SCIENCES

GEOSCIENCE

Dynamics of the Continental Lithosphere

The Variscan Belt of Western Europe 2

Late Magmatic, Metamorphic and Tectonic Events and the Sedimentary Record

Coordinated by
Yoann Denèle
Julien Berger

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Table of Contents

List of Illustrations

SCIENCES

Geoscience, Field Director – Yves Lagabrielle

Dynamics of the Continental Lithosphere,
Subject Head – Sylvie Leroy

The Variscan Belt of Western Europe 2

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Preface

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The idea behind this collective work stems from the request sent to us in September 2018 from Sylvie Leroy, subject head of "Dynamics of the Continendtal Lithosphere", part of the SCIENCES collection produced by ISTE Group, to coordinate a book on the Variscan belt. It seemed appropriate to propose a book on this mountain range by focusing on the French crystalline massifs, while avoiding imposing strict geographical limits in order to devise the paleogeographical and geodynamic framework. As this book aims to reach a wide audience of teachers and students, we have chosen to provide chapters that are based on recent advances in research, with a certain degree of popularization, including detailed descriptions of key zones of the Variscan massifs in France.

The chapters of this book have been written by a number of individuals; it would therefore not have seen the light of day without these various authors who were enthusiastically and passionately involved in this collective work. The author or authors take responsibility for their respective chapter, which primarily sets out their personal vision, while taking into account other opinions. The relative diversity of points of view reflects ongoing debates and shows that the study of the Variscan belt is not complete, but an active field of Earth Sciences. Science is progressing very quickly and as the finalization of this book took longer than expected, with significant differences concerning the writing periods of certain chapters, it seems important to us to specify here, the dates of receipt of the first versions of the various chapters so that they may be inscribed in their historical framework, in particular in relation to recent or current publications, the results of which the authors of the chapters were unable to integrate. The yellow jersey of this book thus goes to Chapter 4 of Volume 1, the first version of which was proposed in August 2019. Chapter 2 of Volume 1 and Chapter 1 of Volume 2 were sent in February 2020, and finally the period running through the end of 2020 and the beginning of 2021 was the most prolific with the successive reception of Chapters 1 and 3 of Volume 1 and Chapter 3 of Volume 2, and then Chapter 2 of Volume 2. The overall rereading and finalization of the Introduction and Conclusion, which are challenging steps, led to the submission of this project at the end of 2021.

March 2023

Introduction

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The rocks forming the crystalline basement of France, Western Europe, parts of America (the Appalachians) and North Africa (the Meseta) are essentially Ediacaran to Carboniferous. They were formed or transformed during a major orogenic period extending from the Devonian to the Carboniferous (see Chapter 1), termed *Variscan*, but *Hercynian* may also be used for historical reasons. At the end of the 19th century, the term Variscan, with reference to the Latin name *Curia Variscorum* of the city of Hof in Bavaria, was suggested by the Austrian geologist *Eduard Suess* (1831–1914) to describe an ante-Permian mountain range of Central Europe with distinct structural directions from other Paleozoic belts observed in Armorica and Iberia. During the same period, *Marcel Bertrand* (1847–1907) proposed, with reference to the ancient forest of Central Europe *Hercynia silva*, the term Hercynian, to characterize all of these domains whose formation seemed synchronous. However, in 1924, *Hans Stille* (1876–1966) used the term Variscan to describe the same system. Thus, the terms Variscan and Hercynian were subsequently used by geologists whether they were of Anglo-Saxon or Latin influence, respectively, before the geological sciences were progressively dominated by the use of Anglo-Saxon terms, and thus Variscan became informally the scientific term of reference.

The topography of French regions is marked by high mountain ranges with sharp peaks (Alps, Pyrenees), large areas of medium mountain ranges (French Massif Central, Vosges) or low hills with rounded peaks (Armorican Massif, Ardennes), and vast plains (Paris and Aquitaine basins). The duality of relief in mountainous areas is sometimes associated with the age of the orogenic phenomena that has affected these massifs (Variscan vs. Alpine). This simplification does not reflect the richness of France's geological history and does not explain certain morphological features. For example, there is a dichotomy between the slightly accentuated topography of hills and valleys of the Armorican Massif, which rises to 384 m in *Tuchen Gador*, and the steep reliefs of the *Cévennes*, which reach an altitude of almost 1,700 m in Mont Lozère. These two regions with contrasting topography are, however, apparently preserved from alpine orogenic phenomena, and show the outcrop of crystalline rocks deformed and metamorphosed during the Variscan orogeny, and could thus be considered to belong to the "old massifs of France". In fact, the Alpine cycle led to the development of high reliefs in hinterland orogenic domains (Alps, Pyrenees) and large flexural foreland basins (Aquitaine Basin, Southeast France Basin), as well as of a discontinuous thinned crustal domain around the Alpine arc. The topography of French regions is also controlled by the development, from the Upper Eocene to the Lower Miocene, of this rift system to which belong various basins of the West European rift and the Gulf of Lion margin. The rift basins (e.g. Rhine and Limagne grabens in the West European rift, Alès graben on the Gulf of Lion margin) are surrounded by summits of medium altitudes (Vosges, eastern and southern parts of the Massif Central), which belong *lato sensu* to the shoulders of the rift basins, on which the Variscan crystalline rocks were exposed. Exhumation and incision of these domains also seem to be controlled by a deep dynamic topography (mantle upwellings) as attested by the Mio-Pliocene (Cantal, Aubrac) or Quaternary (Chaîne des Puys) volcanism in the French Massif Central, as well as evidence of significant uplifts over the same period. The formation of the Cévennes mountains is thus linked to a slow but significant Cenozoic exhumation on the border of rift systems, which, compared to the essentially epeirogenic processes undergone by the Armorican Massif since the Permian, explains the difference in topography between these two areas. Thus, unlike the Pyrenees and the Alps, which form high mountain ranges from a structural and morphological point of view, it is not appropriate to consider in physical geography of France a Variscan mountain range, but only Variscan crystalline massifs (Armorican Massif, French Massif Central, Vosges) surrounded by basin domains (Paris and Aquitaine Basins), sometimes forming discontinuous nuclei in the hinterland of mountain ranges (Alps, Pyrenees). The present-day topography of these massifs is not a direct consequence of the initial Carboniferous orogenic period. Nevertheless, although the formation of the Variscan belt around the 300 Ma period has little or no influence on the relief of France, the exposed crystalline rocks testify to the *building up of a major mountain range* at the end of the Carboniferous, which extends in Europe to more than 3,000 km long and 700 km wide, and whose relief, although subject to debate, was undoubtedly significant, and had a remarkable influence on the climate of the Earth in the Carboniferous and Permian.

This book describes the geological evolution of this paleo-mountain belt through six chapters (Chapters 2–4 of Volume 1 and Chapters 1–3 of Volume 2) mostly focused on French Variscan massifs with a seventh chapter (Chapter 1 of Volume 1) reviewing the evolution of ideas since the 18th century.

The study of ancient mountain belts must take into account several specificities. First, the geologist must restore a system that has undergone significant transformation during subsequent geodynamic events. In the case of the Variscan belt, and in particular for its European branch, it is necessary to restore the Atlantic Ocean system, and more particularly the Bay of Biscay, as well as the Alpine orogenic belts. In this book, this problem is not dealt with head-on in a dedicated chapter. We should remember that although the restoration of the opening of the Bay of Biscay is relatively simple, this is not necessarily the case for the Pyrenean–Alpine belts and the Mediterranean marginal basins, especially when it comes to determining the precise position of isolated crystalline massifs, such as the Maures and the crystalline massifs of the Alps, Corsica and the Pyrenees at the Carboniferous–Permian boundary. Thus, correlations between these massifs and the different units of the main branch of the Variscan belt in France (French Massif Central and Armorican Massif) are not yet clearly established. This explains why these isolated crystalline massifs are discussed separately in the various chapters of this book. Another particularity of the study of ancient orogens is to consider a system for which the *geodynamic framework* is difficult to establish, because the lithospheric plates involved and their kinematics cannot be as clearly defined as in Cenozoic orogenic systems. The geophysical record is more limited, and the absence of preserved oceanic sea floor prevents the determination of high-resolution kinematics of plates over long periods of time. As illustrated in *Chapter 2 of Volume 1*, which summarizes the paleo-geodynamic context of the Variscan chain, geodynamic constraints are essentially the result of confrontation between paleomagnetic data, which make it possible to determine paleo-latitudes, and “geological” data, in particular geochronological, paleontological and geochemical. Despite all of this information, the proposed geodynamic evolution during the ancient Variscan orogeny remains incomplete, and comparison with the more recent systems is a potential source for scientific progress.

Furthermore, the reconstitution of an ancient orogen requires the consideration of data derived mainly from the middle and lower crustal structural levels. Indeed, in the more recent chains, such as the peri-Tethysian systems (e.g. Alps, Himalaya), the upper structural level, marked by an association of fold and thrust belts barely affected by metamorphism, is most often exposed. This is not the case for the core of the ancient belts for which the lower structural level, marked by rocks with penetrative ductile deformation and high metamorphic grades, is most often observed. This pattern is, in part, related to the late orogenic events that have induced an exhumation of these structural levels upon the return to equilibrium of the previously thickened and gravitationally unstable orogenic crust. This pattern is accentuated by the Meso-Cenozoic history, which may have resulted in significant local exhumation and erosion of Variscan crystalline rocks in rift shoulder and hinterland domains of the Pyrenean–Alpine belts. Thus, the study of crystalline rocks that have recorded the construction of the Variscan belt (and ancient orogens in general) necessarily calls for geologists with expertise on this lower structural level. This is particularly the case for magmatic and metamorphic petrology, ductile tectonics and high-temperature geochronology. This fact explains why four chapters of this collective work are devoted to summarizing this type of study, whether concerning pre-collisional magmatism (*Chapter 3 of Volume 1*), metamorphism and early deformations (*Chapter 4 of Volume 1*), or late-orogenic magmatism (*Chapter 1 of Volume 2*) and deformation (*Chapter 2 of Volume 2*). In the uppermost structural level, sedimentary archives are partial and generally observed in spatially restricted external domains (Ardennes, Pyrenees, Cantabrian). In *Chapter 3 of Volume 2*, a group of authors propose an exhaustive summary of sedimentary record associated with the Variscan cycle and show the power of this archive as a vector of our understanding of the morphological evolution of the belt. Nevertheless, the scarcity of sedimentary archives preserved in internal domains, and in particular records associated with the early phases of orogenic construction, implies that the analysis of these domains is largely dependent on the evolution of geochronological methods, as well as on our ability to interpret the results they provide. This book does not contain a chapter dedicated to the geochronology of the Variscan belt, but what appears to be a gap is also an advantage, as all chapters describe the geochronological data and discuss them in the light of knowledge from the field, which are indispensable constraints for interpreting "absolute ages". Of course, the various experts who wrote the chapters of this book do not necessarily have the same way of interpreting these ages, leading to controversies that are thus illustrated.

All of the chapters of this book highlight the contribution of analytical data to constrain the history of the Variscan belt. Nevertheless, the study of mountain ranges still depends on high-quality field observations, which should provide the general framework for analytical studies, whether paleomagnetic, geochronological, geochemical or geophysical. Field analyses are dependent on the quality of outcrops, which are not homogeneous in the French crystalline massifs. Without going into the details related to microclimates, the crystalline massifs, which have recently been exhumed in the core of mountain ranges (Axial Zone of the Pyrenees and internal/external crystalline massifs in the Alps), benefit from excellent qualities of outcrop, which make it possible to study the structures of the rocks with a good continuity. This is also the case in the eastern and southern parts of the French Massif Central affected by slow but significant exhumation, particularly in the Cenozoic. In the Armorican Massif, coastlines present excellent conditions of outcrops but give way to bocages in the hinterland, in which it is rare to observe the bedrock. The pattern is quite similar to that of the Western French Central Massif, where outcrops on the altered crystalline plateaus are rare. In these areas, the accumulation of observations on temporary outcrops (quarries, major road or rail infrastructure) has fortunately made it possible to produce remarkable mapping work, without which any synthesis on the Variscan belt in France would seem incongruous.

In *Chapter 1 of Volume 1, Olivier Vanderhaeghe*, Professor at Université Paul Sabatier, Toulouse, presents the history of the evolution of methods and concepts applied to the Variscan belt, and thus of our vision of this paleomountain belt. This history also highlights the influence of the study of this ancient orogen as a source of inspiration in the history of Earth Sciences. The first methodological developments concern *cartography and stratigraphy*, and the appearance of the first synthetic geological maps at the beginning of the 19th century (United States of America, Great Britain and then France) is thus followed by the development of more detailed maps, at the regional scale, at the end of the 19th and beginning of the 20th century. The study of rocks by *optical microscopy* was gradually developed during the second half of the 19th century and made it possible to develop the analysis of minerals and structures on a microscopic scale, which are essential methods for studying crystalline rocks. These methodological developments made it possible to develop a number of concepts. In ancient concepts, if there is one that emerged in the Variscan belt before the advent of plate tectonics, it is indeed the theory of *geosynclines* that was introduced from the study of the Appalachians in the early 19th century. Geosynclines are defined as submerged domains, accumulating large quantities of sediments and localized deformation and the effects of metamorphism, thus constituting a favorable place for the transformation of rocks. This concept explains the association of three rock types in mountain ranges: primitive rocks, transition rocks and sedimentary rocks. In the geosynclinal framework, sometimes in contradiction with this paradigm, the concepts of zoneography of metamorphism, horizontal displacements of tectonic units (nappes) or partial melting (migmatites) also find their source in the Variscan belt in the middle of the 20th century. Subsequently, geology underwent *the plate tectonic revolution* in the late 1960s and early 1970s. Although this theory was initially developed remotely from the Variscan crystalline massifs, since it was essentially the result of geophysical observations of the globe, it was soon adapted to the study of this belt from the mid-1970s. During this period, various proposals emerged concerning the identification of suture zones, and thus of the continental and oceanic domains involved in the Variscan orogeny, and therefore regarding its paleogeographical context.

In *Chapter 2 of Volume 1*, *Jean-Marc Lardeaux and Karel Schulmann*, Professors at the Universities of Nice and Strasbourg, respectively, offer a summary of the *paleogeographical and paleo-geodynamic context of the Variscan belt.* In this chapter, which is essential for understanding the evolution of the belt, these two authors, based on a summary of litho-tectonic data as well as of paleontological, paleoclimatic, and mineralogical constraints and modern paleomagnetic models, highlight essential points of reference and open questions concerning Variscan geodynamics. Thus, it is shown that the Variscan belt results from the Devonian–Carboniferous convergence of the two mega-plates, Laurussia and Gondwana, whose collision led to the formation of the upper Carboniferous Pangea. Several micro-continents and oceanic domains, whose size and geometry vary in different reconstructions, are highlighted between Laurussia and Gondwana. The “waltz” of these micro-continents (Avalonia, Armorica), which belong to what some authors call a “Variscan continental ribbon”, located on the northern periphery of Gondwana in the Cadomian, before being transversally displaced towards Laurussia during a major rifting episode in the Cambro-Ordovician, is thus highlighted. The involvement of these domains in the construction of the belt led to the formation of four litho-tectonic zones (the northern foreland, Rheno-Hercynian, Saxothuringian and Moldanubian), which reflect as many paleogeographic units whose accretion, during the continental collision following the closure of at least two oceanic domains in two subduction zones with opposite dip, gradually built up the Variscan belt. High-resolution data over the period 360–280 Ma suggest large variations in the kinematics of mega-plates, including a major kinematic reorganization at the beginning of the Permian, and thus emphasize that the gravitational collapse of the belt is not the exclusive cause of post-orogenic extension. Finally, paleogeographical studies show the existence of an oceanic domain, the Paleo-Tethys, between Gondwana and the North Gondwanan micro-continents, which is supposed to be in subduction from the Visean but whose impact on the evolution of the Variscan belt is still ignored.

In *Chapter 3 of Volume 1*, *Julien Berger*, Associate Professor at Université Paul Sabatier in Toulouse, offers a summary of the characteristics of *pre-collisional magmatism*, and illustrates that the lithosphere of the units involved in the construction of the Variscan belt was deeply affected by pre-orogenic geodynamic events during the *Cadomian cycle*, as well as during a major *Cambro-Ordovician episode*, which is still largely misunderstood. Markers of this Cambro-Ordovician magmatism correspond to ophiolitic associations and also to massifs of basic rocks, mafic–felsic associations (the famous leptyno-amphibolitic complex) and especially felsic rocks forming massifs of orthogneiss, whose ubiquitous presence is a characteristic of the Variscan belt. In this chapter, various recognized *ophiolitic massifs* are described and analyzed, in light of recent scientific advances from the ocean floor (mid-oceanic ridges, rifted continental margins). The author shows that the combination of basic and ultrabasic rocks did not necessarily reflect the presence of an ancient mid-oceanic ridge. The presence of *oceanic sutures* in the Variscan massifs of France is thus checked. This *synthesis of cartographic, geochronological and geochemical data on Cambro-Ordovician magmatism* in France reveals an extremely heterogeneous magmatism, which reflects either an active subduction from the Cadomian, involving back-arc domains, or, what seems the most probable hypothesis, a rifting phase affecting a fertile mantle, inherited from Cadomian subduction. The impact of this continental margin magmatism, remarkable by the abundance of felsic rocks, implies that the Variscan belt can no longer be considered simply as the result of the convergence of continental margin domains with Cadomian basement. *Compilation of U–Pb ages on zircons* reflects the formation of a transitional (i.e. partly juvenile) crust in the Cambro-Ordovician continental margins. This chapter also provides a summary of Devonian magmatism, which reflects the formation of continental arcs as well as local back-arc domains during a period of active subduction.

In *Chapter 4 of Volume 1*, *Michel Faure,* Professor at the University of Orléans, describes exhaustively the evidence of *metamorphism and early deformation in the French Variscan belt,* and thus proposes a summary of the characteristics of the phases of subduction and collision, which took place in the Devonian and Carboniferous. The evidence of these early phases is mainly observed in the Moldanubian domain of the belt, and in particular in the French Massif Central and the South Armorican domain for the main branch in France. In the French Massif Central, the Moldanubian domain is marked by a stack of tectonic nappes, with an upper allochthonous unit (Upper Gneiss Unit) forming tectonic klippes and a lower allochthonous unit (Lower Gneiss Unit) and a para-autochthonous unit forming tectonic windows in the Limousin and exposed in the southern front of the belt. Four early tectono-metamorphic events are recognized in the main branch: D_0, D_1, D_2 and D_3. Phases D_0 and D_1, highlighted in the upper allochthonous unit, correspond, respectively, to an episode of burial under HP conditions and to an exhumation stage. Geothermal gradients of the burial episode, between 7 and 15°C/km, are typical of subduction zones. A metamorphic peak pressure of up to 3 GPa represents a burial of units at a depth of more than 90 km. The retromorphosis associated with episode D_1 is associated with the construction of an early southwesterly vergent crustal prism during a period of continental subduction of Gondwanan margins involving strictly continental units (high-pressure granulites) or ocean–continent transition units (eclogites of the leptyno-amphibolitic complex). D_2 and D_3 events are associated with continental collision and are expressed preferentially in the Gondwana margin, illustrating a strength contrast with the Armorica lithosphere, more marked by Cadomian orogeny. Phase D_2 is associated with a Barrovian metamorphism, with an inversion of the metamorphic isograds in the Lower Gneiss Unit, which emphasizes the ongoing thrusting of the Upper Gneiss Unit. The stretching associated with this event has a longitudinal direction with respect to the suture zones, suggesting a strong oblique component of the collisional deformation, which is still poorly understood. Tectono-metamorphic events associated with phase D_3 are recorded in the southern part of the main branch, illustrating the propagation of collisional deformation towards the southern foreland. While the absolute chronology of D_1, D_2 and D_3 events is relatively well constrained between 380 and 340 Ma, the age of the HP event (D_0) is discussed in light of the most recent geochronological datations that appear to converge towards an estimate of this event at the Late Devonian (380–360 Ma). This chapter also proposes a summary of the characteristics of the isolated French crystalline Variscan massifs such as the Maures, Corsican and Alpine crystalline massifs, which record early episodes involving subduction and collision phenomena quite comparable to the main branch.

In *Chapter 1 of Volume 2, Arnaud Villaros, Oscar Laurent, Simon Couzinié and Jean-François Moyen*, PhD in Earth Sciences, Research Fellow at the Géosciences Environnement Toulouse laboratory, Assistant Professor at the University of Lorraine, and Professor at the University of Lyon, respectively, describe the evidence and implications of *high-temperature metamorphism and syn- to late orogenic magmatism* record in the Variscan belt in France. In this chapter, the preponderance of areas that have been affected by high-temperature Carboniferous metamorphism and intruded by large granitic massifs is highlighted from synthetic maps. The synthesis of petrological and geochronological data from these domains shows that the first episode of high-temperature metamorphism (denoted M_2) affected deep rocks of the internal zones around 360–340 Ma, that is, during their exhumation associated with the formation of a crustal orogenic prism. This metamorphic episode, synchronous of the main compressive phase (D_2), is described as syn-orogenic. Subsequently, between 330 and 290 Ma, Variscan

Summary of Volume 1

Chapter 4. Early Metamorphisms and Deformations in the French Variscan Belt
Michel FAURE