). Bedrock incision reached to 500 and even 800 m below sea level. The canyons were later backfilled by Pliocene and Quaternary sediments and present themselves now as flat-floored valleys.

Two types of U-shaped valleys need to be distinguished (see Fig. 2.10a): flat-floored valleys and trough valleys. Flat-floored valleys emanate from glacially over-deepened valleys that are backfilled by glacio-fluvial and fluvial sediments. Figure 2.10c shows the example of an inner Alpine valley, the Gastern valley. It became famous for a misinterpretation by Albert Heim who at the time did not believe that glaciers were able to erode downward. As a consequence the railroad tunnel, which was intended to cross the valley at roughly 1200 m a.s.l., was flooded when it arrived in the water-saturated Quaternary fill. If the bedrock surface is considered only, the Gastern valley resembles more a V- than a U-shaped valley. In case of the Rhone and Rhine valleys (Pfiffner et al. 1997), as well as many other valleys (Wildi 1984), the bedrock surface beneath the valley floors is at and below sea level. These over-deepened valleys were backfilled during the meltdown of the glacier by fine-grained clastics that accumulated at the bottom of lakes underlying the floating dead ice. In trough valleys the bedrock is (still) exposed on the valley floor. Figure 2.10d illustrates a classic trough valley, the Morteratsch valley (Graubünden). The river flows on bedrock and the lateral moraines (in gray) of the Little Ice Age (LIA) testify to the level reached by the glacier in the 1850s. The photograph also highlights the scoured and rounded ridges, which date from the LGM.

Quaternary deposits outside the Alps include glacio-fluvial gravels which accumulated at the front of the glaciers. These gravels occur at several levels, the oldest (*Deckenschotter*) being the topmost (see Schlüchter et al., this volume, for a detailed discussion). The various gravels were incised after their deposition and are now visible as terraces in the landscape.

Several large rock avalanches went down from mountain flanks and covered valley floors in Holocene times. The largest one, the Flims rock avalanche (Graubünden) occurred ca. 9500 years ago (see von Poschinger et al., this volume). It covers an area of 40 km^2 and dammed a lake upstream. Another rock avalanche is located immediately downstream at Reichenau/Tamins (Graubünden). It went down earlier and also dammed a lake. Outbursts of these lakes significantly modified the valley floor of the Rhine River. Notable landforms that were created by the outbursts are "tumas", i.e. hills composed of rock avalanche material that was remobilized and transported over large distances upstream and downstream before being deposited (V. Poschinger et al., this volume, Pfiffner 2019). Other examples of a pre-historic rock avalanche that significantly modified the valley floor can be found in the Kander valley (Bern), near Davos (Graubünden), near Lenzerheide (Graubünden), and around Sierre (Valais). Besides, a number of younger rock avalanches destroyed villages and/or caused heavy damages: Biasca (Ticino), Corbeyrier (Valais), Piuro (Graubünden), Derborence (Valais), Goldau (Schwyz), Elm (Glarus), Randa (Valais), and Bondo (Graubünden).

2.3 Tectonic Structure of the Swiss Alps

The Alps are a classic example for the study of mountain building. Generations of geologists mapped the many valleys and peaks in such great detail that today we can study the interplay between plate tectonics and the creation of the Alpine relief. Plate tectonics involves the breakup of the supercontinent Pangea with the opening of the Alpine Tethys, followed by the subduction of this ocean beneath the Adriatic continent and finally the collision of the European with the Adriatic continent. The convergence between the two continents led to the formation of tectonic nappes, i.e., slices of the Earth's crust piled up on top of each other. One of the advocates of these nappe piles was Emil Argand. He illustrated his conception in a cross-section across the entire

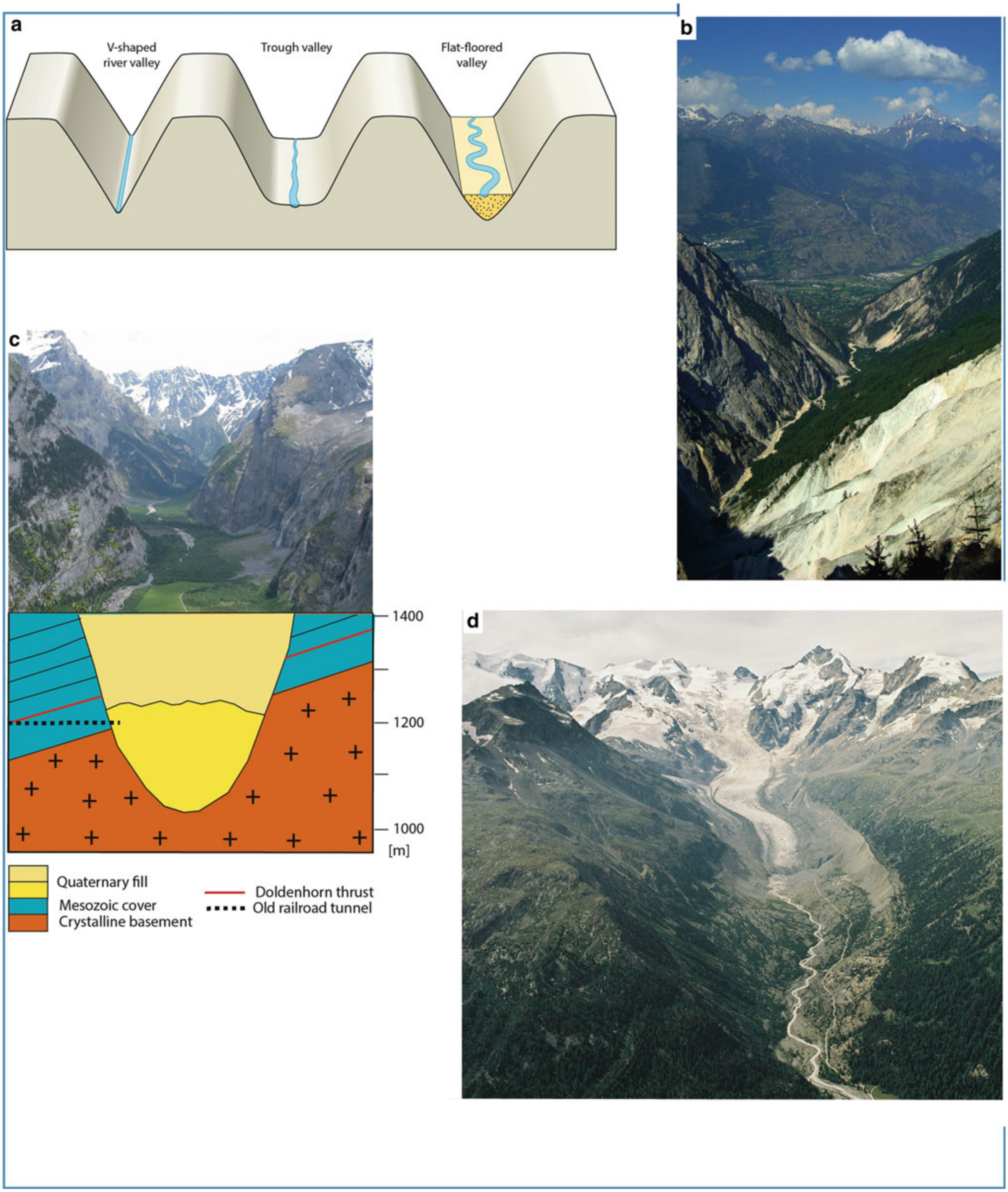

Fig. 2.10 Quaternary landforms. **a** Valley types. **b** V-shaped valley Illgraben (photo A. Pfiffner). **c** Overdeepened flat-floored Gastern valley (photo A. Pfiffner). **d** Trough valley Morteratsch (photo © VBS)

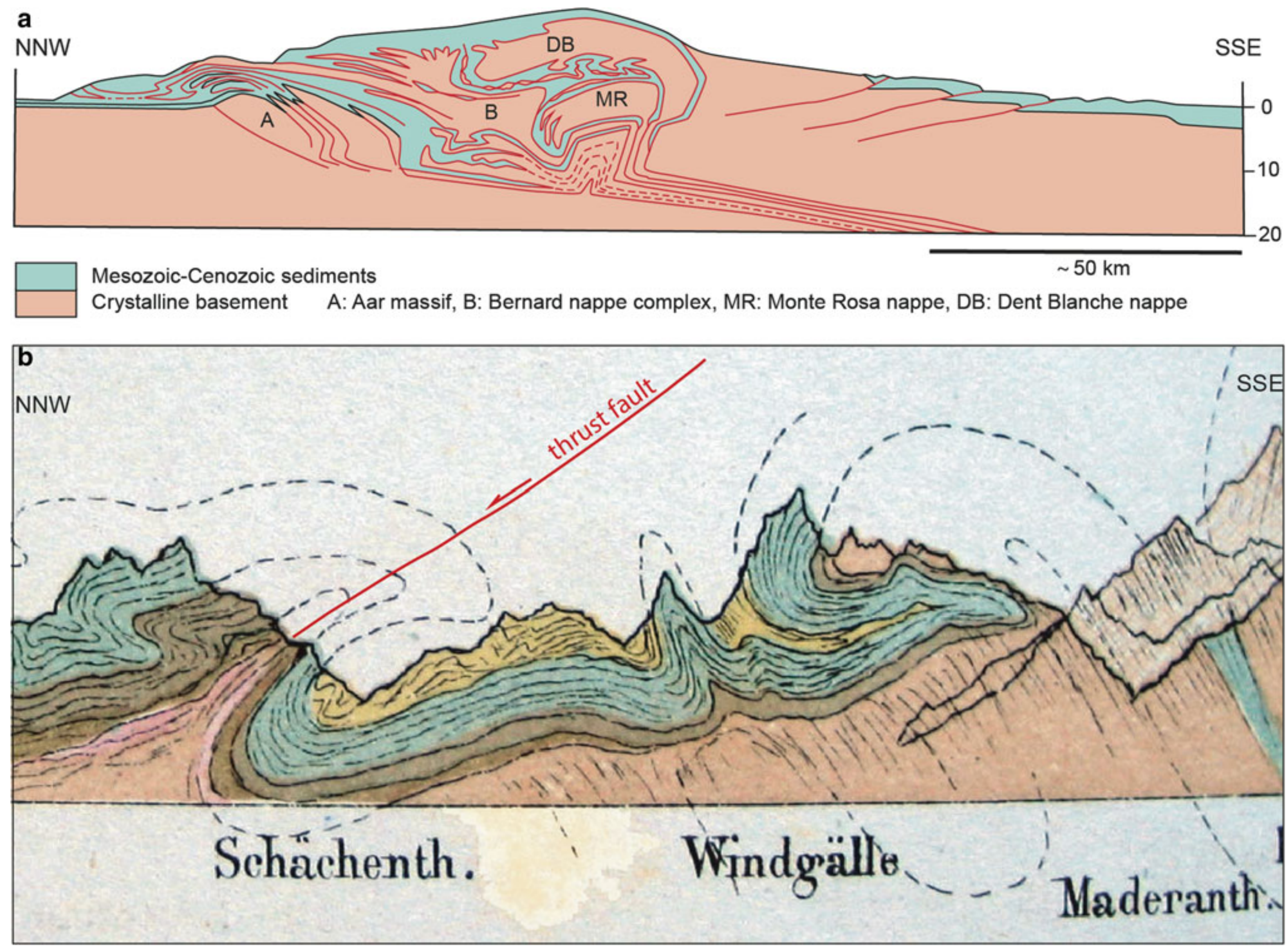

Fig. 2.11 Tectonic style of the Alps as conceived by early workers. **a** Cross-section redrawn after Argand (1928). **b** Detail of cross-section taken from Heim (1919–1922). The thrust fault marked in red was added by the author to indicate the modern understanding of nappe tectonics

Alps (Fig. 2.11a). Nappes of crystalline basement rocks separated by thin slivers of Mesozoic-Cenozoic sediments are piled on top of each other; the contacts between basement and cover is shown to be intricately folded. Albert Heim worked in the Windgälle area (Fig. 2.11b) and was impressed by the pervasive folding he saw there, to a point where he rejected the idea of nappes for a long time. The anticline north of Schächenthal in Fig. 2.11b, with a thin tongue of crystalline basement sticking upward to the south (and not reaching the surface) was drawn to avoid a thrust fault explaining that older rocks are lying on top of younger rocks in the northern flank of Schächenthal. Today we know that this fault (the Axen thrust) is one of the important thrust faults, which moved the Axen nappe over a distance of some 50 km.

Thrusting and folding resulted in a complex nappe stack and the juxtaposition of very different rock types deep in the crust and near the surface. The removal of the top part of this nappe stack by erosion rendered the situation even more complex because deeply incised valleys make the original structure discontinuous. Thus a geological map seems like a puzzle of differently shaped and colored pieces difficult to interpret. In order to make this chaos intelligible, the major geological units are discussed using representative cross-sections and photographs. Generally speaking we distinguish three major nappe systems within the Alpine chain. The Helvetic nappe system consists of units that are derived from the margin of the European continent. The Penninic nappe system encompasses nappes derived from the Alpine Tethys that once existed between the European and Adriatic margin. The Adriatic margin in the Alps is represented by the Austroalpine nappe system in eastern and central Switzerland, by the Southalpine nappe system in southern Switzerland and northern Italy, and the Salassic nappes that outcrop mainly in western Switzerland and neighboring Italy. Apart from the Helvetic nappe system, the former European margin includes also the Jura Mountains and the Molasse Basin of the Swiss Plateau. The discussion of these tectonic provinces will proceed from north to south.