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The Variscan Belt: History of the Evolution of Methods and Concepts

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1.1. Introduction

The Variscan or the Hercynian belt, in its current definition, corresponds to an orogenic belt formed between the Devonian and the Permian by tectonic accretion of oceanic domains, magmatic arcs and continental ribbons ending in the collision between the Gondwana and Laurussia continents and culminating in the assemblage of the Pangea supercontinent (e.g. Matte (2001)). This definition required the collection and synthesis of geological data as well as the development of conceptual geological models that spanned several centuries. Although the representation of the "primary" terrain in the first geological map of the globe by paleontologist and mineralogist *Ami Boué* makes it possible to guess the contours of this belt (Boué 1845), the continuity of structures and lithological units characterizing the Variscan or Hercynian belt from the east coast of North America to the Far East has only been demonstrated in the synthesis work of Eduard Suess, *The Face of the Earth* (Suess 1883) complemented by Marcel Bertrand (1887) (see Figure 1.1).

The Variscan Belt of Western Europe 1,
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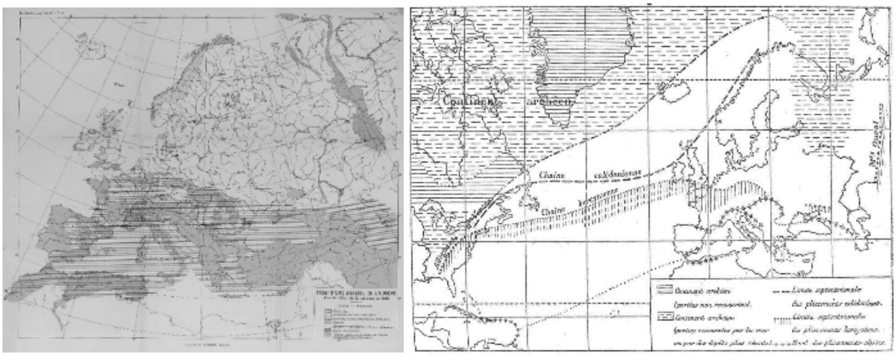

Figure 1.1. *On the left, the mountain ranges of Europe from north to south, the Caledonides (yellow), the Altaïds or Variscan range (blue) and the Posthumous or Alpid Altaïds (orange-green) (modified from Suess 1883). On the right, the extension of the Variscan belt to the Appalachians to define the Hercynian belt (modified from Bertrand 1887). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

Suess defined three systems of mountain ranges that follow one another from north to south and are “pushed back to the north” against the “Huronian” continent exposed in Scandinavia and formed of “Archean” rocks. The “Caledonides” belt, in the northern position, is the oldest (see Figure 1.1). The “Altaïd” belt is in an intermediate position, and it is bordered to the south by a more recent belt that he initially named “Posthumous Altaïds” then “Alpids”. The term “Variscan” was then proposed by Suess to designate only the Central European branch of the Altaïd Mountains with reference to the Varisci, inhabitants of Curia Variscorum, a town in Bavaria, a region in which he identified the main lithological, structural and paleontological characteristics of this ancient mountain range. At the same time, Bertrand (1887), who was interested in the coal belt of northern France and Belgium, took note of Suess’s book and introduced the term Hercynian (from *Hercynia silva*, a Hercynian forest that covered central Germany) to designate the structuring of the whole of this pre-Permian belt integrating the Armorican branch and the Variscan branch (see Figure 1.1). The structural, metamorphic, magmatic and sedimentary controls of this orogenic belt[1] are distributed from the southern Andes to the extreme east of Central Asia, passing through the Appalachians, Mauritanids and various massifs in Europe.

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[1] The term orogeny was later defined by Grove Karl Gilbert as the formation of mountain ranges by tectonic processes, as opposed to epiogenesis which corresponds to the uplift or subsidence of the Earth’s surface (Gilbert 1890).

The objective of this chapter is first to analyze how the evolution of Earth Science approaches has influenced the development of concepts on mountain belt formation in general and more specifically how the study of the Variscan belt has contributed to this evolution. We thus retrace the history of the debates that philosophers, naturalists and scientists have had concerning the construction of the Variscan belt in order to shed light on the impact of this heritage on the current debates. This historical itinerary begins with an overview of the development of geological methods at the origin of the first geological maps, regional syntheses and models of the formation of mountain ranges and ends with the advent of plate tectonics and the first models proposed for the Variscan belt in this context.

1.2. Beginnings of geology, from the Renaissance to the Industrial Revolution

1.2.1. *From Earth's history to regional geology*

The first models of the Earth's history proposed in the early modern times, from the Renaissance to the Enlightenment, are inspired by observations of nature, supported by analogous reasoning for the most part, and provided a first conceptual framework for the formation of mountain ranges (Buffon 1749; Burnet 1684; Descartes 1644; Kircher 1665). However, they were not based on systematic observation of geological data in a given region but were enhanced by scattered observations, drawn from different examples, which were used to develop a case for action in one process or another. They did not therefore include the idea of the succession of distinct mountain ranges and more particularly that of a Variscan belt. Nevertheless, it is clear that some of the observations feeding these reflections have their source in the pre-Permian basement of Europe and, on the contrary, the concepts developed at that time, whether that of the collapse of the Earth's crust, the presence of a central fire or the gradual cooling of the Earth, strongly influenced the reasoning that followed, particularly those on the Variscan belt.

The development of geological methods began with stratigraphy (Stenonis 1669), which served as the basis for the development of the Neptunism theory, according to which all the rocks forming the Earth were deposited at the bottom of a primitive ocean following an original disaster followed by successive collapses (Werner 1787). Rocks were thus classified as primitive rocks, transition rocks, primary, secondary and tertiary rocks. On the contrary, recognizing the importance of transformations of sedimentary rocks under the influence of metamorphism and magmatism led to the Plutonism theory with a cyclical and up-to-date vision of geological processes (Boué 1820, 1822; Hutton 1788; Lyell 1838; Playfair 1802).

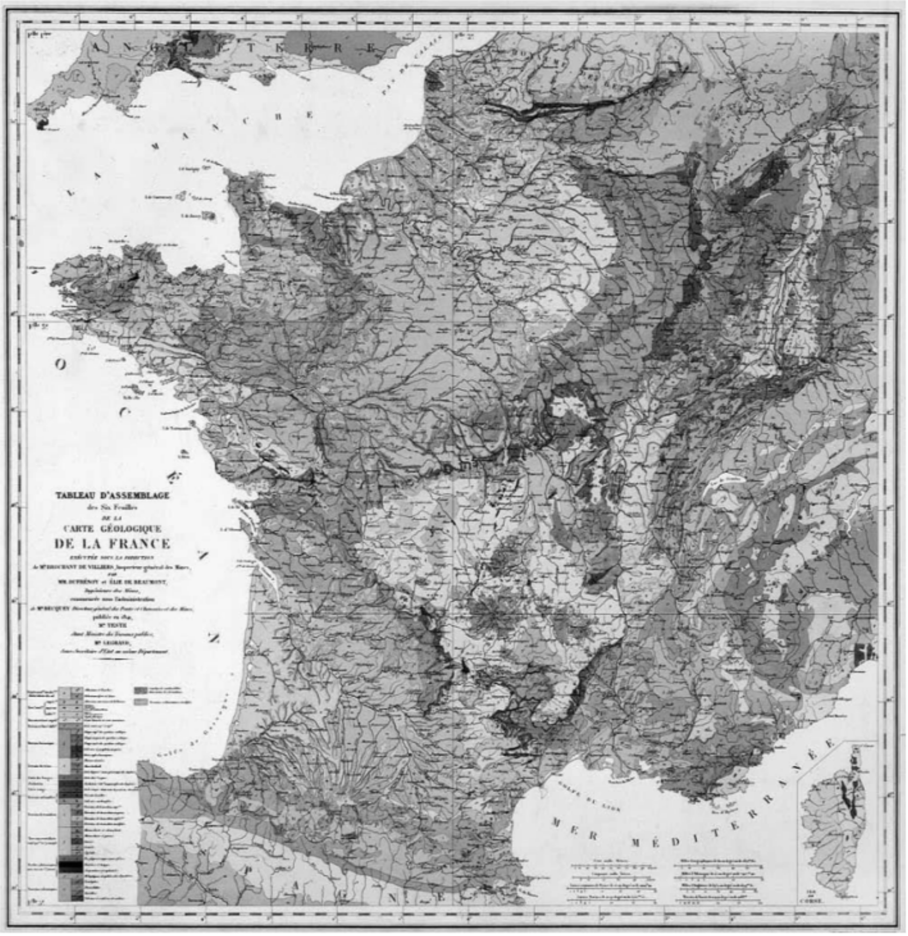

Figure 1.2. *Geological map of France (modified from Elie de Beaumont and Dufrénoy 1841a, 1841b). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

Applying these new tools of Geology made it possible to develop the first synthesis maps of the lithological sets with a particular interest in the associated mineral resources. Indeed, these maps accompanied the Industrial Revolution and the first was the geological map of the United States of America (Maclure 1809), closely followed by the map of Great Britain (Smith 1815) and the map of France (Elie de Beaumont and Dufrénoy 1841a) (see Figure 1.2). Crystalline rock massifs were clearly distinguished from the sedimentary rocks on these maps. In particular, on the map of France, crystalline massifs consisting of granite, gneiss and schists, grouped together, appeared in pink and brown tones and were defined as “old lands and transition lands”. Secondary cycle sedimentary rocks were in blue and green tones and tertiary cycle sedimentary rocks in yellow tones. This color code was a landmark and is still in use today.

1.2.2. *Stratigraphy of the Paleozoic at the front of the Variscan belt*

Preparation of geological maps at the scale of different countries required a monumental synthesis based on regional comparisons. They also provided an essential reference system and were accompanied by the development of the stratigraphic time series based primarily on the analysis of the succession of sedimentary rocks and their fossil content. The main periods of the Paleozoic have been defined in the south of England and in Wales, at the front of the Variscan belt. The first defined period is the Carboniferous, which contains the coal-bearing layers particularly exploited in this region (Conybeare and Phillips 1822). The Cambrian and the Silurian were defined a few years later and named with reference to Wales and the local tribe, the Silures (Murchison 1835; Sedgwick and Murchison 1835), followed by the Devonian (Sedgwick and Murchison 1840) and finally the Permian, after comparison with the sedimentary series of Russia and the Urals (Murchison *et al.* 1842). The transition from Cambrian to Silurian was debated (Sedgwick 1852) and resolved by the addition of the Ordovician a few decades later (Lapworth 1879).

In the Armorican Massif, two series were distinguished (Busnel 1832), “the first, composed of quartz sandstones, conglomerates, limestone-marble, shales, commonly reddish, containing fossils, and whose layers, in general, from the SE to the NW plunge by about 45° to the NE. The second, which appears to precede the first, almost exclusively composed of clay shales and grauwacke, contains only rarely, and perhaps never, organized fossil bodies, with almost vertical layers and from W 15º S to E 15º N”. Busnel mentioned that “it would be desirable to indicate the direction and the inclination of the rocks on the geological maps: this would be easy to do, because the point of the horizon towards which the layers plunge is always 90 degrees from their direction, it would suffice to indicate this by a simple line whose middle, marked with a point, would be the place of observation, and to write, on the inclination side, the number of its degrees”. The detailed cartography of the Armorican Massif is, for the most part, the work of Lillean Charles Barrois who produced more than 20 geological maps based on his knowledge of the Paleozoic series of the Anglo-Norman basin. In particular, Barrois documented the analysis of transition rocks in the St. Lô region, initially attributed to the Cambrian by Dufrénoy (Dufrénoy 1838). He identified shales under Cambrian discordance and redefined these rocks as Brioverian (see Figure 1.3) (Barrois 1899).

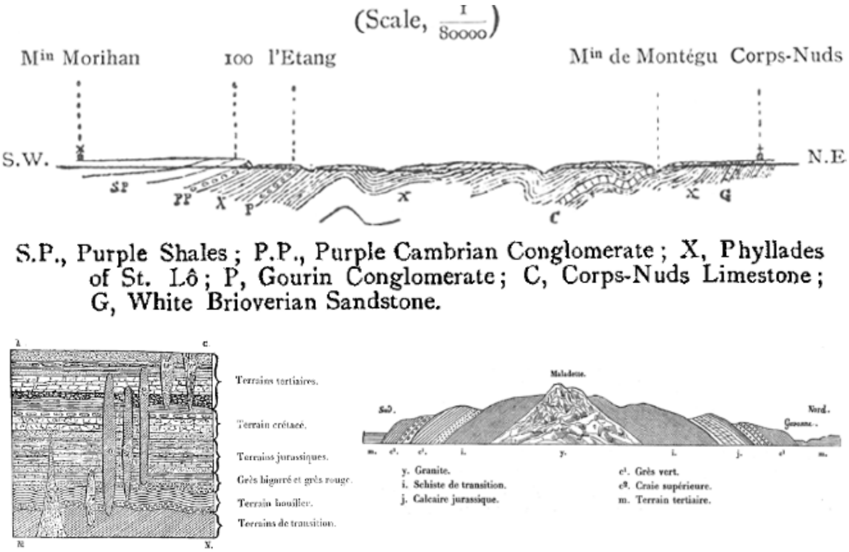

Figure 1.3. *Upper section of Corps-Nuds at the Moulin de Morihan (modified from Barrois 1899); lower left, lithostratigraphic column of the geological map of France (modified from Elie de Beaumont and Dufrénoy 1841a, 1841b) and right cross-section of the Pyrenees (modified from Elie de Beaumont and Dufrénoy 1841a, 1841b)*

By deduction, the micaschists of Groix Island, Audierne Bay and the granitic gneisses of the Quimperlé region, in an even lower stratigraphic position, were attributed to the Archean. However, Barrois confessed "that the earlier Archean gneisses are only a hypothesis and that there is even reason to think that the theory of an origin of these rocks by metamorphism dating from the beginning of the Brioverian is probably closer to the truth". This reasoning has also been applied in the other Variscan crystalline massifs of Western Europe and in particular in the French Massif Central. These observations, enriched by the comparison of the relationships between the transition and primitive soils of the crystalline massifs of Western Europe (Boué 1820, 1822), served to establish the stratigraphic column of national geological maps, notably the geological map of France (see Figure 1.2) and prefigured the definition of Caledonide and Variscan belts.

1.2.3. *Concepts of deep magmatism and metamorphism*

Alongside research on relationships between deformation and sedimentation, based primarily on structural, stratigraphic and paleontological analysis of sedimentary rocks, other authors investigated the origin of transition and primitive rocks (metamorphic and plutonic rocks). This analysis made it possible to understand the deep processes that affect the roots of mountain ranges and the Variscan belt has offered favorable ground for these new advances.

Based on observations in Variscan massifs, Boué divided metamorphic rocks into "contact formation near igneous rocks, and general or latent formation" (Boué 1820). Joseph Fournet, Professor at the Faculty of Sciences of Lyon, clarified these notions from the observation of mineralized veins in the Monts du Lyonnais in the east of the French Massif Central. He defined endometamorphism, which consists of the modification of "an eruptive rock placed in the form of veins in other rocks […] by the absorption of foreign principles", and exometamorphism as "relating to all sedimentary rocks, modified by contact or in the vicinity of a plutonic rock" (Fournet 1848). Furthermore, experimental work highlighted the role of water and heat on mineral transformations (Daubrée 1859) and also that of pressure and deformation (Hall 1805). Crystallization of feldspar or quartz was then linked to the circulation of thermal water to explain observations made in the crystalline rocks exposed in the Black Forest or in the Vosges.

Joseph Durocher, first holder of the chair of geology and mineralogy at the University of Rennes, completed the analysis of the relationship between magmatism and metamorphism by studying "transition lands" and "primordial lands" of the Variscan basement of the Pyrenees, Brittany, the Ardennes and the South of Great Britain. He suggested: "the phenomena of metamorphism are the result of a movement of the particles developed inside the rocks, […] the obvious relationship of modified lands with pyrogenic rocks, their frequent arrangement in the form of zones concentric to these rocks, show that most of these phenomena took place under the action of heat, […] and with the help of pressure, electrical forces, or other physical forces which originate when bodies of different natures are in contact and subjected to the action of long-lasting heat" (Durocher 1844). Some metamorphic minerals have "a zonary or ribbon-like arrangement, parallel to stratification" and others "originated in isolation here and there […] oriented obliquely, or even perpendicularly to the plane of schistosity" (Durocher 1846). The analysis of "granitoid", "porphyric" and "vitreous" rocks of these massifs was also associated with the introduction of the term magma with its present meaning (Durocher 1857). Granitic magma is composed of "three or even four defined combinations, orthosis, albite, mica and quartz, if the temperature of the mass is slightly higher than that which determines the solidification of the most fusible elements, it is understood that these various elements will take little time to pass from the liquid state to the solid state”. The lower, dense, basic and fluid magma which solidifies into basalt, dolerite and melaphyre is distinguished from a higher, less dense acidic and pasty magma at the origin of the granite, trachyte and andesite series.

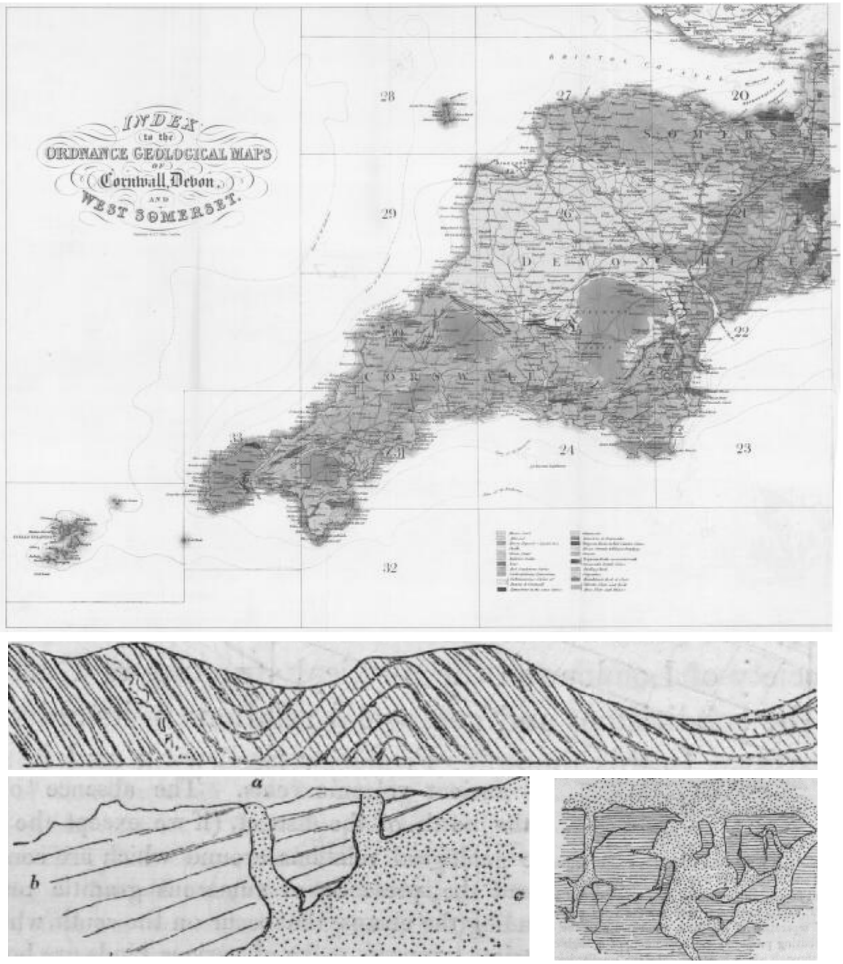

Figure 1.4. *Map of Cornwall (top), illustration of relationships between stratification and cleavage in shales (middle) and between granite (dotted) and shales (hatched) in Cornwall (modified from De la Beche 1839). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

The intrusive character of granite was also demonstrated at the same time in Cornwall, where relationships with Paleozoic shales were particularly well described on the south coast of Great Britain (Carne 1818; Davy 1818; De la Beche 1839). "According to the distribution of granite veins in shale, wherever the two rocks are in contact […] granite veins cross the shale" (Carne 1818). It is also in this region that the obliquity of schistosity ("cleavage") on stratification is mentioned for the first time (see Figure 1.4).

However, the debate between Neptunists and Plutonists was not closed, nor was the one on the cause of metamorphism. For some, the primitive lands, especially those of the Variscan belt of the central plateau or the Alps, were deposited in an overheated, supersaturated ocean and under very high pressure (de Lapparent 1885; Lory 1881; Termier 1889). For others, the notion of primitive terrain was refuted and replaced by the idea that these rocks are equivalent to sedimentary rocks but have been modified by metamorphism (Bergeron 1889). In this context, Georges Mouret mapped the crystalline soils of the Tulle geological map and deduced that the formation of granites corresponded "to the most crystalline products" of regional metamorphism (Mouret 1890). Alternatively, Auguste Michel-Lévy, who produced 11 geological maps at the scale of 1:80,000 in the Variscan basement of the French Massif Central and the Alps, invoked the increase in temperature on contact with a pluton or on a regional scale involving the presence of deep magma (Michel-Lévy 1887). He also introduced the concept of injection gneiss and granulitic gneiss in connection with the emanation of deep fluids and the intrusion of granite into metamorphic rocks.

1.2.4. *Microscopic analysis of crystalline rocks*

Microscopic investigation of crystalline rocks has provided important evidence for the debate about the nature of crystalline terrain and the origin of metamorphism. The first to be analyzed under a microscope were the metamorphic and granitic rocks of Cornwall (Sorby 1858). Rather than describing the minerals themselves, the focus was on characterizing the inclusions contained in quartz, calcite and other crystals, with the objective of demonstrating the importance of fluids in mineral and rock transformations (see Figure 1.5). It was then proposed that "metamorphic transformations are due to high temperature processes in the presence of water and not only to partial melting" and that "the action of water at very high temperature and the dissolution of salts translates the transformation of feldspar into mica, quartz, and tourmaline". On the basis of physical reasoning integrating the elasticity of the pores, the geometry of cavities was correlated with the pressure and temperature conditions of their formation. The systematic microscopic study of the minerals of the metamorphic and plutonic rocks of the Variscan massifs of the Vosges, Black Forest, Massif Central and Cornwall made it possible to identify the mineralogical and textural diversity of these rocks (Fouqué and Michel-Lévy 1879; Rosenbuch 1898), and in particular to document the impact of contact metamorphism (Allport 1876; Rosenbusch 1877) (see Figure 1.5).

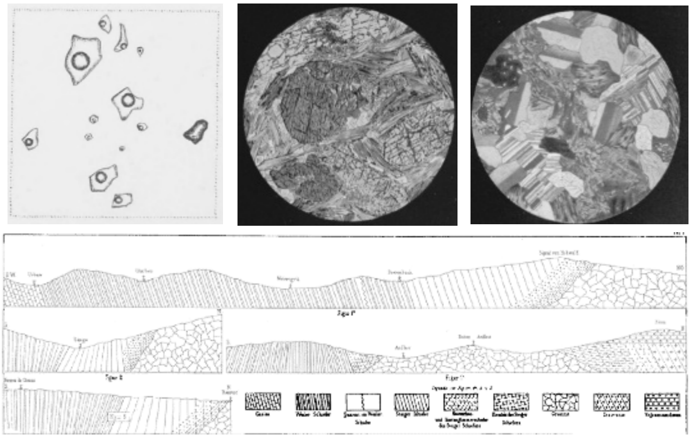

Figure 1.5. *Top left: fluid inclusions of the plutonic and metamorphic rocks of Cornwall, geometries and mineral content (modified from Sorby 1858); top middle: shale with garnet-andalusite of the Great Saint Bernard; top right: Granite des Settons (Nièvre) (modified from Fouqué and Michel-Lévy 1879); bottom: contact metamorphism in the shales of Steige intruded by the granite of the Hochwald in the Vosges (modified from Rosenbuch 1877). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

1.2.5. *Theory of magmatic uplifting*

From the synthesis of data, leading to the building of regional geological maps and to the development of new geological concepts on the formation of mountain ranges, there was only one step and it was taken in the early 19th century. In particular, the theory of collapse, proposed previously, was called into question by that of the uplift craters. The latter was developed from the observation of the domes of “porphyries” of the Chaine des Puys in the French Massif Central (Von Buch 1803) and applied to relationships between primitive lands and transition lands. The idea was that mountains result from the unstoppable vertical expansion of a crystalline massif causing the gravity flow of the flanks of the uplift axis, thus explaining the planar structure of shales and gneisses (see Figure 1.6) (Scrope 1825). This theory of magmatic uplifting was then generalized (Elie de Beaumont and

Dufrénoy 1841b) and the history of Earth would have been marked by a succession of eruptive events, “the first effect of each paroxysm of the igneous action consisted of the emergence of semi-pastuous matter that rose in the form of crests with more or less wide bases, which gave rise to mountain ranges”, and “a similar emergence, taking place in the middle of a resistant ground, must have the consequence of raising or uplifting it”. Consequently, “the sedimentary layers, initially horizontal, found themselves straightened and even sometimes hoisted and perforated by the pasty massifs that emerged from the depths”.

It was proposed that all mountain ranges included a primitive core, consisting essentially of granite, surrounded on either side by sedimentary rocks whose age of deposition and recovery was increasingly young the farther away they were from the core (Elie de Beaumont 1844, 1852). This analysis made it possible to date the formation of a mountain range between the age of the youngest tilted sediments and that of the oldest horizontally deposited sediments. Each uplift is considered a unique phenomenon that occured simultaneously across the Earth with the same direction forming a large circle on the scale of the globe in connection with Earth’s cooling and contraction. In this context, geometric relationships between old and recent belts were illustrated by the Variscan belt in the Vosges on the left of the cross-section, and the Alps on the right of the cross-section (see Figure 1.6).

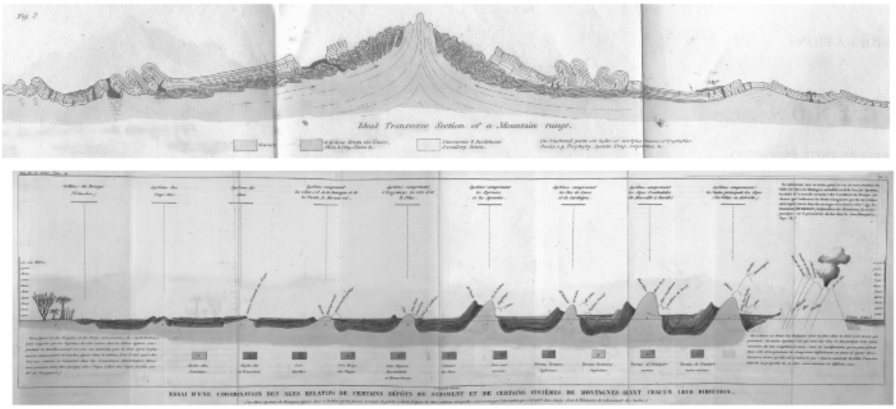

Figure 1.6. *Top: mountain belt formation model (modified from Scrope 1825). The uplift is caused by the crustal flow of magma and the fold belts are generated by the gravitational slip on the sides of the mountain. Geometrical and chronological relationships of mountain systems are shown below (modified from Elie de Beaumont 1852). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

1.2.6. *Geosynclinal theory developed from the Appalachians*

The geosynclinal theory emerged on the other side of the Atlantic, from the analysis of the Appalachians. First, James Hall, an American paleontologist and stratigrapher, observed that the folded Paleozoic sedimentary series in the Appalachians were 10 times thicker than those of the same age deposited on the craton further west. He deduced that "the more sediments accumulate, the higher the mountain range will be". He backed his hypothesis with the observation that "the direction of a mountain range correlates with that of the maximum sediment accumulation zone" (Hall 1859). According to this hypothesis, sediment accumulation causes the basement to subside and buried sediments to fold. His model incorporated the metamorphism that would be "due to movement or fermentation and the change in pressure assisted by an increase in temperature inducing a change in chemistry". Sediment deformation to form a "synclinorium" was attributed to a lateral compressive force; the subsidence must be accommodated by the lateral movement of a mass of rocks that an increase in temperature under the sediments renders deformable.

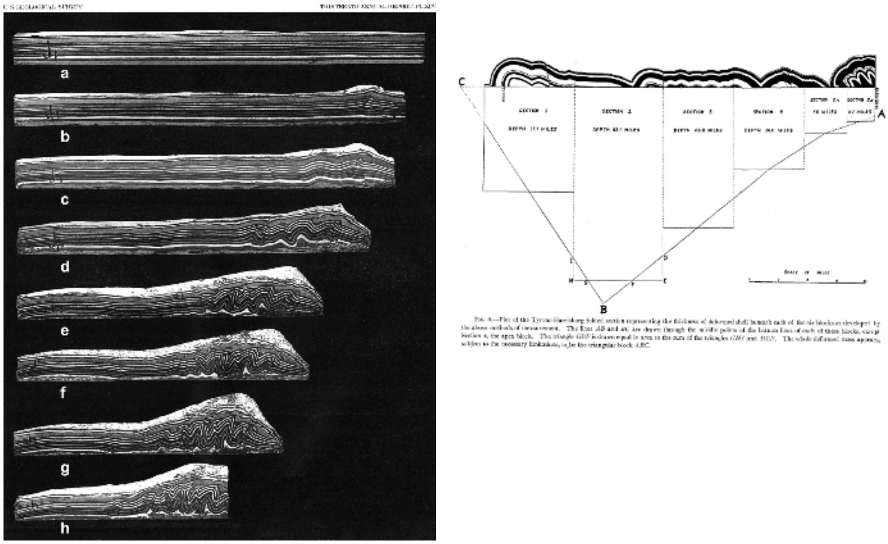

Figure 1.7. *Analogue modeling of mountain belt formation (modified from Willis 1893) and balanced cross-section model (modified from Chamberlin 1910). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

In the case of the Appalachians, this mass moved eastward to form a "geanticline". Subsidence and sediment accumulation phases were considered to be long compared to mountain folding and uplift phases associated with tsunamis and mass extinctions. Moreover, beautiful folded structures in the Appalachians were reproduced experimentally (Willis 1893) and served as the basis for reconstructing the first balanced cross-sections (see Figure 1.7) (Chamberlin 1910).

1.2.7. *Mountain belt vergence theory*

At the same time, Eduard Suess refuted the axial uplift theory in connection with intrusions, criticized that of geosynclines, evoked the idea of Earth's rotation, and promoted the idea of a collapse at the origin of mountain belts. The key observation made by Suess, first in the Alps (Suess 1875) and then in other belts including the Variscan belt (Suess 1883), was that of the polarity and vergence of mountain belt structures. According to him, this polarity is the reflection of a unilateral thrust of continental blocks causing a horizontal shortening highlighted by arc-shaped folds and thrusts molded around ancient continental nuclei in the foreland. He recognized horst and graben structures distributed radially behind mountain ranges; he attributed these structures to subsidence at the origin of oceans. By carefully comparing lithological units, fossils and structures between continents, Suess identified the succession of three folding systems (Suess 1883) (see Figure 1.1), including the Altaïd belt of the end of the primary period, which includes an Armorican branch correlated with the Appalachian belt on the other side of the Atlantic and a Variscan branch that extends to Asia. Earth's contraction caused tangential displacement of continental blocks at the origin of mountains by pushing back into the foreland coeval with a radial subsidence in the hinterland. Suess also defined Earth's constituent envelopes identified by gravimetry and seismology (Oldham 1906; Wiechert 1897), with an iron core (nife) surrounded by a mantle of magnesium silicates (sima) flush with the ocean floor on which lighter continents of aluminum silicates (sal, later redefined as sial) rest (Suess 1883).

Marcel Bertrand complemented the analysis of Earth's crust deformation by demonstrating thrust nappes (Bertrand 1884) from the comparison between folds in connection with the Faille du Midi in the Franco-Belgian coal basin (Cornet and Briart 1863; Gosselet 1874), and the double fold in the Glarus Alps (Heim 1878). Bertrand recognized the importance of the plastic behavior of rocks to allow this extreme thinning and the associated tangential movements which, according to him, were of the order of a hundred kilometers. In contrast to Elie de Beaumont, who associated each mountain range with a structural orientation, Bertrand defined mountain ranges by the continuity of folding and thrust zones. Based on the analysis of structure deformation and sedimentary unconformity relationships, particularly well described in the Franco-Belgian coal basin, he demonstrated that the formation of a mountain range is a slow process, with the uplift of the terrestrial surface gradually pushing marine sediment and lake sediment deposition towards the foreland. He deduced from this “that, at the end of the primary period, there existed in Europe a mountain range quite comparable to the Alps” (Bertrand 1887).

Continuing the comparison of different mountain ranges, Bertrand drew general conclusions concerning the relationships between deformation, magmatism, sedimentation and the distribution of metal-bearing deposits (Bertrand 1888, 1892). According to him, the rise of granite in the axial part of a belt in connection with the initiation of tectonic movements is followed by porphyry and alternately acidic and basic eruptions in the central zone, followed by basic eruptions subsequent to the last movements. In the depths of the crust, molten silicates cause these different eruptions and their gradual cooling first exhausts the potash during the rise of granites and then the silica during the eruption of porphyries. Similarly for sedimentation, he recognized the first deposits of fine flysch transformed into gneisses and shales that form a geosyncline’s core corresponding to the Culm facies of the lower Carboniferous. The evolution of a geosyncline is then marked by coarser flysch deposits of upper Carboniferous coal. Finally, conglomerate coarse sandstone deposition at the foot of a belt, such as Permian red sandstones, testifies to the erosion of associated large fold layers. Bertrand adopted the geosynclinal model and proposed that the collapse of troughs led to nappes being carried from a peripheral ridge to the neighboring basin. He dissociated nappe emplacement and the later belt uplift caused by a lack of gravity and a lack of weight and mentioned that “the coordination of folds around polar regions conjures the idea of a theoretical link with the flattening or with the rotation of the Earth”. According to this idea, “the Earth would be comparable to an orange whose peel could be rotated by hand as one piece without moving the fruit”.

1.3. Debate between fixists and mobilists from the late 19th to early 20th centuries

1.3.1. *Geosynclinal theory and the European Variscan belt*

The geosynclinal theory returned to the forefront and dominated the scientific community of the early 20th century. Its merit was that it provided a common framework to account for sedimentation, magmatism, deformation, metamorphism and even metallogeny. Paleontologist Emile Haug described geosynclines as narrow, mobile areas between stable continental areas (Haug 1900). Louis De Launay, confirmed Suess’s proposal that, to a great extent, the Alpine belt was superimposed on the oldest Variscan belt after peneplanation and he ventured this anthropomorphism: “Nature acted as humans do by constantly rebuilding on the same ruins” (De Launay

1921). The tectonicist Hans Stille described correlations between the Appalachians and the Variscides on both sides of the oceans and seas, and made an accurate inventory of orogenic phases based on an analysis of deformation structure and sedimentary unconformity relationships (see Figure 1.8) (Stille 1928, 1929).

Much of this work was based on macroscopic analysis of rocks, minerals and fossils. The main objective was to establish the relative chronology of deformation phases, based on overlapping relationships, with respect to sedimentation and magmatism phases as well as to discuss the forces behind isostatic readjustment caused by sediment accumulation or behind the contraction of the Earth.

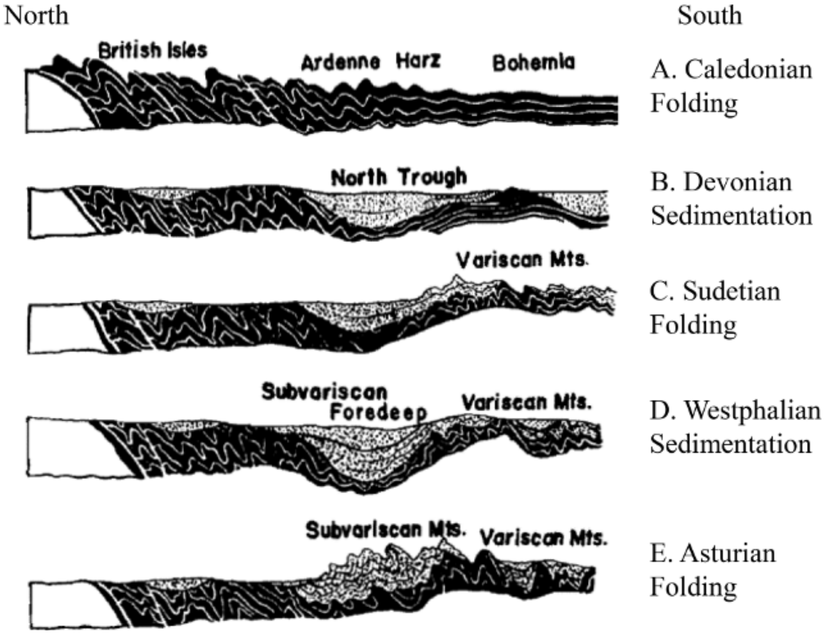

Figure 1.8. *Schematic sections representing relationships between fold and discordance during the formation of the Variscan belt (modified from Stille 1929)*

1.3.2. *Zoneography of metamorphism in the Variscan belt*

Reflections on the causes of metamorphism and its relationship with magmatism led to the development of the metamorphic zoneography model by Jean Jung and Maurice Roques, drawing on George Barrow's book of 1893 on metamorphic zone distribution of. This model was built from the distribution of metamorphic rocks derived from clay shales form the French Massif Central example (Jung and Roques

1936; Roques 1941). From top to bottom, isometamorphism zones (upper and lower micaschists, upper and lower gneisses) were defined on the basis of the presence of neoformed minerals (see Figure 1.9). These areas were identified as regionally discordant on stratigraphic boundaries but locally parallel and considered to be due to the gradual increase in temperature and pressure affecting sedimentary and volcanic rocks accumulated in a geosyncline. During burial, layers underwent a curvature leading to their extension, which would be at the origin of the preferred orientation of minerals, which is almost horizontal and very slightly oblique to the stratification. These deformed metamorphic rocks were called "ectinites" whose chemical composition has not been modified by metamorphism. The presence of aplitic quarto-feldspar "ichoric" is considered to result from the transformation of ectinites under the influence of a fluid flow which gives rise to migmatites (Roques 1941). The progression of this metasomatism front results in the formation of diadysites, embrechites and anatexites, the limits of which can be secant on isometamorphism zones. Anatexites pass continuously to "fundamental" granite. Metamorphism and metasomatism are pre-tectonic according to this model and Raguin (1946) summarized the implications as follows: "J. Jung and M. Roques have described, in the French Massif Central, injection gneisses or embrechites arranged in undisturbed and slightly inclined stratification over large areas, […] and suggest that these granitizations were carried out within immobile compartments." The authors of this model amended it by adding an "ultra-lower gneiss" zone and the "stratoid migmatites" notion to account for the presence of gneiss levels within micaschists as in the Upper Limousin (Chenevoy 1958; Jung and Roques 1952).

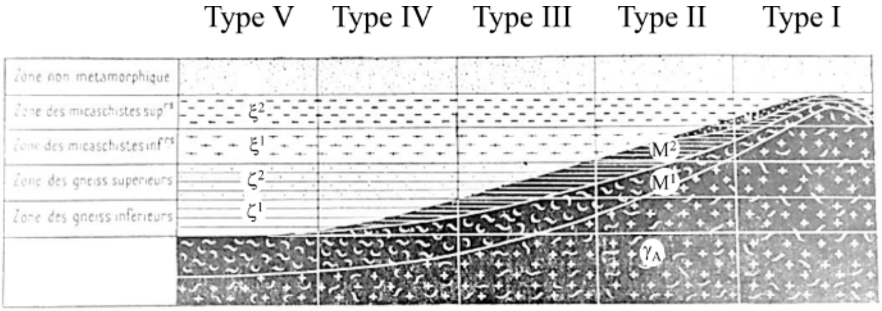

Figure 1.9. *Five types of crystallophyll series: relationships between isometamorphic zones and migmatization zones. Migmatites: M_3, dyadisites; M_2, embrechites; M_1, anatexites; γA, anatectic granite (modified from Roques 1941)*

Jung (1954) proposed to subdivise the French Massif Central into three orogenic regions (see Figure 1.10).

– In the north, the “Auvergnian-Vosgian nucleus, formed during a very old orogenic phase, in discordant Dinantian, on deeply eroded series: Auvergne, Forez, Lyonnais, Morvan”.

– In the south, the “peripheral Hercynian belt” molded on the Auvergnian-Vosgian nucleus characterized by a “concordance between the crystallophyllous substratum and the primary soils up to the Dinantian”.

– A transition zone; in fact, “no boundary: stratigraphic or very clear zoneography” separates the two preceding domains.

Jung also proposed, from the interpretation of gravimetric and magnetic measurements, an initial characterization of the deep structure of the French Massif Central and identified the so-called coal trench, which corresponds to the western limit of a thinner crustal domain (Jung 1933).

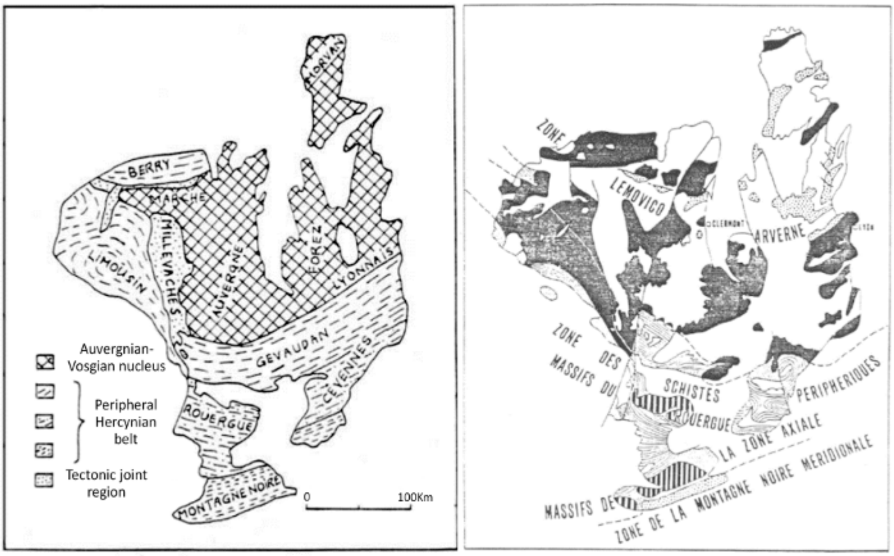

Figure 1.10. *Left: a geological diagram of the French Massif Central with a Precambrian Auvergnian-Vosgian nucleus around which the peripheral Hercynian belt is molded (modified from Jung 1954); slightly modified on the right by the redefinition of the Auvergnian-Vosgian nucleus into a Limousinian-Auvergnian zone of smaller extension (modified from Roques 1941)*

Following this work, Gérard Guitard recognized the abundance of orthogneisses in the Canigou massif of the Axial Zone of the Pyrenees and interpreted them as a basement onto which the Paleozoic series were deposited (Guitard 1970). He observed that the metamorphic isograds of the cover tightened on contact with the base, which formed the basis for the development of the "basement effect" concept (Fonteilles and Guitard 1964). Metamorphism reflects the progression of "isoeotherms" towards the surface of the crust. In this context, isograds correspond to places where endothermic metamorphic reactions are triggered, which slow the rise of isotherms. The basement effect is explained by the fact that the latter has already been affected by a certain number of endothermic reactions and that, consequently, isotherms are not slowed down in the latter.

1.3.3. *Nappes, migmatites and plutons of the internal Variscan belt*

At the turn of the 19th and 20th centuries, the development of microscopic analysis of minerals and structures made it possible to better understand processes that affected crystalline rocks in the internal zone of the Variscan belt. This led to the identification of metamorphic nappes and therefore the importance of horizontal movements affecting crystalline terrains. Furthermore, this analysis opened the way to further reflection on the links between metamorphic rocks and plutonic rocks.

For the Massif Central, Marcellin Boule, whose book focused more on fossils and volcanoes than on primitive rocks but who was from Cantal, wondered as early as 1900 about the Lot series, in the heart of the central plateau: "either all this ground is overturned and we are in the presence of a gigantic fold layer, a convenient hypothesis but very unlikely, or the petrographic characters of the Archean series do not always have great importance from the chronological point of view" (Boule 1900). This intuition was confirmed by Pierre Termier, a tangential tectonist who demonstrated the presence of pre-Stephanian nappes in the crystalline rocks of the Pilat Massif on the basis of lithological variations (Termier 1889; Termier and Friedel 1906). Similarly, Pierre Bergeron, Professor of Mineralogy and Geology at the Ecole Centrale, relied on recognizing reference stratigraphic levels in the Paleozoic series and distinguished "deep folds" formed under sediments of several thousand meters of thickness "south of the Cevennes" and surface folds in the Black Mountains (Bergeron 1889, 1902). He also identified the relationship between deformation and granite location and stated that, in this region, general metamorphism affected the Cambrian and that granite location and granulitization are subsequent to the folding of the ante-Stephanian Paleozoic layers but that in places, granites and gneisses were crushed. Bernard Gèze specified the geometry of the nappes of the Montagne Noire with a detailed map and followed Bergeron's proposal of a northern vergence (Gèze 1949).

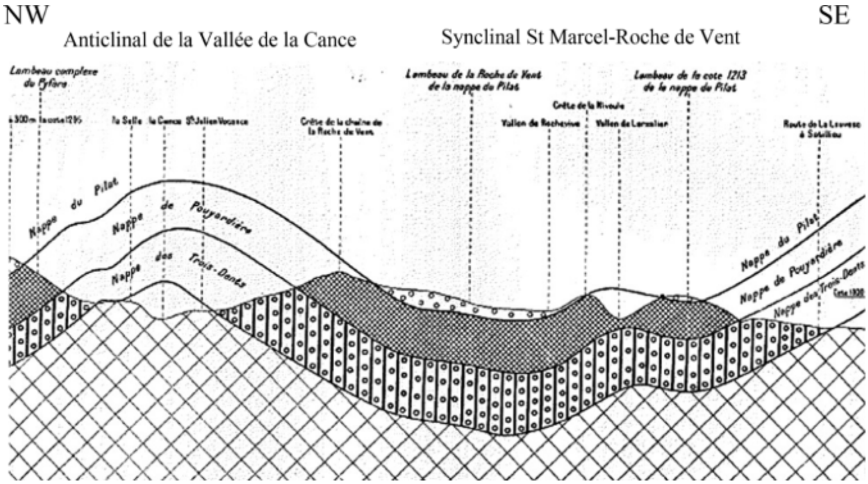

Figure 1.11. *Nappes in the Massif of the Cévennes (modified from Demay 1931)*

Bruno Sander, Professor at the University of Vienna and later Innsbruck, complemented the macroscopic analysis of deformation by the analysis of microstructures (Sander 1912, 1948). In particular, he defined "tectonites" as rocks whose texture makes it possible to demonstrate movements of its constituent elements, which are correlated with the overall movements of general tectonics. André Demay, Professor at the Ecole des Mines de St Etienne, added to this analysis of crystalline rocks very detailed observations of textures and microstructures in thin sections (Demay 1942). This led him to make the connection between deformation and metamorphism and to reconstruct the history of metamorphism from the relationships between "crystalloblastesis" of the minerals of metamorphism and microstructures. He described "the fluid or laminated texture where elements, although deformed and solid, seem to have flowed, like a viscous material" and "syn-kinematic" or "syn-tectonic" metamorphism based on the presence of "inclusion lines" within porphyroblasts. He also made the connection between "diapthoresis", "regressive metamorphism, characterized by the birth of minerals of the epizone to the detriment of minerals of the mesozone or of the catazone" and "dynamic phenomena". As an example, he cited, "the chloritization of the biotite and the sericitization of the calco-sodium feldspars in a laminated rock". He also identified the importance of "mylonite" zones which he defined as "crushed and laminated rock" and recognized large fold layers in the south of the Massif Central, particularly in the Cevennes (Demay 1931) (see Figure 1.11). He proposed that microtectonics be the reflection of general tectonics, on "relationships between deformation and crystallization phases", on "relationships between dynamic phenomena and crystallizations" and on "alternating or simultaneous phases of orogenesis and injection or magmatic impregnation". According to him, "there is nothing to define a deep metamorphism independent of granitic action" (Demay 1937) and he distinguished, "syn-tectonic or post-tectonic magmatic phenomena". His books thus demonstrate the syn-metamorphic and syn-magmatic tangential nature of tectonics with nappes whose "apparent thrusts and path were almost everywhere directed towards the South". He attributed inverse metamorphism associated with the nappes of the central zone of the Massif Central to tectonic reversal.

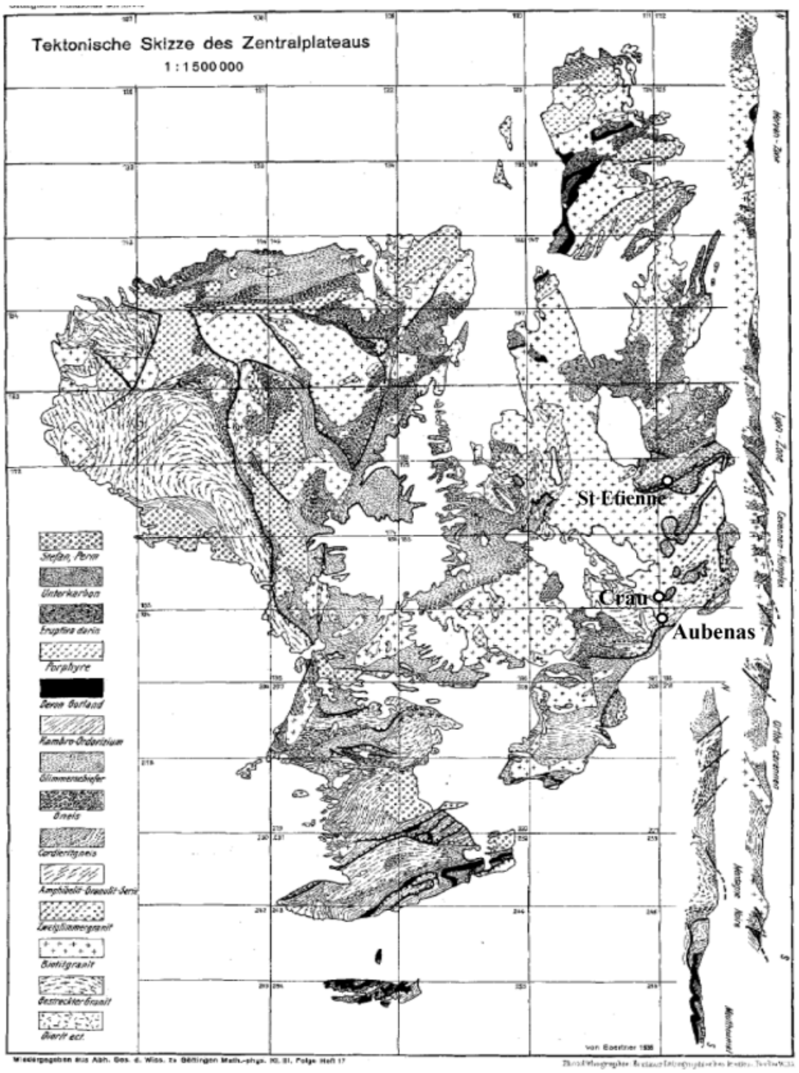

Figure 1.12. *Litho-tectonic map of the French Massif Central (modified from von Gaertner 1937)*

At the same time, Hans-Rudolf von Gaertner, Professor of Geology at the University of Hamburg, published a remarkable synthesis article combining all the knowledge available on the Central Plateau (von Gaertner 1937). In particular, he proposed a litho-tectonic map and sections that illustrated the relationships between metamorphic rocks, plutonic rocks and migmatites in an original way (see Figure 1.12). He observed that, in what he defined as the "Cévennes complex" in the Velay region, "micaschist and alkaline granite nappes lie flat on a sub-structure of migmatites. Nappes have been moved towards the S. Variscan tectonics in this area is marked by the action of granites in the substructure for which a pre-Carboniferous age is assumed. Moreover, younger two micas granite intruded the nappe". Further south, in the Cevennes region, which he described as an "orthocevenol complex", "phyllite and epizonal micaschists of presumably Cambrian–Ordovician age are intruded by syn-tectonic migmatic granites".

Large nappes were also described in the Bohemian massif, with the klippe of the Münchberg gneisses (Suess 1912). Following Suess, Franz Kossmat, a German-Austrian geologist and Director of the Geological Service of Saxony, made a significant contribution by also identifying new nappes, which led him to add an orogenic phase to the Upper Carbonifer (Kossmat 1927). The beginning of the geosyncline's evolution is marked by the establishment of basic magmas as demonstrated by basic magmatic rocks and in particular marine basalts at the base of sedimentary series. During the sediment folding stage, the dominant magmatism is granitic, attributed to the dissolution of the sialic root, which subsided within the sima due to isostasis. The cooled crust solidifies and breaks, thus facilitating lava eruption. Isostatic subsidence of a mountain range is associated with the flexure of the foreland and this depression is filled by sediments from the mountain range. On this basis, he defined the main litho-tectonic zones of this branch of the Variscan belt as follows (see Figure 1.13):

– the Westphalian Zone corresponding to the foreland folded belt;

– the Rhenohercynian Zone dominated by metagraywacke;

– the Saxothuringian Zone;

– the Moldanubian Zone consisting of basement nappes.

Granite massifs were identified in the Saxothuringian and Moldanubian zones (Kossmat 1927). Some of these plutons are associated with significant metal stocks such as in the Erzgebirge (meaning "ore mountains"). In the Black Forest, granites alternate with metamorphic rocks and also form plutons intersecting sedimentary rocks of the lower Carboniferous (Hoenes 1940). Granites deformed with metamorphic rocks were interpreted as representative of a deep location, while others associated with a contact halo were considered equivalent of the former but located closer to the surface. The whole was deformed into a vast syncline. Granite pebbles are present in mid-Carboniferous "erogenous" sediments, which have themselves been tilted and caught in overlapping scales and have been unconformably covered by Stephanian and Permian sediments.

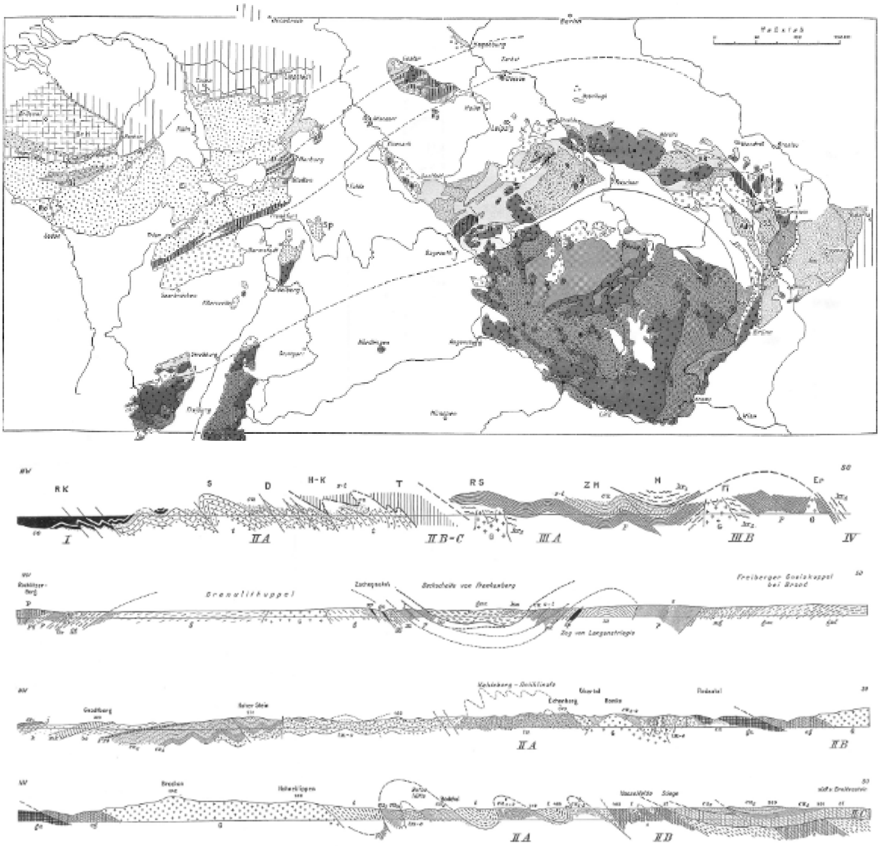

Figure 1.13. *At the top: principal litho-tectonic zones of the Vosges to Bohemian Variscan belt (Kossmat 1927). I. Westphalia Zone; II. Rhenohercynian Zone; III. Saxothuringian Zone; IV. Moldanubian Zone. Below: various Variscan nappes in Bohemia (modified from Kossmat 1927). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

The Black Forest was also the principal ground used by the German mineralogist and petrologist Karl Richard Mehnert to develop reference work on the structural analysis of migmatites, macroscopically heterogeneous rocks composed of a gneissic part and a granitic part (Mehnert 1968). He distinguished the principal entities of migmatites, which are leucosome composed of quartz and feldspar with a magmatic texture, melanosome, bordering the leucosome and composed of ferro-magnesian minerals and mesosome of intermediate composition. The leucosome–melanosome association was interpreted as representing the neosome formed by partial fusion; leucosome were derived from the crystallization of a silicate liquid and the melanosome corresponding to minerals associated with the partial fusion reaction. The rest of the rock is called the paleosome and would be representative of the protolith. From the geometric relationships between these three entities, Mehnert defined a dozen types of migmatites which he subdivided into metatexites (rocks dominated by the mesosome for which the protolith is recognizable) and diatexites (rocks dominated by the neosome and for which it is difficult to identify the protolith).

1.3.4. *The Variscan belt and continental drift*

At the beginning of the 20th century, the continental drift theory (Wegener 1915) provided an alternative to explain horizontal shortenings and large displacements identified not only in recent mountain ranges, as proposed by Wegener, but also for older ones (Staub 1928; Van Waterschoot van der Gracht 1928; Wegmann 1935). In particular, Emile Argand, a Swiss geologist and excellent tectonicist, highlighted the importance of horizontal movements in connection with “continental transverse displacements”. “It is because tectonic objects, shrinking under tangential force, are indeed forced to go up or down by warping: there is therefore a vertical effect that derives directly from the tangential force, and too often this effect has been taken for a vertical movement independent of the deformation.” He was thus clearly in favor of mobilism and provided a considerable amount of geological evidence, notably from the Alpine belt (Argand 1916). In addition to Wegener’s proposal, however, Argand extended the scope of continental transverse displacements to older Hercynian and Caledonide belts (see Figure 1.14) in his masterpiece, *Tectonics of Asia* (Argand 1924).

According to him, “the Indo-African landmass and what was to be Eurasia lasted, intermittently, since the Cambrian. It had continued in the rest of the Paleozoic times and we found traces of it even in the Himalayan geosyncline. Old Eurasia was formed in one piece before the end of the Paleozoic. Paleozoic geosynclines were filled. New Caledonian folds united Precambrian poles; Hercynian folds perfected this bonding. […] A strong axial exaltation was marked, in the Hercynian times, in what was to be the French Massif Central. As a result, post-Hercynian erosions stripped the Paleozoic sedimentary cover, which remained normal and deeply rooted in crystalline terranes”. We should note that he continued to use geosynclinal terminology while supporting the transverse displacement theory in a lyrical style: “it seems that, on these rafts where our destinies float, no fact is sufficiently annoying to prevent us from the delight of wise ‘outbursts’ to which Mr. Wegener invites us”.

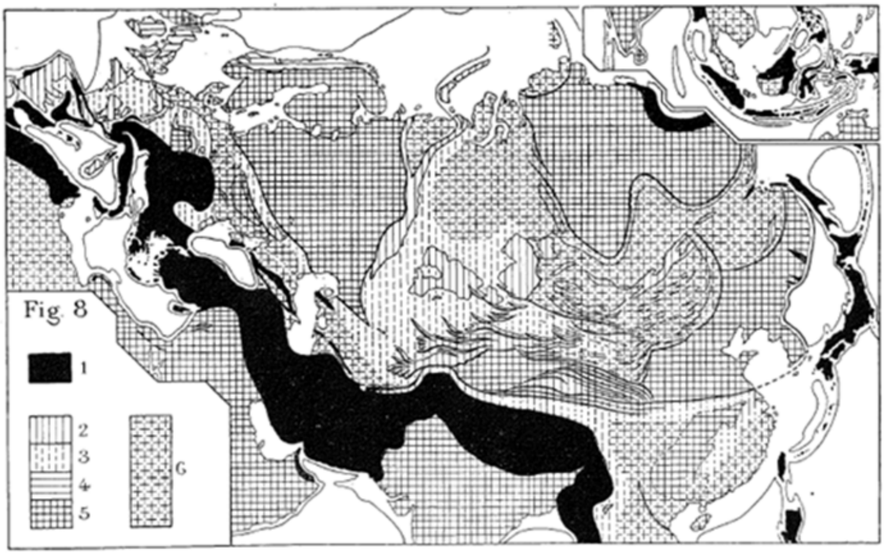

Figure 1.14. *Schematic tectonic map of Eurasia. (1) Geosynclinal belts and liminal belts of the Alpine belt, with enclosed bottom folds. Alpine bottom folds from (2) to (6): Hercynian material (2, 3), New Caledonian material (4), Precambrian material and old platforms in general (5) and Ante-Alpine material in general (6) (modified from Argand 1924)*

Boris Choubert continued applying the continental drift theory to pre-Alpine belts. He was a specialist of Precambrian belts in Africa and South America. Wegener’s proposal challenged him, leading him to make some significant additions (Choubert 1935). To convince himself of the relevance of the continental drift from a single continent, he carried out a test of the complementarity of peri-Atlantic continent coasts (see Figure 1.15). He then covered a terrestrial globe with a paraffin-coated veil on which he drew the contours of continents. It was based on the position of continental slopes, thus omitting the platforms currently covered with water and improving the correspondence. This reconstruction, well before that of

Bullard *et al.* (1965), enabled him to distinguish three continental masses (Laurentia, Baltica and Gondwana) which were separated by the Iapetus, Rheic and Medio-European oceans, in the Paleozoic, then by the Atlantic in the Mesozoic (see Figure 1.15). He proposed the following: “it is between these three masses, already fixed from before the Cambrian, that the Paleozoic belts are compressed. […] The relative play of these three landmasses has wrinkled the entire Mediterranean basin of the Paleozoic times, thanks to their multiple position changes. […] If the folds of the Paleozoic belts were undone, continental masses that were set before the Cambrian would be separated by much larger spaces and their reciprocal positions would be modified. […] The constant changes of position of Precambrian masses during primary times have resulted in the formation of Paleozoic belts, and in the tertiary times, they gave birth to the Alpine belts”.

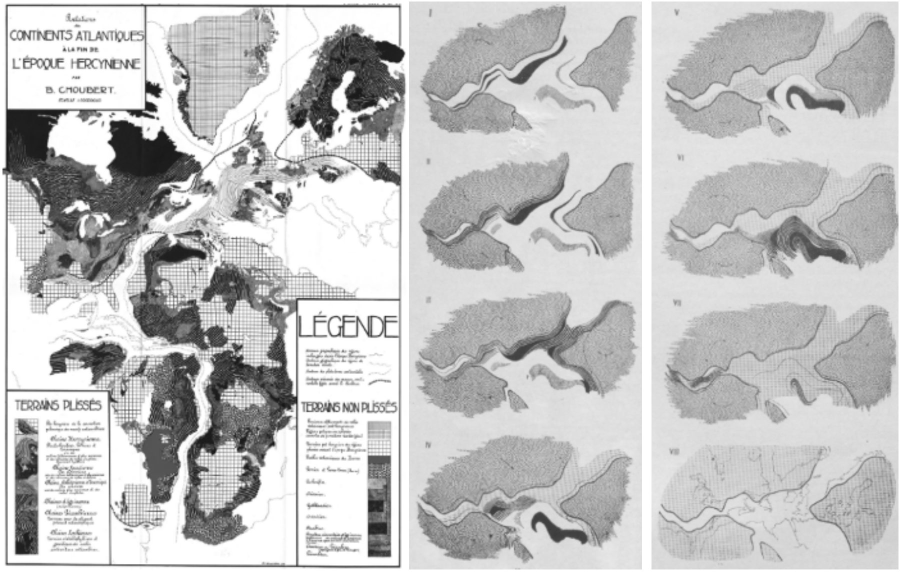

Figure 1.15. *Reconstruction of the Hercynian belt before the Atlantic was opened (left) and reconstruction of the history of deposits and deformations during the formation of the Hercynian belt (right) (modified from Choubert 1935). For a color version of this figure, see www.iste.co.uk/denele/variscan1.zip*

Choubert analyzed the succession of sedimentary deposits involved in mountain ranges, which helped him reconstruct topographical evolution. He thus concluded:

"pre-Cambrian shoals where sial predominates have contributed to the formation of all the Paleozoic belts by playing the role of geanticlinals. Furthermore, during primary times, geanticlinal ridges were formed in front of drifting continents. […] Everything happens as if the slow and gradual closing of the distance between two continental masses were digging a trench in front of each of them". Finally, he suggested that "the principal movements of the Hercynian orogeny took place during the Carboniferous period" and that "as the land gains ground through the formation of successive mountain ranges, the Tethys of the Paleozoic times gradually retreats to the East".

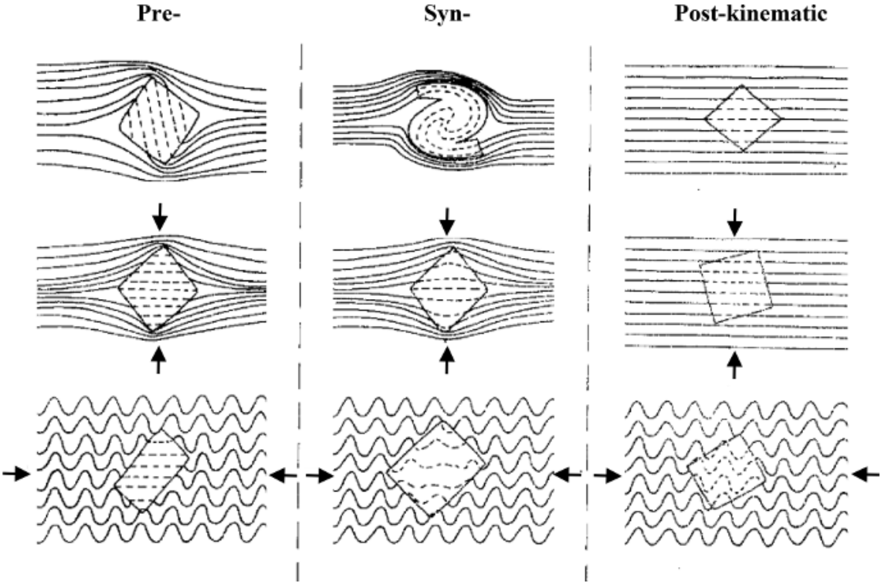

Figure 1.16. *Relationships between metamorphism minerals and microstructures from analysis of crystalline rocks of the Pyrenees (modified from Zwart 1962)*

At the advent of plate tectonics, Henk Zwart, Professor of Petrology and Structural Geology at the University of Utrecht, completed the analysis of deformations by correlating microstructures with metamorphism minerals from the study of the Axial Zone of the Pyrenees (Zwart 1953). On the basis of porphyroblasts and ductile fabric relationships (see Figure 1.16), he identified four metamorphic zones that recorded LP/HT metamorphism and a tectonic evolution subdivided into five deformation phases (Zwart 1962, 1964). These investigations served as inspiration to define the "Hercynotype" and "Alpinotype" belts (Zwart

1967), which were distinguished by: “(1) a low-pressure metamorphism with andalusite and cordierite or a high-pressure metamorphism with glaucophane, sodium pyroxene, lawsonite, and disthene; (2) thin or thick metamorphic zones; (3) granites and abundant or rare granites; (4) rare or abundant ophiolites and ultrabasites; (5) broad or narrow orogens; (6) weak or significant uplift; (7) rare or predominant nappes” (Zwart 1967). These characteristics were integrated into a geosynclinal model formed following a mantle plume (Zwart and Dornsiepen 1978).

1.4. Unification of the Earth sciences in the late 1960s

1.4.1. *The Variscan belt at the time of plate tectonics*

Plate tectonics theory, the current paradigm of all geosciences, was developed primarily from geophysical data to explain lithospheric plate movement first identified in the oceans (Isacks *et al.* 1968; Le Pichon 1968; Morgan 1968). Its application to the interpretation of active mountain belts on the basis of geological data came afterwards with the distinction of subduction belts or Cordilleras, and collision belts such as the Alps and the Himalayas (Dewey and Bird 1970; Dickinson 1971).

Proposals to integrate the Variscan belt within the plate tectonic context followed closely first with an Andean belt model associated with the subduction towards the north of the Tethys ocean separating Africa and Europe (Nicolas 1972). This model was developed on the basis of the presence of “volcano-sedimentary clastic series […] forming a quasi-continuous belt from northern Brittany to the Urals, which may have corresponded to a line of active volcanic eruptions from the end of the Devonian to the end of the lower Carboniferous” (see Figure 1.17). This model was immediately refuted on the basis of paleogeographical and paleobotanical arguments and the presence of a suture in the south of the British Isles and Scandinavia, which show an ocean between southern and northern Europe (Burrett 1972; Johnson 1973; Laurent 1972) (see Figure 1.17). A model supported by the analysis of foreland folded belt distribution bordering a central metamorphic zone reconciles these different propositions by involving two sutures and an intermediate continental block (Riding 1974). The folded belts correspond in North America to the northwestern part of the Appalachians, known as the Alleghanids, which extend to the south of Great Britain and Scandinavia and, in Africa, to the Mauritanids that continue from the Tethys. The metamorphic zone coincides with the central zone of the Appalachians which extends into the Galicia and Moldanubian zones in Europe.

Dewey and Burke (1973) enriched the collision model and compared the Variscan belt with the Himalayan range and the Tibetan plateau. They proposed that “the continental collision is followed by a crustal thickening that accommodates convergence and a partial melting of the lower crust. At the higher structural level, silica- and potassium-rich ignimbrites are extruded into a horst and intermountain basin system surmounting granitic plutons. At the lower structural level, a dry, refractory lower crust composed of pyroxene granulites and anorthosites is generated” (see Figure 1.18).

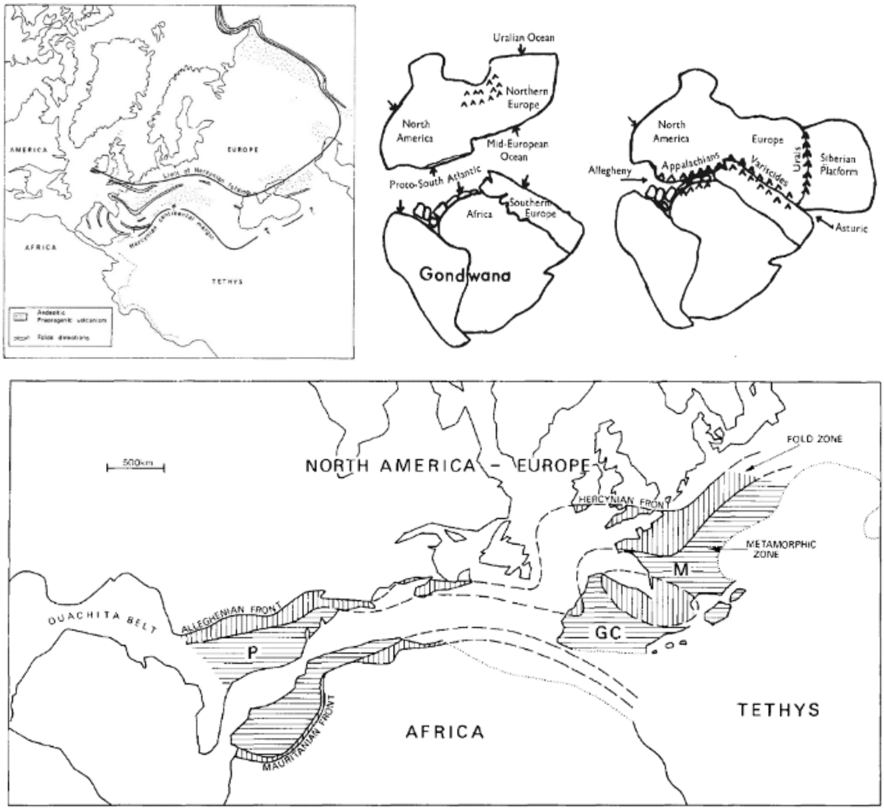

Figure 1.17. *First geodynamic–paleogeographic models in terms of plate tectonics for the Variscan belt. Top left: the Andean model with a northern vergence subduction along the southern European margin (modified from Nicolas 1972); top right: the subduction–collision model between the North America–Europe continent and Gondwana following the closure of a Mid-European Ocean (modified from Burrett 1972); bottom: the subduction–collision model with two sutures and a continental block (modified from Riding 1974)*

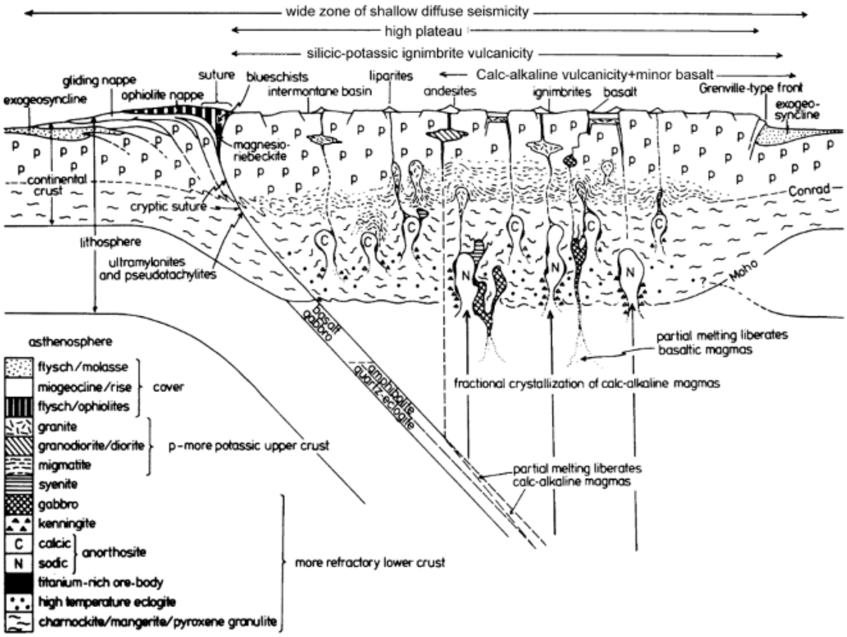

Figure 1.18. *Schematic representation of a thickened and partially melted continental crust following a continental collision in a plate convergence zone to illustrate the processes at work in the Himalayan and Variscan belt (modified from Dewey and Burke 1973)*

1.4.2. *Principal sutures and continental blocks*

Plate tectonics have highlighted the importance of horizontal movements on a lithospheric scale, which implies the opening and closing of oceanic domains separating continental domains. Continental blocks had already been largely identified by the analysis of the distribution of principal lithological units (Kossmat 1927; Stille 1928). Following the first models of geodynamic evolution of the Variscan belt as part of plate tectonics, presented in the previous section, the principal challenge was to identify sutures separating continental blocks. These oceanic sutures are underlined by discontinuous ophiolites, the definition of which has evolved according to interpretations and geodynamic models.

The Iapetus–Tornquist suture, marking the contact between Avalonia and Laurussia, was first identified in the Appalachians and Caledonides, marked by a discontinuous ophiolite belt emphasizing the boundary between lands with contrasting fossil content and tectonic recording (Church and Stevens 1971; Dewey 1969; Harland and Gayer 1972; Wilson 1966). This suture, which is more difficult to follow because of the overlap by post-Paleozoic sedimentary series, was later recognized south of Baltica (Cocks and Fortey 1982).

South of Avalonia, the most important Variscan suture is marked by the Lizard ophiolite in the south of Great Britain, highlighted in particular by serpentinites. These serpentinites were first identified and referred to as "soap rocks" by William Borlase, an English antique dealer, geologist and naturalist (Borlase 1758). Serpentinite mapping and associated ultramafic and mafic rocks were used to establish their relative chronology with respect to sedimentary series and deformation (Bonney 1877; De la Beche 1839; Flett and Hill 1912; Sedgewick 1822). This assemblage was first interpreted as representing an ultramafic intrusion (Flett 1946; Green 1964), then as an ophiolite based on the resemblance of mafic rocks with basalts in ocean ridges (Kirby 1979; Thayer 1969). The significance of mafic rocks and turbidite shales outcropping in the Harz massif, as a continuation of this eastern suture, has also been debated between the proponents of intrusion (Krebs and Wachendorf 1974) and supporters of ophiolite assemblage (Anderson 1975). At the same time, an ophiolite complex was identified south of the Armorican Massif (Hanmer 1977). The oceanic opening associated with the formation of this ophiolite dates back to the Early Devonian (Clark *et al.* 1998).

As a result of this work, ophiolite sequences have been identified in the internal zone of the Variscan belt, in Galicia (Bernard-Griffiths *et al.* 1985), in the Armorican Massif (Hanmer 1977), in Limousin (Dubuisson *et al.* 1989; Mercier *et al.* 1985), in Bohemia (Misar 1984) and in the Alps (Bodinier *et al.* 1982; Ménot *et al.* 1988). Attention was focused on a rock assemblage known as the "leptyno-amphibolite complex" (Forestier 1961), locally comprising ultrabasic rocks in boudins. These rocks have been identified in different internal parts of the Variscan belt in Iberia (Floor 1966; Ribeiro 1987), in the French Massif Central (Bodinier *et al.* 1986; Maillet *et al.* 1984; Mercier *et al.* 1985; Piboule and Briand 1985) and the Massif des Maures (Seyler 1986), and have a geochemical signature that varies from alkaline to tholeitic, passing through calc-alkaline. For this reason, some attributed these rocks to a continental rift context and others to an oceanic opening in a back-arc position (Pin 1990). The emplacement of the magmatic protoliths of the leptyno-amphibolite complex has been dated to the Ordovician by U–Pb zircon geochronology (Pin and Lancelot 1982).

1.4.3. *Paleogeographical reconstructions*

Paleogeographic methods, mainly supported by paleomagnetism as well as the reconstruction of sediment deposition environments and associated fossils, provided information on the size of the former oceans and the location of continents.

Early paleomagnetic data on the Paleozoic position of the peri-Atlantic continents have documented the existence of a wide oceanic domain of the order of 3,000 km between Laurussia (Laurentia + Baltica) and Gondwana, presumably from the Late Neoproterozoic to the Devonian with an intermediate continental block, called "Armorica", relatively close to Gondwana until the Late Devonian (Hagstrum *et al.* 1980; Jones *et al.* 1980; Van der Voo *et al.* 1980).

Some paleomagnetic data suggest that Armorica remained attached to Gondwana up to the Devonian (Kössler *et al.* 1996), but others indicate a migration from Armorica to Laurussia during the Ordovician period, implying the closure of the Rheic Ocean and the opening of a 2,000–3,000 km wide ocean between Armorica and Gondwana (Tait *et al.* 1997). Sedimentological and paleontological data from Early Ordovician deposits imply a location close to the South Pole for Gondwana and for Avalonia and Armorica, but between the tropics and the equator for Laurentia and Baltica (Paris and Robardet 1990).

1.4.4. *Geodynamic tectonic models*

For the Massif Central, the interpretation of the leptyno-amphibolite complex (LAC) as a suture led to recognition of the Upper Gneiss Unit surmounting the leptyno-amphibolite complex and overlapping the Lower Gneiss Unit. This structure was first demonstrated in the Marvejols area on the basis of structural and metamorphic arguments emphasizing a southward emplacement of the Upper Gneiss Unit and an inverse metamorphism marked by HP relics in the Upper Gneiss Unit and a metamorphism ranging from green shale facies to amphibolite facies in the Lower Gneiss Unit (Burg and Matte 1977). Nappes were then recognized throughout the FMC (Burg and Matte 1978; Ledru *et al.* 1989). In the first proposal, three distinct nappes made of Upper Gneiss and cordierite migmatites were identified in the Sioule, Haut-Allier/Marvejols and Rouergue from north to south (Burg and Matte 1978; Matte 1986). According to this proposal, each unit of the LAC was interpreted as a suture then corresponding to the root zone of a nappe. In contrast, the following tectonic models proposed that these separate nappes form only one with a root zone beneath sediments of the Mesozoic of the Paris Basin (Mattauer and Etchecopar 1976; Matte 1986, 1991). The deep drilling of Sancerre Couy confirmed this rooting by crossing the LAC (Ballèvre and Balé 1992; Burg *et al.* 1989a).

According to this model, the different outcrop zones of the Upper Gneiss Unit are considered to be klippes.

As a result of this work, the recognition of various nappes and sutures of the Variscan belt allowed the development of more substantial geodynamic–tectonic models than those proposed since the advent of plate tectonic theory in the early 1970s. To account for the two major sutures, the Rheic suture in the north and the Medio-European suture in the south, and also for the general fan structure with antithetical vergences, the formation of the Variscan belt has been attributed to a converging system accommodated by two subduction zones of opposite polarity (Matte 1986, 1991). This model has been modified to incorporate the formation of Devonian arc and back-arc basins in the French Central Massif (Bébien 1971; Sider and Ohnenstetter 1986), correlated to a subduction to the southern Rheic Ocean (Faure *et al.* 1997). In this context, the closure of the Mid-European Ocean by north polarity subduction during the Silurian and Devonian led to the collision between Gondwana and Armorica and was followed by the subduction of the Rheic Ocean to the South under the newly-formed collision belt, marked by arc magmas coming into place and induced opening of the back-arc basins during Devonian times. Regardless of the polarity of the subduction, all authors agreed on attributing the deformation, metamorphism and magmatism recorded during the Carboniferous by the Variscan belt to continental collision (Bard *et al.* 1980; Burg *et al.* 1989b; Downes *et al.* 1990; Williamson *et al.* 1992). The Variscan belt has also been central in the discussion of post-collision orogenic evolution. This evolution was marked in the Carboniferous by: (i) transverse shear zones, the exhumation of metamorphic rocks and the location of plutons with a stretching lineation parallel to the belt in the Moldanubian zone exposed in the Armorican Massif and the Central Massif (Burg *et al.* 1987; Faure and Pons 1991); and (ii) fold and thrust belts in the forelands (Cazes *et al.* 1985; Echtler 1990; Engel *et al.* 1981). These characteristics have been interpreted as reflecting either the lateral escape of the crust during the progressive formation of the orogenic belt (Arthaud and Matte 1975; Burg *et al.* 1993; Gleizes *et al.* 1997; Lardeaux and Dufour 1987; Matte 1986; Mollier and Bouchez 1982) or the syn-orogenic extension of the previously thickened crust (Burg *et al.* 1993; Faure 1995).

The Variscan belt also provided a key target for the discussion of the role of partial melting during orogenic evolution. More specifically, the Bohemian Massif, the French Massif Central and the Iberian Massif show high-pressure, medium-pressure and low-pressure migmatites at different structural levels. Granulite facies migmatites with amphibolite dating back to the Devonian have been attributed to partial melting during the exhumation of continental and oceanic units previously brought along with the subducting plate (Faure *et al.* 1997). Medium-pressure migmatites, from the French Massif Central and the Armorican Massif, associated with a Barrovian metamorphism and with ages ranging from the middle of the Devonian to the middle of the Carboniferous (c. 370 to c. 310 Ma), were associated with the increase in temperature within the crust after the continental collision and the emplacement of nappes (Ledru *et al.* 1994; Montel *et al.* 1992). Low-pressure migmatites, in the core of crustal-scale domes such as the Velay or the Montagne Noire in the French Massif Central, or in Bohemia have been interpreted as the root of the Variscan belt exhumed during its gravity collapse (Burg and Vanderhaeghe 1993; Costa and Rey 1995; Echtler and Malavieille 1990; Faure 1995; Malavieille *et al.* 1990). The increase in temperature required to generate this large volume of partially melted rock has been attributed to a sudden rise in the asthenosphere associated with the emplacement of mantle magmas such as vaugnerites in connection with the delamination of the lithospheric mantle (Ledru *et al.* 1994; Montel *et al.* 1992). This model is corroborated by the presence of mafic and felsic granulites in the lower crust in enclaves in the volcanoes of the Chaine des Puys (Leyreloup 1974) or exposed in the northern zone of the Pyrenees (Vielzeuf *et al.* 1990) which are interpreted, respectively, as magmas coming from the mantle and residues of partial melting after magma extraction. The alternation of these mafic and felsic rocks provides an explanation for the layering of the lower crust identified on the reflection seismic profiles (Rey 1993).

The Variscan belt has also served as an example for the characterization and development of the concept of gravity collapse with the development of a Permian rift system, superimposed on the mountain belt (Ménard and Molnar 1988) and following the activation of low-dipping detachments recognized in different parts of the French Massif Central (Burg *et al.* 1993; Faure 1995; Malavieille *et al.* 1990).

1.5. Conclusion and challenges of the 21st century

This brief historical overview highlights the extent to which the Variscan massifs in Europe and North America have contributed to the development of geological methods and in particular to the analysis of metamorphic and plutonic rocks. In turn, these developments have inspired conceptual models of the formation of mountain belts and in particular of the Variscan belt.

In the years following – the advent of plate tectonics and the first models of the evolution of the Variscan belt in this context – debates have focused and still focus on the nature of the pre-Paleozoic basement, the nature and number of continental blocks and oceanic domains, the number and polarity of subduction zones, and the number of metamorphic nappes and their emplacement ages. Advances in geochronology have made it possible to refine the calendar of magmatic, metamorphic and tectonic events and have highlighted the diachronism of these events at the belt scale. Moreover, these new data question the established model of the orogenic cycle involving a subduction-collision-extension succession (Wilson 1966) by demonstrating the contemporaneity between subduction, high-pressure metamorphism, crustal source magmatism, and back-arc oceanic opening, as in the Devonian, for example, propagation of overlaps in the forelands and extension parallel to the belt in the inner zone in the middle to upper Carboniferous or between exhumation of the partially melted root by means of shallow-dipping detachments in the inner zone and transpressive relays in the outer zone.

Finally, in the course of this history, determining the relative contributions of mantle or crustal magmas, the evolution of topography, and the consequences of deep and surface processes on the redistribution of matter within the crust – with implications in terms of heritage for recent tectonic and volcanic history and also in terms of distribution of mineral resources and potential for deep geothermal energy – are all challenges for the geoscientists of the 21st century.

1.6. References

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