GEOSCIENCE

Dynamics of the Continental Lithosphere

Geodynamics of the Alps 2

Pre-collisional Processes

Coordinated by
Claudio L. Rosenberg
Nicolas Bellahsen

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Dynamics of the Continental Lithosphere,
Subject Head – Sylvie Leroy

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First published 2023 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

ISTE Ltd
27-37 St George's Road
London SW19 4EU
UK

www.iste.co.uk

John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

www.wiley.com

Library of Congress Control Number: 2022941465

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-78945-117-7

ERC code:
PE10 Earth System Science
PE10_4 Terrestrial ecology, land cover change
PE10_5 Geology, tectonics, volcanology
PE10_13 Physical geography

Contents

Introduction

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The European Alps represent an archetypal mountain belt, mainly because its orogenic wedge is the most studied one. It results from a period of Mesozoic divergence forming the Tethyan Ligurian oceanic realm, linking the Neo-Tethys in the east with the Central Atlantic in the west. This followed the Variscan orogenic event affecting the European lithosphere and preceded a period of convergence starting during upper Cretaceous times with the northward movement of the Adria/Africa plates. This convergence was first accommodated by oceanic subduction, and later followed by continental subduction and eventually collision *sensu stricto*. The transition between oceanic and continental subduction is characterized by exhumation of high-pressure (HP) nappes of oceanic origin during early Eocene times, followed by HP metamorphism and exhumation of continental units during middle to late Eocene (Briançonnais and European distal continental margin). Collision started at the Eocene–Oligocene transition and is characterized by barrovian metamorphism, crustal shortening, high topographic relief and molasse-type peri-orogenic basins. During the whole convergence history, the amount of magmatism was very small. Today, convergence has slowed down, varying from almost zero in the Western Alps to approximately 2 mm/yr in the Eastern Alps, although vertical movements, extensive and compressive earthquakes are recorded, even in the Western Alps.

In spite of the latter observations, the European Alps may be considered as simpler than many other mountain belts that also result from the closure of oceanic domains. Indeed, in many other mountain belts, subduction and collision do not

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follow a simple sequence. For example, in the middle Paleozoic, during the Caledonian cycle and the Iapetus closure and more recently, during Cenozoic times and the Tethys closure between India and Asia, HP metamorphism events occurred long after the onset of collision. This is possibly due to the subduction of larger oceanic domains, and to longer and more vigorous convergence dynamics, which probably did not affect the Alpine realm.

The book *Geodynamics of the Alps* consists of three volumes. The first includes the recent and present-day structure and tectonic setting of the Alpine chain, from lithospheric mantle to brittle crust and surface topography, but also a historical overview of Alpine research and includes two chapters covering specific Alpine regions (Corsica and Eastern Alps), through all phases of Alpine history.

The second volume presents the pre-collisional history of the Alps. It starts with the Variscan orogeny in the Alpine realm, and continues with the inferred paleogeography, structure and extensional processes affecting continental margins, and their mantle structure in the pre-orogenic Alpine realm. This volume finishes with two chapters describing oceanic and continental subduction processes.

The third volume is entirely dedicated to Alpine collision. It describes and interprets the following elements of the Alpine chain: (1) Alpine magmatism, which is mainly contemporaneous to the very first stages of collision; (2) the formation of the external massifs, which represent a peculiarity in the Alpine chain, rarely occurring in other collisional orogens; (3) the foreland (Molasse) basin, in relation to the lithospheric processes that controlled its evolution; (4) exhumation of the internal part of the chain as constrained from the thermo-chronological record of the foreland basin sediments, and finally (5) the northern deformation front of the Alps, the youngest out of the large-scale collisional structures of the orogen.

This book will not provide a single, consistent and unique view on Alpine geodynamics, but rather create a space for experts on Alpine research to present their state of the art of specific subjects, not withdrawing from proposing their own interpretations, whether or not they are entirely consistent with those suggested in other chapters.

Volume 1

The first volume starts with a chapter on the history of Alpine cross-sections. This chapter does not review the historical evolution of tectonic and geodynamic processes in the Alps, but it shows how the style and format of geological cross-sections have evolved through time in relationship and as a consequence of major tectonic discoveries and debates. It also underlines changes through time in the scientific approach of scientists, showing how the very close link to observations in the mid-19th century evolved toward more conceptual interpretations, eventually lacking an observational base at the beginning of Plate Tectonics, when entirely new concepts of Alpine orogeny were formulated. Only in the last decade of the 20th century, have these conceptual models regained a close link to structural and geophysical observable data.

Chapter 2 of Volume 1 describes the present-day deep structure of the Alps, in which several slabs and slab segments can be identified. The dip-direction and the presence or absence of break-offs in the European slab are discussed in this chapter, strongly suggesting continuous, vertical slabs. In addition, the surface of the Alpine Mohos and the first-order structures of the deep crust are reassessed. Finally, based on the integration of receiver function, Vp/Vs seismic tomography and local earthquake tomography, the geometry and orientation of the west-Alpine subduction channel is imaged.

Chapter 3 of Volume 1 provides a quantitative description of the present-day surface topography of the Alps and its inferred uplift history. Several processes affecting the Alps since the Pliocene, such as sedimentation in the foreland basins, cooling ages and geochemically inferred erosion rates are integrated in the discussion of the present-day topographic structure, suggesting that changes in both climatic and tectonic processes must be invoked to explain the uplift history of the Alps.

Chapter 4 of Volume 1 reviews stress patterns inferred by the analysis of the youngest Alpine brittle fault systems, in addition to inferred deformation fields based on seismic and GPS data. These analyses show that the topographically highest portions of the Alpine chain in the Western and Central Alps were affected by orogen-perpendicular extension during Pliocene time, and this state of deformation is still recorded by seismic activity. The areas affected by such orogen-perpendicular extension coincide with high uplift rates in the northern and central parts of the Alpine arc. The possible collisional and post-collisional large-scale geodynamic causes of this deformation and uplift patterns are discussed.

Volume 1 concludes with two chapters which are both regionally focused. Because of their broad approach, providing the geologic al history of the Alpine realm throughout its entire history and up to the present, they are included within the first volume. Chapter 5 of Volume 1 presents the geology of the Eastern Alps discussing its underlying geodynamic processes. It shows that the stacking of nappes within the upper plate of the Alpine orogen can be inferred to represent a syn-collisional Cretaceous event, hence leading to the conclusion that two distinct orogenies, each of them consisting of a subduction/collision process, affected the Eastern Alps. The younger (Cenozoic) history is also described, with its peculiar style of collision, very different from that in the Western and Central Alps. Indeed, syn-collisional extrusion-related faults accommodate a significant part of collisional convergence in the Eastern Alps.

Chapter 6 of Volume 1 gives an overview of the geology of Corsica. Because the Sardo–Corsican block rifted away from the rest of the Alpine chain at the beginning of collision, it is not affected by the latter process, and it is ideally suited to study subduction and Cenozoic extension, and in particular, to relate the Alpine to the Appeninic chain. This chapter describes and illustrates how the Eocene-aged Alpine/Corsican east-directed subduction is followed by slab break-off and the initiation of a new, west-directed subduction system, which eventually generated the Appenninic chain.

Volume 2

Chapter 1 of Volume 2 deals with the Paleozoic evolution of basement rocks in the Alps. The oldest events recorded correspond to the formation of a Neoproterozoic peri-Gondwanian arc before its accretion to Gondwana, presumably during an Ordovician collisional event. The Cambrian–Ordovician period was marked by tectonic subsidence and widespread magmatic activity, prior to the opening of the Rheic Ocean. Convergence between Laurussia and Gondwana started in the Devonian, which marked the closure of Rheic Ocean, followed by the Variscan collision during the Carboniferous. Evidence of this convergence is provided by Devonian HP-LT eclogites preserved in the Austroalpine units, and Devonian–Tournaisian arc-related magmatism in the External Crystalline Massifs (Western Alps). The main period of nappe stacking and crustal thickening took place during the Mississipian and it was followed by strike-slip tectonics and extension from Pennsylvanian to Permian times. The orogen-scale dextral strike-slip east-Variscan shear zone was active from the Late Carboniferous to the Permian. Because of the intense reorganization during the Alpine orogeny, replacing the Alpine basement in the European Variscan puzzle remains a challenge to be solved.

Chapter 2 of Volume 2 provides an overview of the continental margins involved in Alpine orogeny. The reconstructed stratigraphic sequence and structure of both the European and Adriatic margin are presented based on a literature review showing numerous case studies from all over the Alpine chain. The questions on how many ocean basins and continental blocks existed before the onset of Alpine subduction, and their inferred paleo-geographic positions are reviewed, taking into account the nature of the oceanic substratum, that is, exhumed mantle versus oceanic crust. In addition to describing numerous interpretations of this complex paleo-geographic realm, a new Jurassic paleo-geographic map and a Jurassic-to-Cretaceous evolution are proposed. It suggests the existence of a main oceanic axis, which propagated into different parts of adjacent, pre-fractured continental blocks. A similar pattern is inferred to characterize the North Atlantic ocean in the Early Eocene, where numerous oceanization attempts, leading to hyper-extended crust and exhumed mantle, initiated from one major, stable central axis of accretion.

Chapter 3 of Volume 2 summarizes the petrology, the geochemistry and the age data of mantle and oceanic crustal remnants in the Alps and Appennines, and discusses these data in the frame of rifting and seafloor spreading preceding Alpine subduction. The comparison of these data with those of peridotites worldwide, including mantle samples dredged offshore, points to their origin from passive margins and ultra-slow spreading ridges. Their association with lower crustal granulites and mafic intrusions, in addition to their sedimentary cover typical of continental margins, suggest that they originate from the mantle lithosphere beneath a continental crust. The small volumes of gabbroic dikes recording melt extraction and magmatism during formation of the Piemonte–Liguria Ocean, and the similarity between the REE signature of their basalts, and that of MORB from ultra-slow spreading ridges, point to a likely origin from an ultra-slow spreading ridge.

Chapter 4 of Volume 2 is the first of two chapters on Alpine subduction. Based on a large synthesis of P-T conditions and PTt paths determined from HP rocks, this chapter reconstructs the 3D architecture of oceanic subduction in the Alpine realm and draws several conclusions on the dynamics of Alpine subduction. The consistent alignment of compiled P/T data along a P-T gradient corresponding to that of mature subduction zones suggests that Alpine HP rocks record the P-T conditions of subduction without being significantly affected by overpressure. The magmatic age of subducted and exhumed oceanic HP rocks points to the fact that only oceanic domains next to the continental margin and/or OCT were exhumed, whereas the remaining oceanic crust disappeared during the first stages of subduction. Integrating observations on syn-subduction sedimentary deposits all along the Alpine arc to petro-chronological data on HP rocks shows that an along-strike segmentation of the subduction zone both in terms of crustal-lithospheric structure and processes existed, with subduction accretion dominating in the Western Alps and subduction erosion dominating in the Central Alps. These differences in the nature of the subduction processes are discussed in relationship to the inherited structure of the continental margins and the oceanic crust itself. Finally, the Alpine case study is compared with larger scale subduction zones of the Mediterranean and Pacific.

Chapter 5 of Volume 2 reviews the available data about the subduction of continental crust in the European Alps. The type of crustal material that was involved in the subduction process is characterized (lower vs. upper crust, tilted blocks vs. extensional allochthons) and the data on pressure, temperature and age of metamorphic units are summarized. Finally, a discussion of the present geometry of the subducted continental units allows the setting of some constraints on the kinematic evolution of the mountain belt, and on the exhumation of HP-UHP rocks in particular.

Volume 3

Chapter 1 of Volume 3 focuses on Alpine magmatism, reviewing petrological, geochemical and geochronological data of Alpine magmatic bodies in relationship to their distribution all along the Alpine chain. Based on their spatial occurrence, age and geochemical signature, Alpine magmatic bodies are shown to be generated by different geodynamic processes, which are inferred to be (1) subduction of both continental and oceanic crust, whose melting produced magmas that were emplaced in the upper plate in the Middle and Late Eocene; (2) slab break-offs at the transition from subduction to collision, allowing for the rise of asthenosphere and its direct contact to the lower Alpine crust, whose melting and mixing with asthenospheric melts generated the largest volumes of Alpine magmas, forming the Periadriatic Plutons; (3) extensional processes related to mantle dynamics, limited to the marginal areas of the Alpine chain (the Alpine/Apennine junction and the Alps/Dinarides/Pannonian junction); (4) ascent along inherited lithospheric-scale faults, possibly explaining intraplate magmatism as observed in the Veneto magmatic province, which is located relatively far from the Alpine front.

Chapter 2 of Volume 3 summarizes the present-day knowledge on the external crystalline massifs, basement units deformed during the collisional stage of the mountain belt. In these massifs, the amount of shortening increases from south to north, as well as the P-T conditions of barrovian metamorphism. Each massif experienced a complex sequence of shortening: after slicing off the Dauphinois cover, ductile internal shortening affected the basement, before localization of deformation along basement thrusts resulted in “en bloc” exhumation of the massifs. Specificities between different massifs are described in detail and different hypotheses on the driving forces leading to the formation of the massifs are synthetized.

Chapter 3 of Volume 3 reviews the structure, age and stratigraphy of the northern foreland basin of the Alps, and it discusses the large-scale geodynamic processes underlying its stratigraphic architecture, its facies relationships and the provenance of its clastic material. The along-strike similarity versus change of the stratigraphy through time is synthetized and related to the drainage pattern of the basin. The historical evolution of inferred geodynamic processes is reconstructed over the past decades, thus showing that the stratigraphy and structure of the Molasse Basin may not only reflect thickening of the more internal part of the orogen, but rather the slab dynamics of the lower plate. Hence, subduction loads at deeper crustal levels rather than surface loads may exert the first-order control on basin subsidence.

Chapter 4 of Volume 3 reviews the currently available detrital thermochronological record of exhumation for the European Alps. It allows tracing and discussing temporal and spatial patterns of exhumation across the Alpine chain. The higher temperature white mica 40Ar/39Ar ages, if considered as cooling ages, depict phases of very rapid exhumation, on the order of 3 ± 1 km/Myr, in the Western Alps during the early Oligocene, and somewhat slower exhumation of ~1 km/Myr in the Central Alps during the late Oligocene–early Miocene. Detrital zircon fission-track data indicate a relatively steady exhumation signal since the late Oligocene for the Central Alps, whereas detrital apatite fission-track data emphasize regional differences in exhumation rates since at least Miocene times.

Chapter 5 of Volume 3 focuses on the northern deformation front of the Alps, that is, on the youngest, large-scale structure accommodating collisional shortening by the relative displacement of the orogen on its foreland basin. It shows that the structural style of this fault system varies along strike, with triangle zones being replaced by duplexes and basal décollements changing depth and the stratigraphic level. These variations are correlated to lateral changes in the mechanical stratigraphy, to differences in the links between these faults and their roots in the more internal parts of the orogen, or even to differences in the mechanical properties of the entire European Plate.

Acknowledgments

Romain Bousquet generously provided the vectorized version of his Tectonic Map of the Alps, used in most of the chapters in the three volumes of this book.

1

Paleozoic Evolution and Variscan Inheritance in the Alps

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Large outcrops of the Paleozoic basement have formed about half of the exposed rock in the Alpine belt. These Paleozoic domains preserve evidence of the long and complex pre-Alpine history, which has spanned more than 300 million years, from the Ediacaran to the Permian, and reflect the general evolution of the European Paleozoic basement: the oldest events recorded to correspond to the formation of a Neoproterozoic peri-Gondwanian arc that remained active during the Cambrian before its accretion into Gondwana, presumably during an Ordovician collision. The Cambrian–Ordovician period was marked all over the Alps by tectonic subsidence and widespread magmatic activity, which reflects the general extension that affected North Gondwana prior to the opening of the Rheic Ocean and the rifting of Avalonia and the

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Hun Terranes during the Ordovician. The following Silurian period was relatively calm, marked by crustal subsidence and extension at the margin, and deposition of clastic sediments. These are mostly preserved in the Eastern Alps, and they announced the future opening of the Paleotethys from the Late Silurian to the Devonian. Then, convergence between Laurussia and Gondwana started in the Devonian, which marked the closure of the Rheic Ocean, followed by the Variscan collision during the Carboniferous. Evidence of this convergence is provided by Devonian HP-LT eclogites preserved in the Austroalpine units, and Devonian–Tournaisian arc-related magmatism in the External Crystalline Massifs (The Western Alps). The Variscan collision is recorded to various degrees across all of the Alpine basement domains. The main period of nappe-stacking and crustal thickening took place in ca. 350–320 Ma, which was followed by strike-slip tectonics and an extension from the Westphalian to the Permian (ca. 315–290 Ma). In the Helvetic domain, the orogen-scale dextral strike-slip East-Variscan shear zone was active from the Late Carboniferous to the Permian and was responsible for large-scale displacements in the Variscan structure at the end of the orogeny. Following the Variscan orogeny, a high-temperature event occurred during the Permian, which preceded the opening of the Tethys Ocean and the initiation of the Alpine cycle. This evolution is in many ways similar to that of other Paleozoic massifs in Europe. However, due to the intense reorganization of the crustal basement during the Alpine orogeny, the Alpine domain does not form a coherent block that can be easily correlated with other Variscan domains in Europe. Replacing the Alpine basement in the European Variscan puzzle remains a challenge to be solved.

1.1. Introduction

Prior to the Alpine cycle, which began with the extension and the opening of the Tethyan oceanic domains during the Lower Jurassic, the Alpine domain underwent a long and complex evolution that can be traced back to the Late Neoproterozoic. In many places, the basement that preserves this pre-Alpine history has been covered by a thick layer of Mesozoic and Cenozoic sediments and is therefore not accessible to geologists. However, areas where the pre-Mesozoic basement is exposed represent about half of the Alpine domain (Von Raumer et al. 2013), which makes this one of the largest Paleozoic massifs in Europe, together with the Bohemian Massif, the Massif Central, the Armorican Massif, and the Iberian Massif. This basement is exposed along all of the domains that form the Alpine belt and was variously overprinted by the Alpine tectonics and metamorphism (Bousquet et al. 2004; Schmid et al. 2004). Like the other Paleozoic massifs of southern and central Europe, the Paleozoic basement of the Alps derives from the northern margin of Gondwana (Stampfli et al. 2011) and has recorded a long and complex history that culminated during the Carboniferous with the Variscan orogeny, during which Gondwana and

Laurussia became amalgamated to form the Pangea supercontinent (Matte 2001). However, this apparently simple history hides great complexity, which is far from being fully understood. This chapter aims to present the current knowledge and outstanding issues concerning the pre-Mesozoic history of the Alpine basement.

1.2. The Paleozoic setting in Europe

1.2.1. *General setting: a crustal basement structured by Paleozoic orogenies*

The pre-Mesozoic domains of the Alps represent only a small part of the European Paleozoic basement and form a small piece of the former Variscan belt, a large orogen that can be followed across all of the different Paleozoic massifs of southern and central Europe (Figure 1.1). The Variscan belt of Europe itself belongs to a larger orogenic system that extended over about 8,000 km, from the Caucasus to the Appalachian and Ouachita mountains of North America (Matte 1986). It arose from the Devonian to the Permian by progressive closure of the oceanic domains between Laurentia–Baltica in the North, and Gondwana in the South (Figures 1.2 and 1.3). Between these two large continental masses, small continental blocks detached from the northern margins of Gondwana during the early Paleozoic, and then from the Late Devonian to the Carboniferous, they underwent accretion to form Laurussia and the Variscan orogen (e.g. Franke 1989; Matte 2001; Stampfli et al. 2013).

There have been major advances during the last few decades in our understanding of the Paleozoic evolution of the European basement, and most studies have agreed on the first-order structure of the Variscan belt (e.g. Kroner and Romer 2013; Ballèvre et al. 2014; Lardeaux et al. 2014; Franke et al. 2017). On a European scale, its strongly arcuate shape was acquired more recently in Variscan history (Upper Carboniferous–Early Permian). It can be subdivided into several lithotectonic domains. On the northern and southern flanks of the Variscan assemblage, the basement is formed by the Avalonia and North Gondwana shelves, respectively (Figure 1.1), which formed the foreland basins of the belt. In between this, the Variscan basement is composed of several lithotectonic domains which represent the assemblage of peri-Gondwana terranes that were squeezed between Gondwana and Laurussia during the Variscan orogeny, and then were variously overprinted by the associated tectono-metamorphic and magmatic events. The "core" of the European Variscan belt is formed by the Moldanubian zone, which includes a large part of the Bohemian Massif and the Massif Central, and extends toward the southern Armorican massif and the northern Iberian massif (Figure 1.1). This represents the exhumed crustal root of the belt, and it contains high-grade migmatites and granulites, with relics of high-pressure rock (eclogites, high-temperature eclogites/ high-pressure granulites), and dismembered ophiolites (Lardeaux et al. 2014).

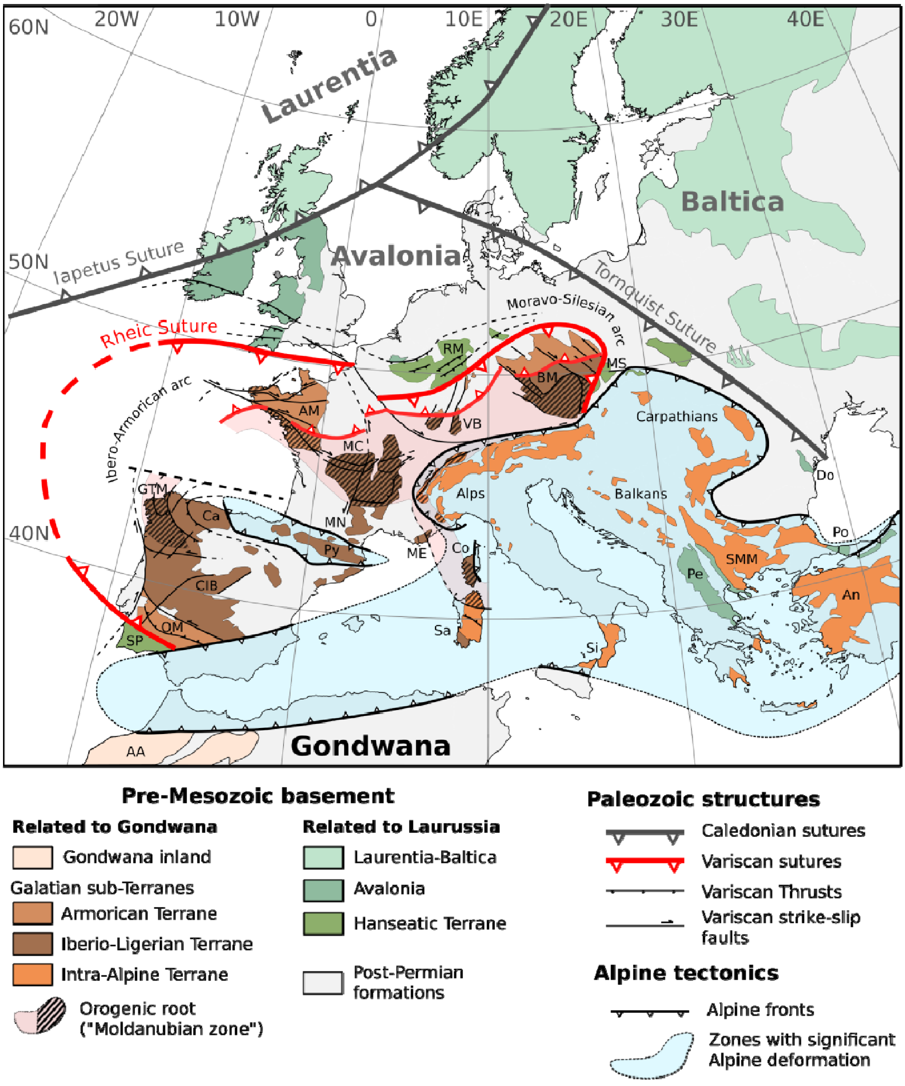

Figure 1.1. *Simplified tectonic map of Europe that shows the exposures of the Paleozoic basement and the Paleozoic sutures*

COMMENTS ON FIGURE 1.1.– *The Avalonian crust in the middle of Gondwana-derived domains in southeastern Europe (the Pelagonian zone) is mostly inferred from the study of sedimentary sequences and detrital zircons (Stephan et al. 2019 and references therein) and is not discussed here. AM, Armorican Massif; An, Anatolia; BM, Bohemian Massif; Ca, Cantabrian zone; CIB, Central Iberian zone; Co, Corsica; Do, Dobrogea; GTM, Galicia–Trás-os-Montes; MC, Massif Central; ME, Maures-Esterel; MN, Montagne Noire; MS, Moravo–Silesian zone; OM, Ossa–Morena zone; Po, Pontides; Pe, Pelagonian zone; Py, Pyrénées; RM, Rhenish Massif; Sa, Sardinia; Si, Sicilia; SMM, Serbo-Macedonian Massif; SP, South Portugese zone; VB, Vosges, Black Forest. Modified from Stephan et al. (2019a), with data from Ballèvre et al. (2014) and Franke et al. (2017).*

1.2.2. *Pre-Variscan history of the European basement*

Prior to the opening of the Rheic Ocean during the Ordovician, the future Variscan domains of Europe were located along the northern margin of Gondwana (Matte 2001; Von Raumer et al. 2002; Stampfli et al. 2011). From the Neoproterozoic to the Early Cambrian, a western-Pacific-type accretion zone was developed along this margin, which resulted in the accretion of various elements to form a consolidated crust (Garfunkel 2015). This period of accretion peaked during the Late Ediacaran (ca. 600–580 Ma) with the accretion of an arc which had previously rifted off Gondwana, during the Lower Ediacaran. This event is known as the Cadomian orogeny, and it has been poorly preserved in the European basement, except in a few places. These include northern Brittany and the region of Caen in northwestern France (Ballèvre et al. 2001; Chantraine et al. 2001), from which the name "Cadomian" originates (as derived from Cadomus, the Latin name of the city of Caen). Elsewhere, the Cadomian orogeny is mainly inferred from the study of zircons in detrital sediments, which has defined a major peak of zircon crystallization at ca. 600 Ma, which corresponds to the Cadomian orogenic events (e.g. Chu et al. (2016); Chelle-Michou et al. (2017)).

The Cambrian–Ordovician period (ca. 540–450 Ma) was characterized by extensional tectonics, with rifting and subsidence over northern Gondwana in a back-arc setting (von Raumer and Stampfli 2008). This eventually led to the opening of the Rheic Ocean (Linnemann et al. 2007; Nance et al. 2010) and the northward drift of the Avalonian microplate (Figure 1.2, sketches 1–4). This widespread extension resulted in the formation of a thinned continental shelf on the northern margin of Gondwana, which was associated with the opening of back-arc basins

(Kroner and Romer 2013; Stampfli et al. 2013) and the limited production of some arc or back-arc oceanic crust (e.g. Chamrousse: Figure 1.2, sketch 1; Pin and Carme 1987; Ménot et al. 1988; Guillot et al. 1992). The Cambrian–Ordovician extension was accompanied by widespread bimodal magmatism (Figure 1.2, sketch 3), which consisted of alkaline and tholeiitic mafic rock that was associated with alkaline and peralkaline rhyolite (e.g. Pin and Marini (1993); Crowley et al. (2000)). A possible orogenic event occurred during the Ordovician (Figure 1.2, sketch 2) is referred to as the Sardic phase or the Cenerian orogeny and was inferred from the widespread production of peraluminous granitoids from ca. 500–450 Ma (Valverde-Vaquero and Dunning 2000; Villaseca et al. 2016; Zurbriggen 2017). However, the geodynamic setting associated with this peraluminous magmatism remains unclear. Different mechanisms have been proposed, which include continental rifting associated with the break-up of northern Gondwana (Montes et al. 2010; Ballèvre et al. 2012), back-arc extension in an active arc setting (Valverde-Vaquero and Dunning 2000; Fernández et al. 2008), thermal relaxation of a thickened arc crust (Villaseca et al. 2016; Soejono et al. 2019), and melting of fore-arc sediments driven by underplating of mafic magma (Zurbriggen 2017).

1.2.3. *The Variscan orogeny in Europe*

From the Late Silurian to the Early Devonian, convergence between Gondwana and Laurussia led to the closure of the Rheic and Saxo-Thuringian Oceans (Figure 1.2, sketches 5 and 6). This then culminated during the Late Devonian–Carboniferous (360-320 Ma) with the collision between Laurussia, Gondwana, and peri-Gondwana fragments (Figure 1.3). During the Middle-to-Late Carboniferous, two successive stages of post-orogenic extension occurred (Faure and Becq-Giraudon 1993; Burg et al. 1994). The first of these was associated with lateral East-West extrusion of material in a still convergent setting and the second was associated with North-South orogenic collapse via the activation of low-angle detachment faults. These were accompanied by the development of migmatite complexes, emplacement of large volumes of peraluminous granitoids, and formation of intra-continental, coal-bearing sedimentary basins (e.g. Ledru et al. 2001; Faure et al. 2009; Lardeaux et al. 2014). This general collapse associated with extensive crustal melting may have been driven by the delamination of the subcontinental mantle lithosphere during the late orogenic stages (e.g. Žák et al. (2018)).

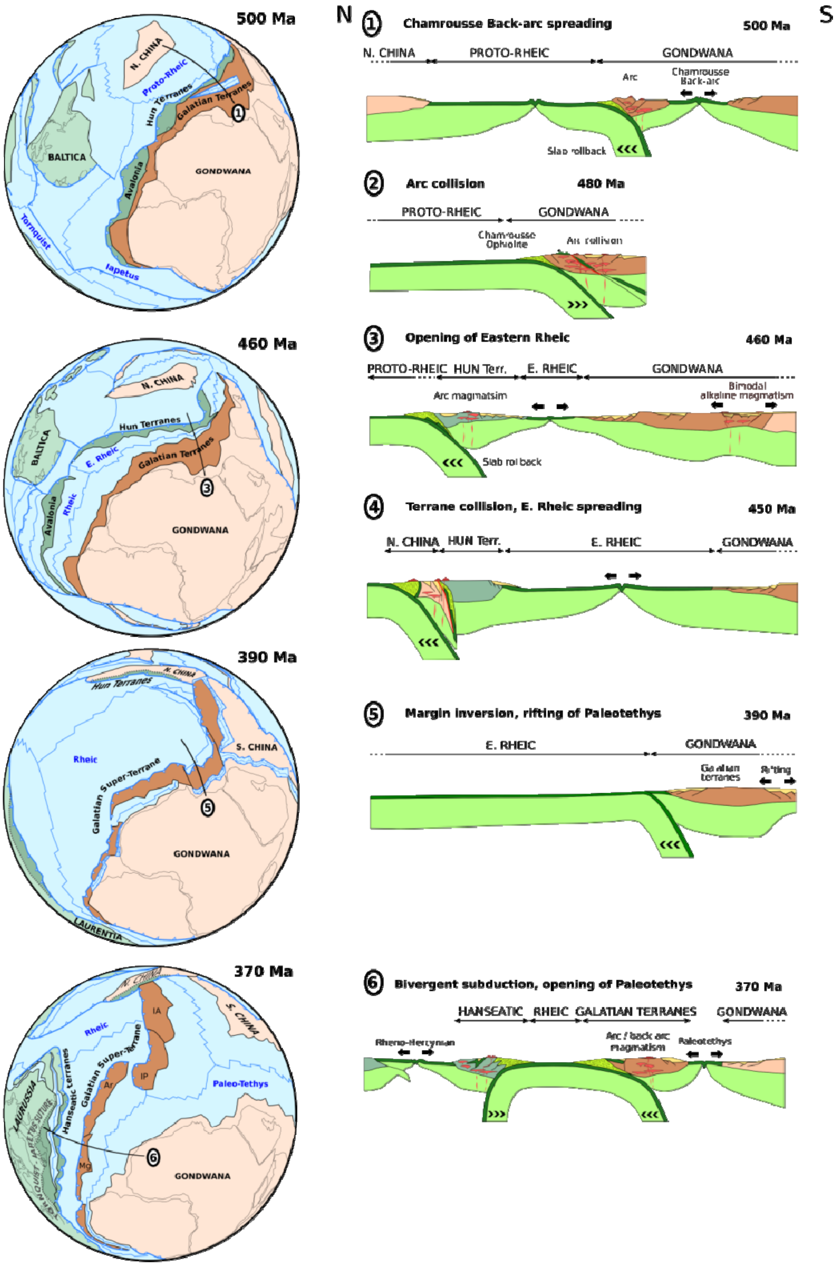

Figure 1.2. *Palinspastic reconstruction that shows the evolution of North Gondwana from the Cambrian to the Devonian, with the associated cross-sections that cut through the northern Gondwana margin*

COMMENTS ON FIGURE 1.2.– *The position of the cross-sections is indicated by the number on the corresponding globe. This period records the progressive opening of the Rheic domain and the drifting of Avalonian and Hun Terrane during the Ordovician, followed by the rifting of Paleo-Tethys during the Silurian and the Devonian, and the progressive closure of the Rheic Ocean. Mg, Meguma; Ib, Iberia; Ar, Armorica; IA, Intra–Alpine. Colors of the continents follow the same code as for Figure 1.1: light green, Laurentia–Baltica; dark green, Avalonia and Hun Terrane; light brown, Gondwana; dark brown, Galatian Terranes. Modified from Stampfli et al. (2011, 2013).*

However, the Variscan orogen has a complex structure that cannot be solely explained by a simple continent-continent collision. In particular, many relics of mafic-ultramafic complexes, mid-ocean ridge basalt (MORB)-type eclogites, and alkalic magmas of the Upper Cambrian–Lower Ordovician can be found within the Variscan domains of western and central Europe, south of the Rheic suture. This disposition suggests that multiple oceanic basins separated the microplates south of the Rheic Ocean (Figure 1.1). Different tectonic models have been proposed which differ in the numbers of plates and oceans involved, and in the initial pre-Variscan positioning of these blocks along the peri-Gondwana margin (Matte 2001; Kroner and Romer 2013; Stampfli et al. 2013; Franke et al. 2017). Moreover, discussion continues as to the size of the basins that separated the different blocks, and the subduction vergencies. Based on the continuity of the benthic fauna and paleomagnetic data, it is now recognized that these continental fragments were not separated from Gondwana by a large oceanic domain (Cocks and Torsvik 2002; Fortey and Cocks 2003). These micro-continents were more likely separated by either small oceanic basins similar to the Mesozoic Alpine Ocean (Franke et al. 2017), or by zones of hyperextended crust that possibly showed continent-ocean transition (Kroner and Romer 2013; Lardeaux et al. 2014).

Finally, the global picture is further complicated by the non-cylindricity of the Variscan belt and its diachronous evolution from West to East, as indicated by palinspastic reconstructions, detrital zircon patterns in the Lower Paleozoic sediments, and lithostratigraphic, tectonic, and magmatic records (Stampfli et al. 2013; Casas and Murphy 2018; Stephan et al. 2019a). Several recent models now separate the Variscan domains south of the Rheic suture into eastern and western segments that underwent contrasting geodynamic evolution (Stampfli et al. 2013; Stephan et al. 2019a, 2019b). In the western domain, the final collision of Gondwana with Laurussia has been well recorded and corresponds to the indentation of Avalonia by the western Gondwana shelf during the Late Devonian–Carboniferous (ca. 360–340 Ma; Faure et al. 2009; Ballèvre et al. 2014). In the eastern domain, the situation was complicated by the opening of Paleo-Tethys during the Devonian (Figure 1.2, sketch 6 and Figure 1.3). The main Tournaisian–Visean tectonothermal event corresponded to the accretion of the terranes into a cordillera-like orogen (Figure 1.3, sketches 7 and 8). The final collision of Gondwana with Laurussia occurred later (330–300 Ma; Figure 1.3, sketches 9 and 10) and was less pronounced than for the western domain (Haas et al. 2020). Eastward, the collisional system evolved toward a purely accretionary orogen along the northern Paleo-Tethys, to form the Altaids in central Asia (Wilhem et al. 2012).

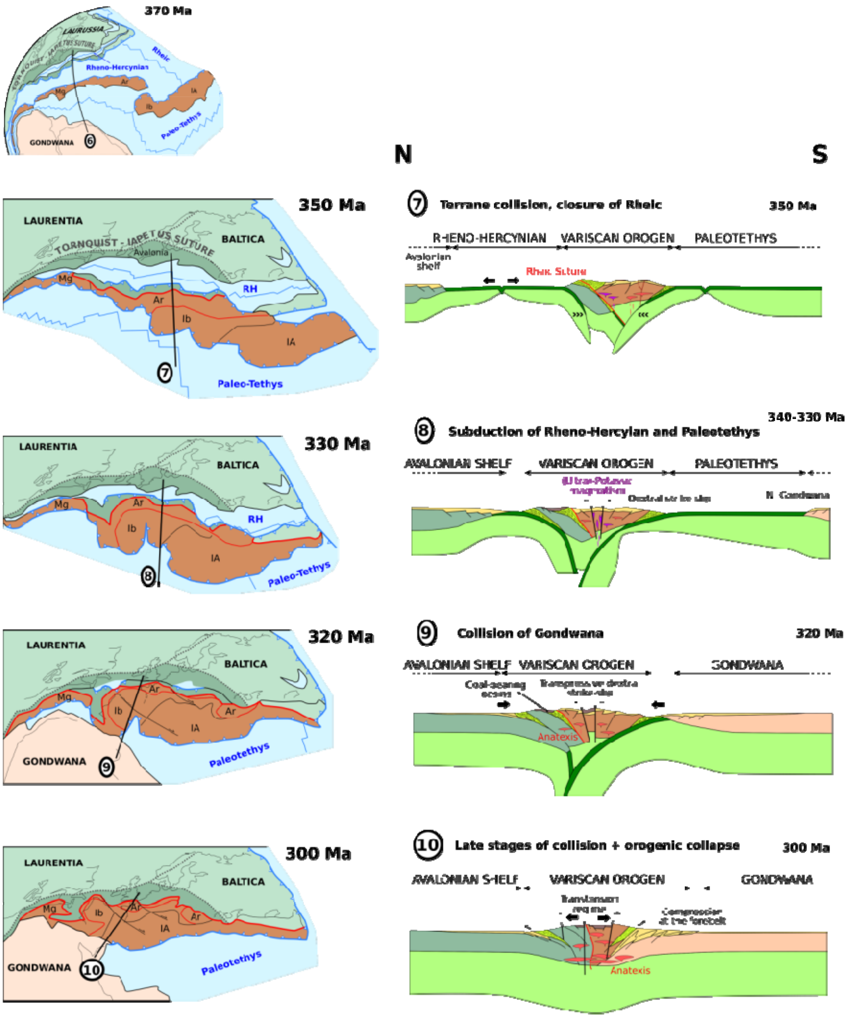

Figure 1.3. *Palinspastic reconstruction of the Variscan domain from the Devonian to the Late Carboniferous, with associated cross-sections through the Variscan collision zone*

COMMENTS ON FIGURE 1.3.– *This period records the closure of the Rheic Ocean and other smaller basins, and the collision between Laurussia, Galatian Terranes, and Gondwana. This collision is polyphasic: a first arc–arc collision occurred at ca. 350 Ma between the two sets of Galatian Terranes; a second collision occurred at ca. 320–300 Ma with indentation of Gondwana in the Galatia–Laurussia terrane assemblage; this was followed by extension and lateral extrusion of material accommodated by the lithospheric-scale strike-slip faults. See Figure 1.2 for labels. Modified from Stampfli et al. (2011, 2013).*

The following sections will present an overview of the Paleozoic massifs in the Alps and discuss their pre-Mesozoic history according to the general setting proposed by Stampfli et al. (2013) for the Paleozoic evolution of northern Gondwana (see Figures 1.2 and 1.3). According to this model, the Variscan belt was formed by the amalgamation of terranes derived from Gondwana. Two major sets of ribbon-like peri-Gondwana terranes that extended from the North of South America to Southern China drifted from Gondwana at different times during the Lower Paleozoic. A first segment known as the Hun Terrane corresponded to the eastern equivalent of Avalonia, and this detached from the eastern domain of North Gondwana during the Ordovician, with the opening of the eastern Rheic Ocean. This segment then drifted to the northeast and collided with northern China during the Silurian. A second segment known as the Galatian super-terrane detached from Gondwana during the mid-Devonian, synchronous with the opening of Paleo-Tethys, and that comprised most of the European Variscan elements. This ribbon-like micro-continent quickly separated into four sub-terranes. The final collision between Gondwana, Laurussia, and the Galatian Terranes during the Middle-to-Upper Carboniferous (ca. 340–300 Ma) created a complex amalgamation that formed the Variscan belt.

1.3. The basement outcrops in the Alps

The Paleozoic basement is exposed discontinuously all along the Alpine arc, and it forms about half of the Alpine domain (Von Raumer et al. 2013). Pre-Alpine rocks are exposed in the four main tectonic domains that have been defined at the lithospheric scale for the Alpine belt (Figure 1.4): the Dauphinois–Helvetic; the Penninic; the Austroalpine; and the south Alpine domains. The Dauphinois–Helvetic domain forms the external zone of the European margin west of the Penninic thrust. The Penninic domain is composed of various nappes that are derived from the distal European margin (e.g. the Tauern Window basement nappes; Schmid et al. 2013), the Valaisan basin, and the Briançonnais microplate in the Western and Central Alps. The Austroalpine domain is composed of allochthonous nappes that form the