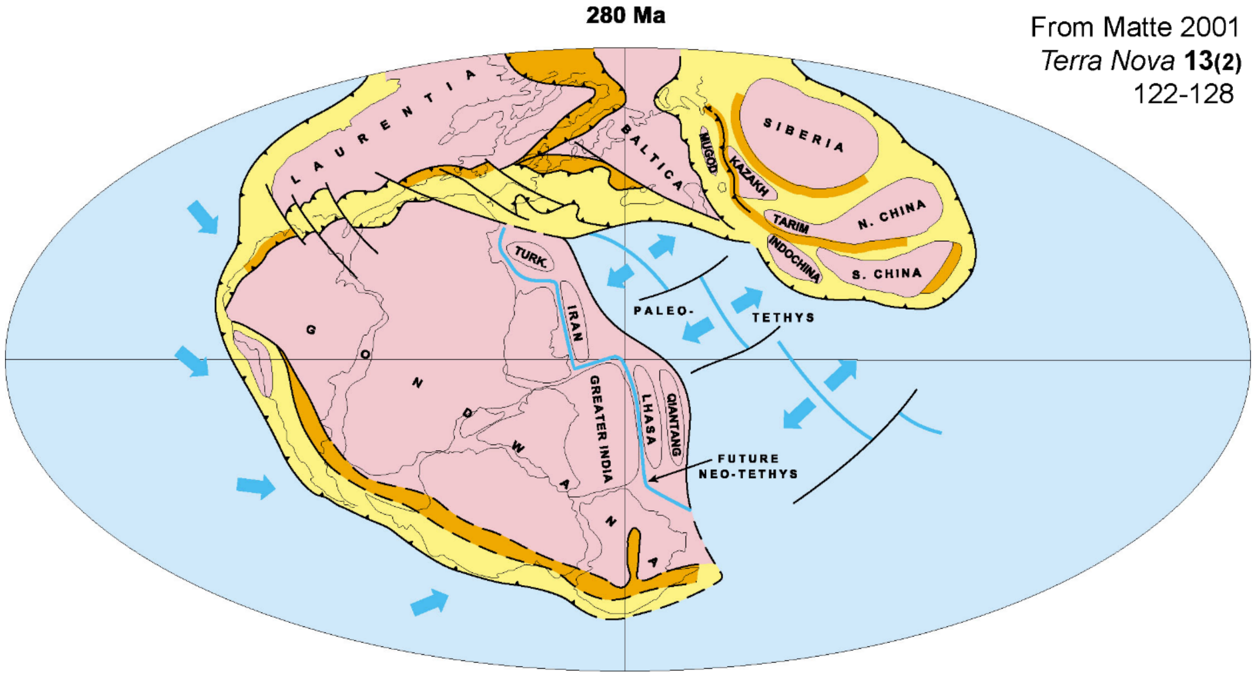
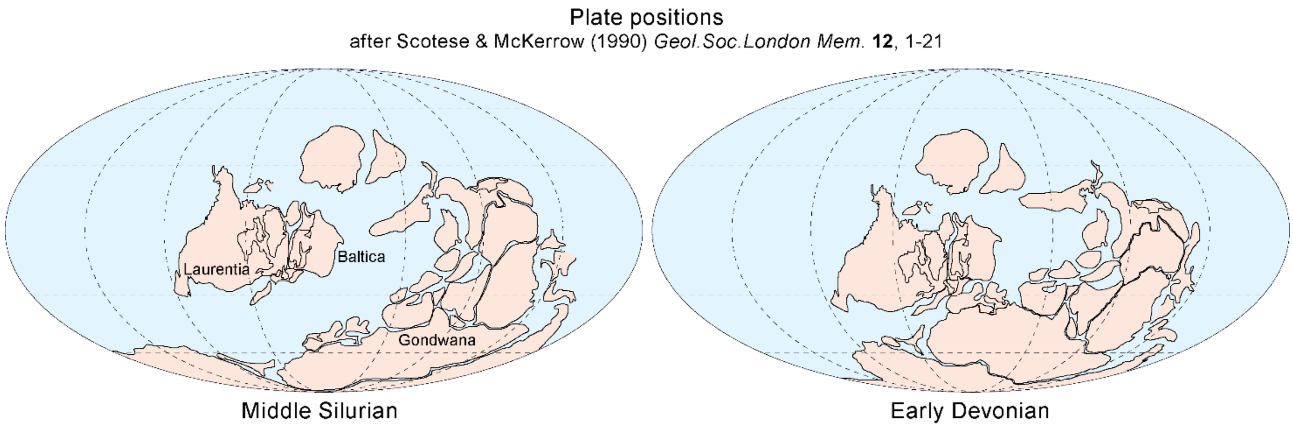
The Variscides: An old collisional orogen

A succession of Paleozoic collisional orogenic events (e.g., Caledonian, Appalachian-Variscan, Ouachita, Uralian) marked out the amalgamation of the Pangea supercontinent. The Variscan Belt stretches across the whole expanse of Europe, covering virtually the same area as the modern Alpine Orogen. Its name is due to Suess who referred to a legendary Teutonic tribe in Northeast Bavaria. The Variscides, the youngest European orogen before the Alpine one, has forged much of the continental crust of Europe during the Late Palaeozoic. Along with the Appalachians in America, the Mauritanides in Africa, the Caledonides in Scandinavia and Scotland, the Urals in Russia, the Tien Shan in Asia, and the Lachland Fold Belt in Australia, the Variscan Belt is a segment of a mountain system that has existed all around the world during the Paleozoic, as the Alpine mountain system encircles the globe today.



Paleomagnetic reconstructions indicate that the Variscan Belt resulted from convergence and collision between two main continental masses: Laurentia-Baltica (i.e. North America–Scandinavia+North Europe+Russia) earlier welded by the Caledonide Orogen to form Laurussia, now to the northwest, and Gondwana to the southeast. Various microcontinents such as Avalonia (from Newfoundland to Poland), Armorica in Britany and Barrandia in Bohemia were accreted in between, while convergence closed several oceanic basins that pertained to the Rheic Ocean.



The geology of the Variscides is complex and is made even more so because the inliers occur in many different countries with different languages and scientific approaches. However, sedimentological, structural and petrological information documents an old orogen with elements of plate-tectonic cycles such as continental rifts, remnants of oceanic lithosphere (ophiolites), magmatic arcs, and belts of high-grade metamorphic rocks, some of which having been buried to mantle conditions (subduction) before re-ascending to the surface. While the amount of oceanic lithosphere lost by subduction can be assessed only by paleomagnetic methods, geological studies allow reconstructing the deformation of the continental crust. For this purpose, this lecture will focus descriptions on Western Europe.

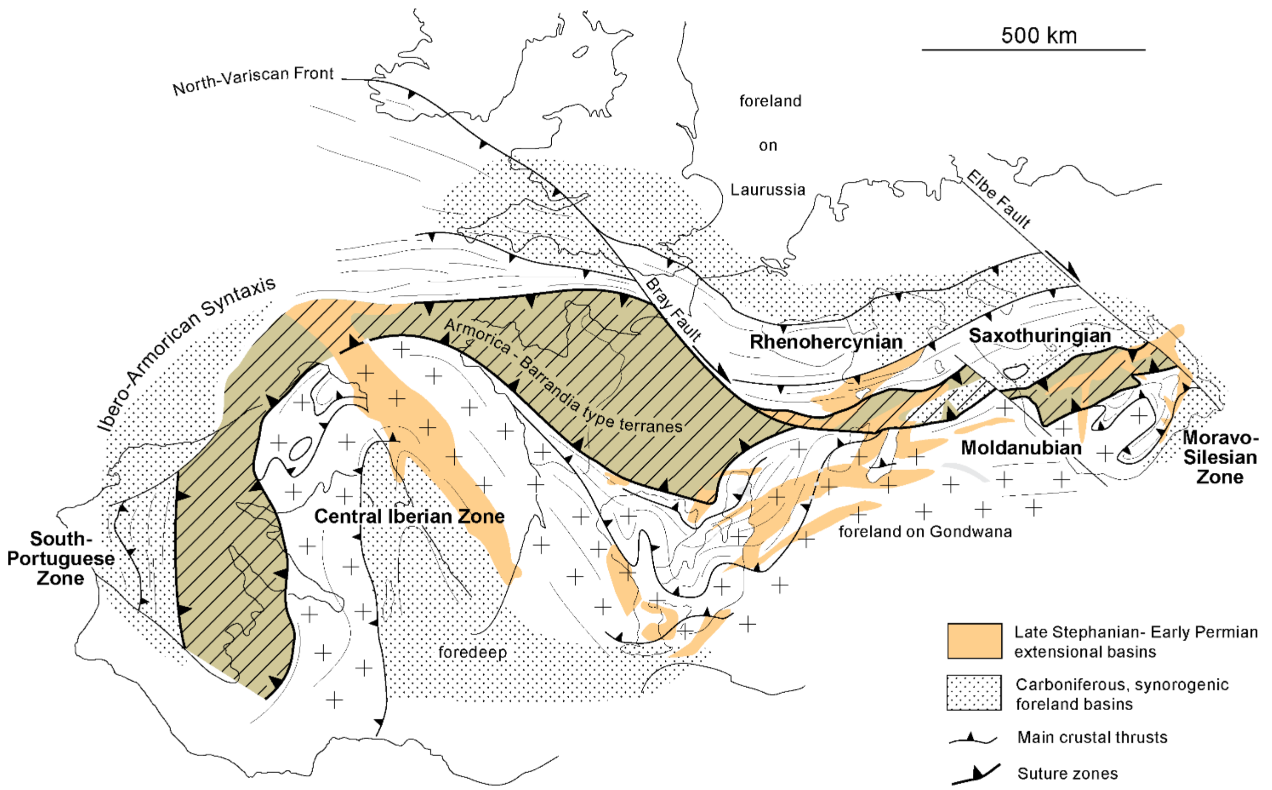
Main inliers of the Western European Variscides

The major unconformity of clastic sediments in the foredeep and in scattered basins shows that the Variscan Mountains were already deeply eroded in the late Carboniferous. The angular unconformity between the Variscan basement and its Permian to Cenozoic sedimentary cover is one of the key features of European geology. This basement is exposed in a number of inliers. From the west to the east the main ones are: SW Iberian Peninsula and Northern Spain, Brittany and the British Isles, the French Massif Central, Vosges and Schwarzwald, Belgium and NE France (Ardennes), the Rheinische Schiefergebirge and the coal basins of northern Germany, and the Bohemian Massif,
The Variscan orogeny also created the basement now exposed within the Alpine-Mediterranean mountain belts (including the islands). The Atlas Mountains and, further south, parts of the Mauritanides are presumed to be southern exposures of the European Variscides.

Shape of the Belt; Major Features

Despite Meso-Cenozoic oceanization (opening of the Bay of Biscay), sedimentation in large basins of cover rocks (Paris, Aquitaine, Ebre) and deformations (Pyrenees, Alps, Carpathians), it is possible to produce a pre-Permian reconstruction of the European Variscides. Two main parts seem to represent two major suture zones:

(1) The western Variscides which include the main inliers of France (Brittany and Massif Central) and the Iberian Peninsula and
(2) The central Variscides which extend from central Europe to the British Isles.



Both parts share some common features such as migration of the tectonometamorphic events from the internal crystalline parts (400-380 Ma) toward the external basins (330-300 Ma) and changes in deformation style from deeper levels (with ductile thrusts and recumbent folds) to the higher levels (superficial décollement, thin skin fold and thrust belts). Cross-sections show a fan-like orogen with opposite vergence on both sides of the hinterland: the axial microcontinents were squeezed and thrust over both Laurussia and Gondwana during the Carboniferous. This fan-like geometry suggests that the two suture zones result from oppositely dipping subduction zones, to the north for the western Variscides, to the south for the central Variscides.

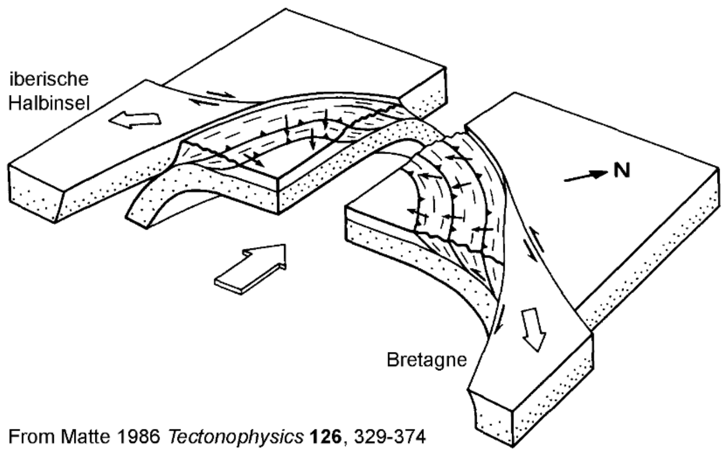
Syntaxes

Gondwana indented into Laurussia, thereby forming syntaxes and imparting to the European Variscan belt its modern aspect: it is a long strip of deformed crust bent into:

- the Ibero-Armorican Syntaxis, in the west, which is comparable in size and shape to that of the Alps.
- the Moravian-Saxothuringian Syntaxis, in the east.

Ibero-Armorican Syntaxis

Tectonic reconstructions are based on the well-known relative movements between the Iberian Peninsula and stable Europe and on the best fit of the Variscan structures and the orientation of gravimetric and magnetic structures below the Mesozoic cover on both sides of the Bay of Biscay. Once Iberia is rotated into its pre-Mesozoic position by closing the Bay of Biscay, the Variscan Orogen follows a hair-pin curvature that tightens inwards: the “Ibero-Armorican Syntaxis”. This prominent, arcuate shape is actually seen in northern Spain where the Variscan strikes are bent through almost 180° in the Cantabrian Mountains.



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Moravian-Saxothuringian Syntaxis

This nearly 90° orogenic bend is less conspicuous and its Variscan origin is in question. It is possible that it is an artefact of NW-SE striking strike slip faults linked to the Teisseyre-Tornquist Line and reactivated during Mesozoic tectonics.

Geological zones

The Variscan Belt joining the two syntaxes has a very large width (in places 2000 km). It is divided into zones of geodynamic significance. These zones are from north to south:

- The North-Variscan Foredeep, which is filled with Lower Carboniferous shelf successions ("Kohlenkalk") and thick sequences of Upper Carboniferous clastic sediments and coal during the final orogenic stages.
- The Rhenohercynian Zone represents the southern, passive continental margin of Laurussia (called sometimes Avalonia) in the Devonian, which was overlain by Carboniferous turbidites.

This zone may continue in the South Portuguese zone which exposes a Late Devonian to Early Carboniferous volcanosedimentary basin and massive sulphide deposits.
- The Giesen and Lizard Ophiolites represent Middle-Late Devonian ocean floor obducted onto the Rhenohercynian Zone. They mark the suture between Laurussia, to the north, and microcontinents to the south.
- The Saxothuringian Zone includes microcontinents (Armorica, Barrandia) accreted to Laurussia during the Carboniferous. Its northern margin comprises remnants of supra-subduction magmatic and metamorphic rocks.
- The adjacent Moldanubian Zone, to the south, is the actual metamorphic hinterland that can be followed from the Bohemian Massif to Galicia on the Iberian Peninsula. It comprises several high-grade tectonic units and a major suture zone marked by high-pressure metamorphism (eclogites, granulites, and blueschists), ophiolitic fragments, mélanges, and upper mantle rocks. All sections display large recumbent folds and ductile low-angle thrust sheets which carry high grade rocks over great distances (c. 200 km). Polyphase, syntectonic metamorphism lasted from early high-pressure events (400-380Ma, subduction related?) to a later intermediate to low pressure phase with local inversion of isograds (350-330 Ma). Altogether the metamorphic history shows decreasing pressures and increasing temperatures through time. Large volumes of granitic material originated in Carboniferous times from the melting of the continental crust when this crust was thick. The Moldanubian Zone also shows a change of orogenic polarity as its northern margin was transported towards the north, the southern margin towards the south.
- The southern fold-and-thrust belt (Montagne Noire, Cantabrian Zone) exposes fossil-rich Cambrian to Carboniferous sequences deposited along the northern, passive continental margin of Gondwana.

Unconformities and tectonic phases

One of the classic concepts used in the study of orogenic belts is that an angular unconformity between folded lower successions and a relatively undeformed cover sequence implies an orogenic phase, which occurred in the corresponding time gap. Such an "event" was then bracketed by the biostratigraphic control in these lower and cover successions. Following this approach, three main orogenic phases were defined across the European Variscides: the Bretonic phase, the Asturian phase and the Sudetic phase.

- The Bretonic Phase (Early Carboniferous, 345Ma), defined in Brittany, is responsible for the widespread Devonian-Carboniferous unconformity after significant shortening occurred across Europe.
- The Sudetic Phase (Middle Carboniferous, 325 Ma), defined in Poland, marks the main uplift phase of the orogenic hinterland.
- The Asturic Phase (Latest Carboniferous, 290-295Ma), defined in Spain, was attributed to the main marginal fold and thrust belts as well as further deformation in the interior.

Further unravelling of the orogenic history involved correlating these phases across Europe. But does the presence of an angular unconformity mean that there were major orogenic phases?

There are several modes in which angular unconformities can develop. The classic mode involves a shortening phase followed by uplift and erosion followed by renewed sedimentation. However, important tilting uplift and erosion can also be accomplished during extension. It is critical to distinguish between compressional and extensional modes because each has a very different tectonic implication. But it is often difficult to clearly define the nature of some unconformities and thus controversy exists over their interpretation. One example is the Sardic unconformity in SW Sardinia. This was identified and used by Stille in 1920s to identify a Sardic orogenic phase in the Ordovician. Yet, it may represent a block-tilting phase during a long-term extensional phase on the northern continental margin of Gondwana.

Geological Plates

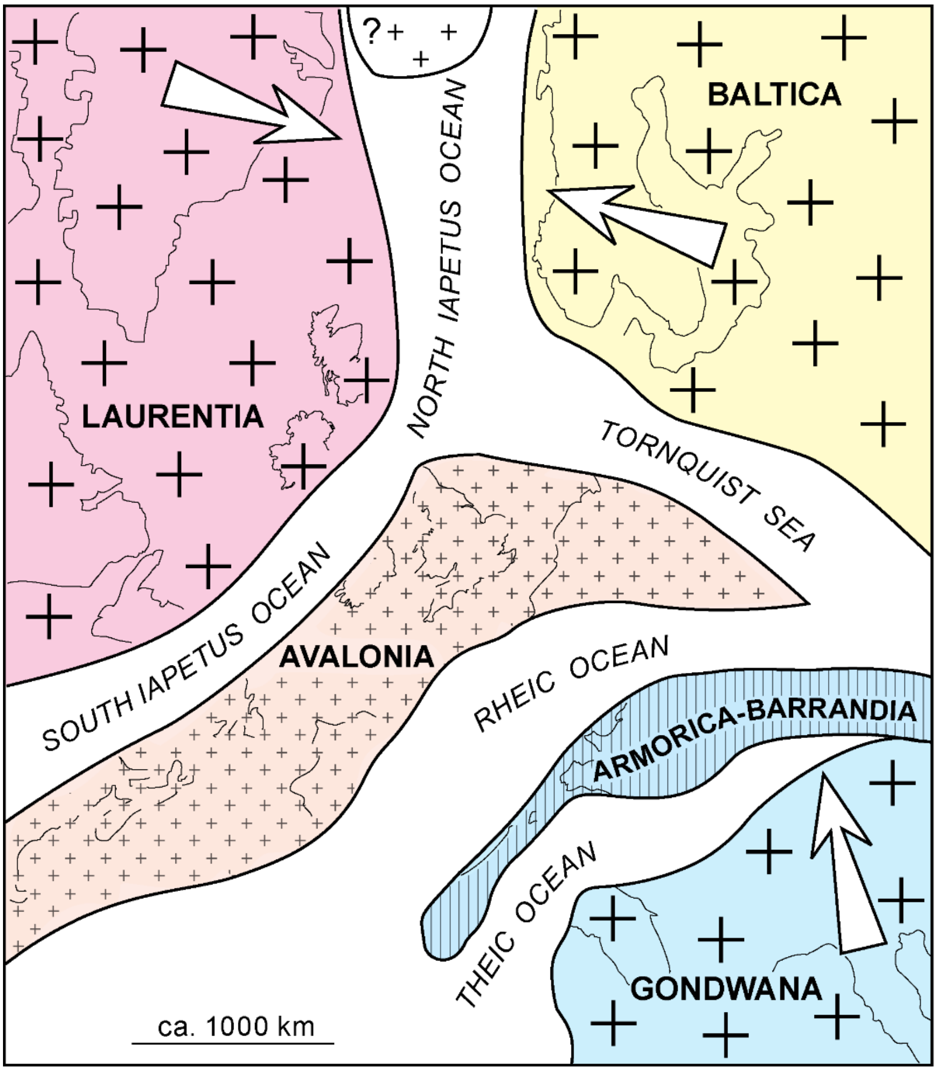
Structural, petrologic, geochemical, geophysical, and radiochronological studies carried out in the internal crystalline zones reveal oceanic sutures contained in large-scale thrust systems. Therefore, plate tectonics were involved in the building of the belt that has welded:

Continental lithospheres:

- A long, narrow and continental back-bone between two ophiolite bearing sutures. The related continental fragments include central Spain, central Brittany, northern France and parts of Germany up to the Prague area. These microcontinents are represented by Late Precambrian schists (e.g. the so-called Barrandian) overlain by a typical quartzite sequence of Early Ordovician age.
- The northern continent was Laurussia, covering northern and north-eastern Europe;
- The southern continent was Gondwana;

Oceanic lithospheres

- The northern ocean whose closure has developed the northern branch of the Variscides, is known as the Rheic Ocean.
- The southern ocean is diversely known, say proto-Tethys for this lecture.



Paleomagnetic information

The Rheic Ocean formed when several peri-Gondwanan terranes (e.g., Avalonia, Carolinia) drifted away from the northern margin of Gondwana in the Late Cambrian–Early Ordovician. Palaeomagnetic data constrain rather well the positions and drift history of the major pre-Paleozoic continental blocks (Gondwana, Baltica, Laurentia, Avalonia, Armorica).

Opening and setting of oceanic basins

In Cambrian times Avalonia and Armorica were contiguous with the northern margin of Gondwana. In the Early Ordovician, this margin was situated at high southern paleolatitudes, while Baltica was situated between 30 and 60°S and was up-side down with respect to its present-day orientation; Laurentia was in an equatorial position.

By the late Early Ordovician (Tremadoc), Avalonia had started to drift northwards, away from Gondwana, opening the Rheic Ocean in its wake. It continued to drift northwards throughout the Ordovician, gradually closing the Tornquist Sea and the Iapetus Ocean, which separated Avalonia from Baltica and Laurentia. Armorica was following a similar but independent movement with a slightly later separation from Gondwana.

By the Late Ordovician, Gondwana had moved some 30° northwards, and northern central Africa was situated over the south-pole. Baltica had found its present-day orientation and its northern margin was at the equator. Laurentia remained straddling the equator and was separated from Baltica and Gondwana by the Iapetus Ocean. The Rheic Ocean still separated Avalonia/Baltica from Armorica, which was situated at intermediate to low southern paleolatitudes.

Closure of the oceans

Late Ordovician collision of Avalonia with Baltica closed the Tornquist Sea and formed the narrow "Polish Caledonides".

Closure of the Iapetus Ocean between Baltica/ Avalonia and Laurentia occurred in the Late Devonian, after which Laurussia remained in equatorial paleolatitudes until the end of the Palaeozoic.

The paleogeographic position of Gondwana from Silurian to Late Devonian times is disputed but Armorica was at 20–30°S. This implies gradual migration towards the southern margin of Baltica/Avalonia and closure of the intervening Rheic Ocean. There are two models:

- The conservative model involves gradual northward movement of northern Gondwana throughout the Paleozoic, with final closure of the ocean separating northern Africa from southern Europe in the Late Carboniferous.
- The alternative model requires rapid northward movement of Gondwana in the Silurian, followed by rapid southerly movement in the Devonian.

Collision

The Rheic Ocean between Avalonia and Armorica closed in the late Mid-Devonian. In Gondwana, the Late Devonian remains one of the controversial periods. Central Africa was over the south-pole, requiring an ocean between the northern margin of Gondwana and Laurasia. Collision of Gondwana with Laurasia to form the Variscan Belt and the supercontinent Pangaea occurred in Late Carboniferous.

Erosion

Rapid erosion down to leucogranites took place during the Namurian and the Wesphalian (ca 325 to ca 305 Ma). Fault-bounded Stephanian (ca 305-ca 300 Ma) coal basins cover the Variscan basement. Essentially clastic, fluvio lacustrine sediments witness progressive aridification of the climate. Mostly rhyolitic volcanism may indicate efficient decompression melting of the crustal root while dominantly strike slip faulting typifies a mature collisional stage. This stage contrasts with extension, which started immediately after with the unconformity of Lower Permian (Autunian of Europe) fluvio-lacustrine sediments that frequently contain bituminous shales. The Carboniferous-Permian boundary thus marks the change in tectonic regime, from Variscan compression to the fore shadows of Tethys opening.

Regional descriptions

The main European parts of the Variscan Belt are briefly described to provide information used in plate tectonic models and discuss how these parts might fit together on the larger scale.

Iberian Peninsula

In the SW Iberian Peninsula, a reactivated suture, the WNW-ESE trending Coimbra-Cordoba Shear Zone, separates two continental blocks with different lower Paleozoic histories: the North Block, in the core of the Ibero-Armorican Syntaxis, with centripetal vergence, and the South Block with south-west-facing folds and thrust sheets.

North Block: Gondwana Promontory

The Northern Block has been subdivided into three concentric zones, from center outward the Cantabrian, the West Asturian-Leonese and the Central Iberian Zone. All are intruded by Carboniferous granitoids. The ca. 330 Ma ones are associated with low-pressure domes and detachment systems. Leucogranites of crustal origin have intruded at ca. 300 Ma. Stephanian continental deposits are unconformable on the orogen.

Cantabrian Zone: Foreland

The foreland domain is characterised by a thin-skinned fold-and-thrust belt of Late Carboniferous age, without metamorphism. Cambrian to Devonian sediments were deposited in a relatively thin shallow sea on a passive margin. Late Devonian erosion was followed by basin deepening in the early Carboniferous, followed by syn-orogenic sedimentation, some in piggy-back basins. Structures are complicated by the tight arcuate bend in the core of the Iberian-Armorican syntaxis, which began to form during thin-skinned tectonics. The main décollement runs within a mid-Cambrian marl layer.

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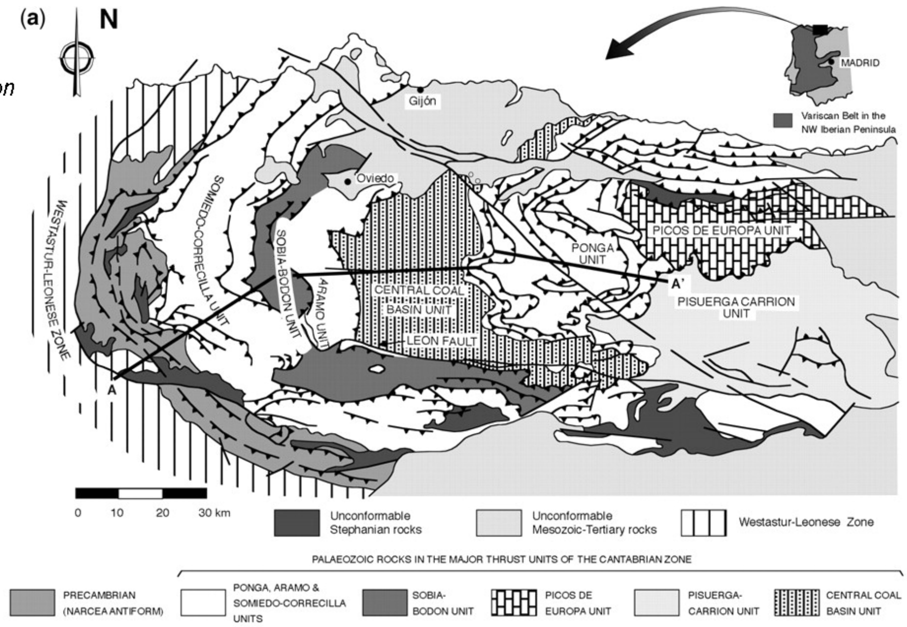
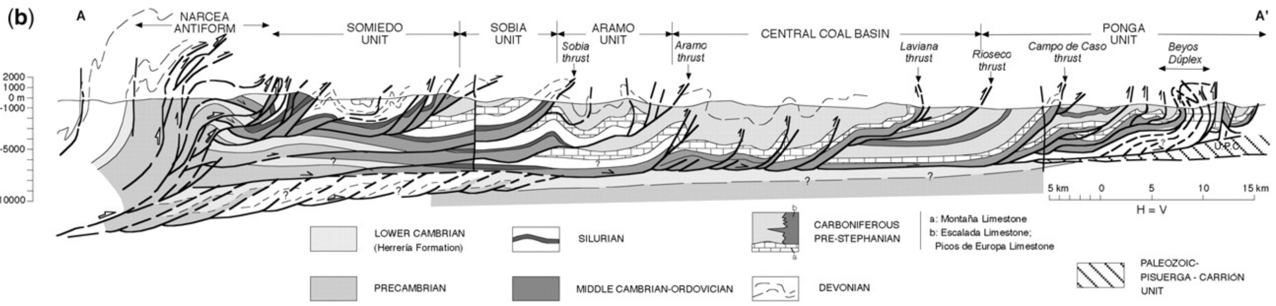




<u>West Asturian-Leonese Zone: Slate Belt</u>

The foreland is overridden by a thick sequence of Late Precambrian to Silurian schists. They are imbricate and deformed by large-scale recumbent folds overturned to the foreland. Deformation took place during low-grade metamorphism in the external part, reaching kyanite and sillimanite zones of intermediate pressure type in the internal parts of the belt.

<u>Central Iberian Zone:</u>

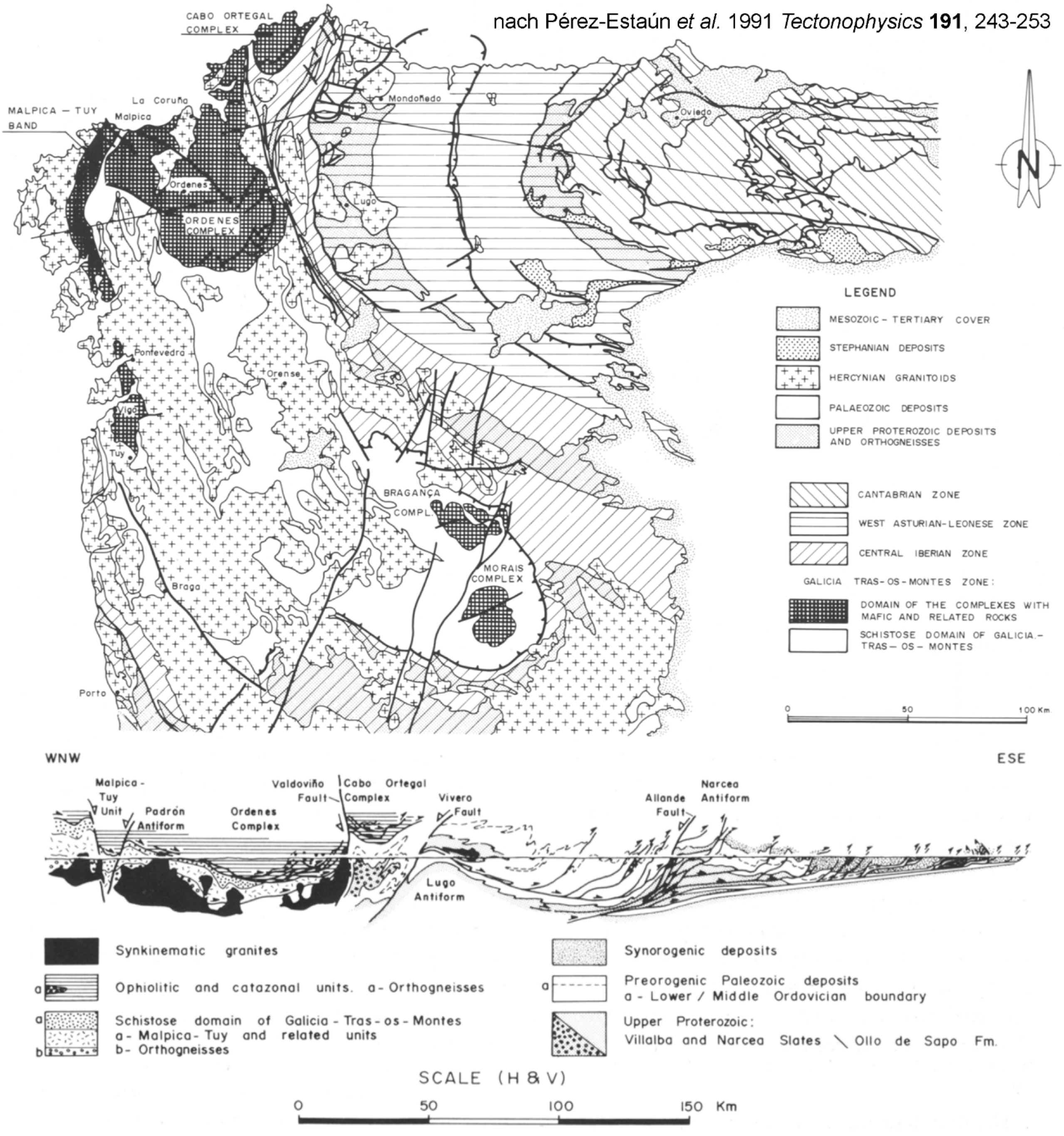
The Central Iberian Zone includes a Proterozoic basement unconformably covered by epicontinental Ordovician-Devonian sediments (shallow water carbonates and terrigenous platform facies) followed by Upper Devonian to Lower Carboniferous marine turbidites. These sediments accumulated on a passive continental margin as synsedimentary normal faults (in particular in the Ordovician) further demonstrate.

Structures are dominated by pre-lower Carboniferous recumbent folds facing towards the core of the Ibero-Armorican Syntaxis. Post lower Carboniferous upright folds with a weak axial plane cleavage deform the recumbent folds and their axial planar slaty cleavage. Several domes have been related to extensional detachments.

Rootless klippen

Granulite facies and rocks including eclogitic boudins constitute far-travelled klippen on top of the North Block. Throws reach several tens of kilometres. The vergence is generally forelandward. Four main units constitute these klippen, from bottom to top:

1. A Lower Allochthon Unit made of Ordovician metasediments, acid and basic metavolcanics and alkaline to peralkaline gneisses. This unit underwent blueschist facies metamorphism in the northern Portugal and UHP/ MT eclogite facies metamorphism in western Galicia.
2. An intermediate Ophiolitic Unit. This dismembered ophiolite (diabase, gabbro, serpentinite, amphibolites and few plagiogranites) underwent greenschist to amphibolite metamorphism. In western Galicia, a gabbro of this unit has been dated at 395 Ma.
3. An Upper Allochthon Unit made of various, partly oceanic high grade metamorphic rocks (paragneisses, eclogites of MORB composition, mafic granulites, pyroxenites and peridotites).
4. An ‘‘Ultra’’ Unit preserved on top of the Moraïs (N. Portugal) and Ordenes (W Galicia) synformal klippen. This unit is made of thick turbiditic metasediments of Upper Proterozoic to Lower Paleozoic age intruded by Ordovician granites and gabbros. These rocks underwent greenschist to amphibolite and rarely granulite facies metamorphism.



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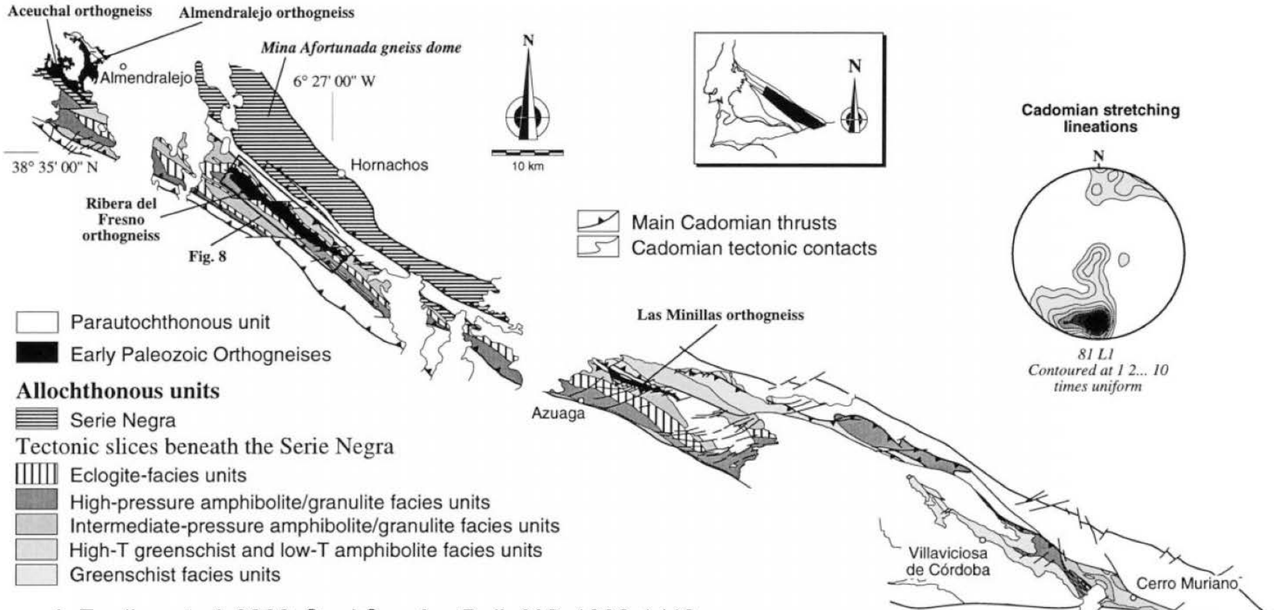
The lower contact of the klippen is marked by metaophiolites. High-pressure conditions are dated at around 400Ma

Coimbra-Cordoba Shear Zone: the suture

Steep S-C fabrics with horizontal lineation and sheath folds indicate sinistral movements of the ca. 20km wide Coimbra-Cordoba Shear Zone. Sliced up lithologies include pelagic metasediments, acid and basic volcanic and magmatic rocks of greenschist to amphibolite grade and granitic orthogneisses, the oldest representing Ordovician alkaline to peralkaline magmatism. High-pressure and eclogite facies metamorphism is preserved in boudins. The main shearing event is pre-Lower Carboniferous in age.



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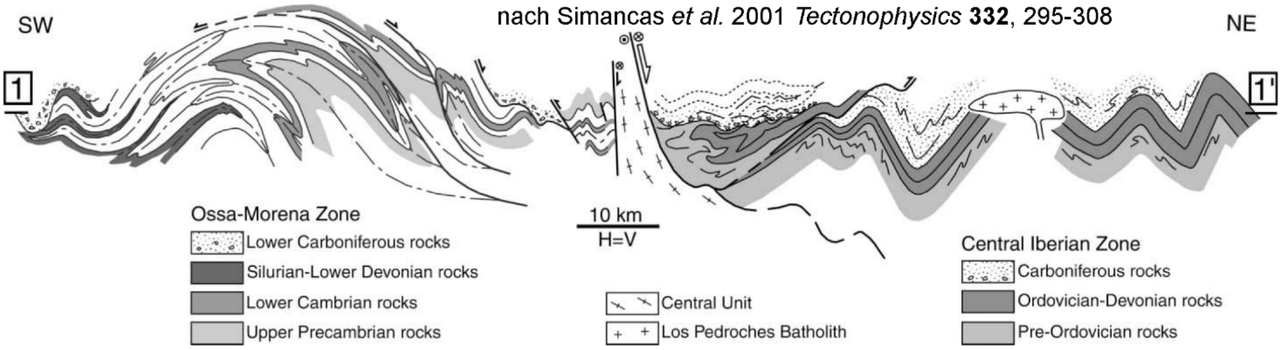

Plate tectonic interpretations involve a cryptic suture reactivated as a sinistral shear zone on the side of a rigid indentor, after collision. The shear zone probably corresponds to an Early Paleozoic ocean or marginal basin, since most of the mafic rocks showing rare earth elemental patterns of oceanic tholeiites and calc-alkaline rocks have ages between 550 and 480 Ma.

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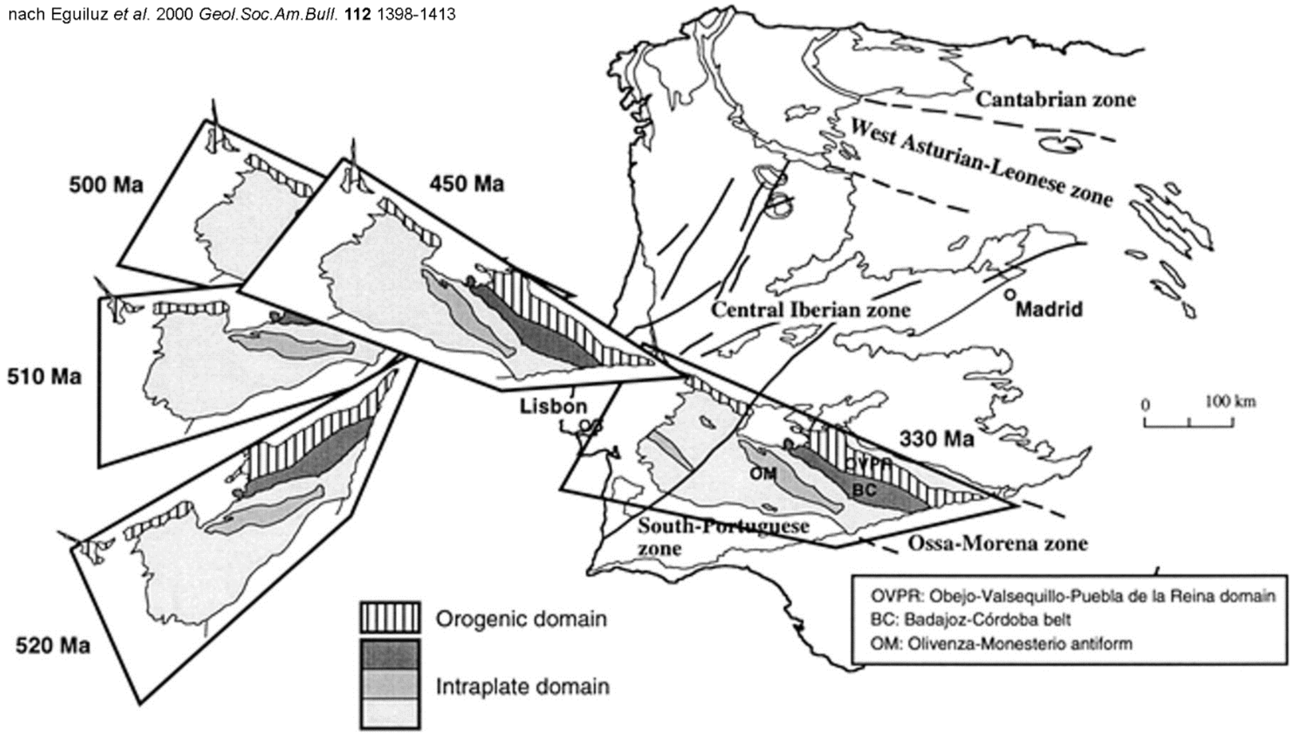
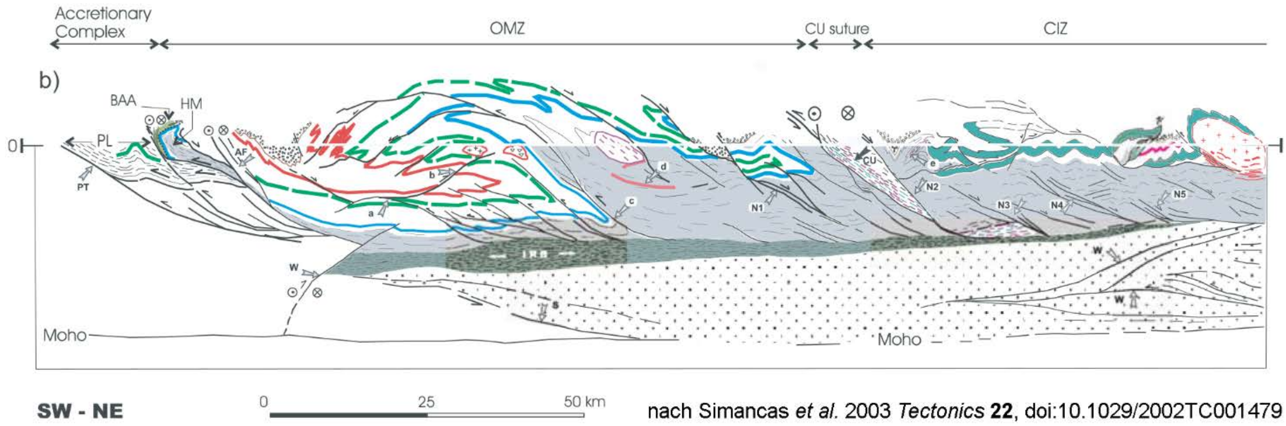


South Block

The South Block is divided into two zones: The Ossa-Morena Zone along the Coimbra-Cordoba Shear Zone and the South Portuguese Zone. The NW-SE-trending boundary between these two zones has been reworked as a sinistral wrench fault. Some authors consider that it was a suture because it contains calc-alkaline (arc-related) basic and ultrabasic rocks (Beja Unit).

Ossa Morena Zone: Passive to active margin of Armorica?

The Ossa Morena Zone includes an Upper Proterozoic basement unconformably covered by a 1-2km thick, relatively complete sequence of fossiliferous lower Cambrian to Devonian greywackes, shales, siltstones and reef limestones. Precambrian rocks are characterized by black cherts metamorphosed and intruded by 550–500Ma granitoids. Basic volcanites sign Cambrian rifting before sedimentation on a passive continental margin.



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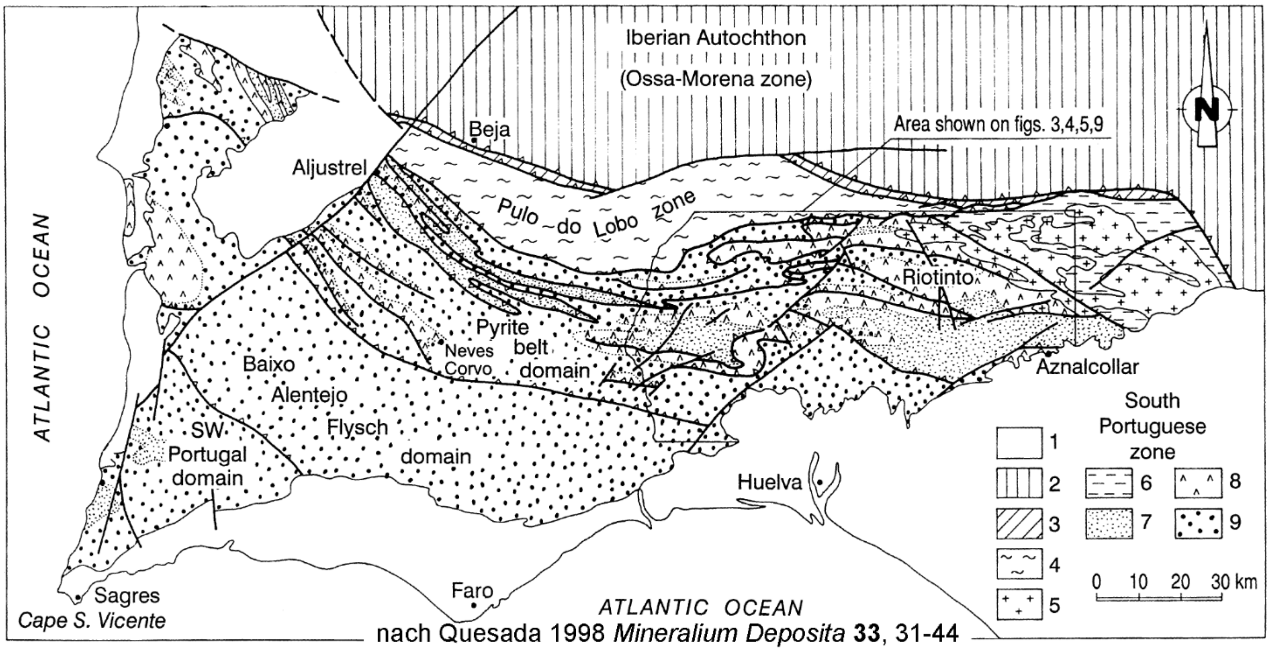
The Ossa Morena Zone may have been a marginal basin represented by oceanic amphibolites (Beja-Acebuches Ophiolites) thrust over a possibly Devonian accretionary wedge with slices of oceanic metabasalts. The Variscan, late Paleozoic evolution is that of an active margin with large, southwest-facing recumbent folds.

South Portuguese Zone: Avalonia?

The South Portuguese Zone exposes only Devonian and Carboniferous sediments. Thus, it is uncertain whether this oceanic realm pertained to the early Paleozoic Rheic Ocean or is a younger Devonian feature. Important bimodal Tournaisian volcanic deposits, which contain the largest copper ore bodies in Western Europe (the South Portuguese Pyrite Belt) are time equivalent to the volcanic rocks in south-west England and the Rheno-Hercynian Belt of Germany. The Rheno-Hercynian and, hence, Avalonian affinities of the South Portuguese Zone are also suggested by a thick turbidite sequence deposited in a foreland basin ('Culm' facies), with a change towards paralic deposits in the south-west. It comprises the Visean to Westphalian D.

The South Portuguese Zone is characterized by south-west-facing folds and thrusts. Thin-skinned deformation occurred during the Late Carboniferous. Accordingly, the South Portuguese Zone first developed as a foredeep basin, and later as an accretionary complex, particularly in the northern part.

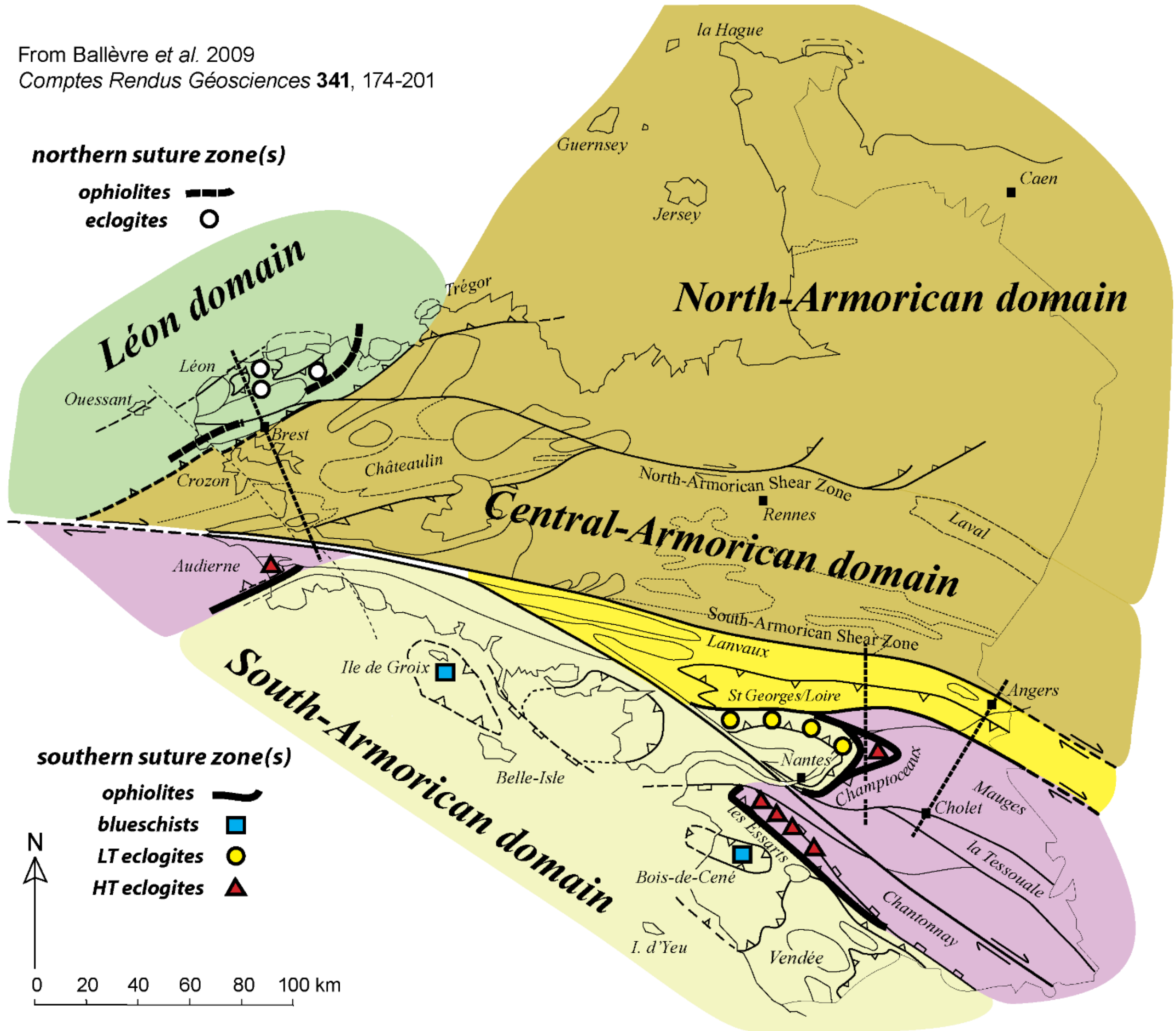


Brittany - Ile de Groix:

Variscan Brittany is dominated by crustal-scale strike slip tectonics coeval with 320-300Ma granitoids. The Armorican Massif is divided into three domains separated by the hundreds km long and few km wide dextral Northern and Southern Armorican Shear Zones.

The central Armorican massif comprises the late Precambrian Brioverian metasediments affected by the Cambrian "Cadomian" orogeny before deposition of its Paleozoic cover. Both were deformed and metamorphosed (low grade) during the emplacement of the 330Ma two-mica granites. Clasts of mylonitized granite are found in Stephanian sediments, which are themselves deformed in the strike slip shear zones.

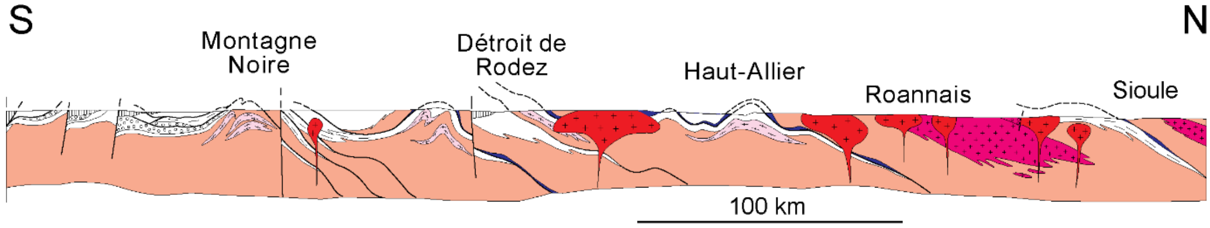
The South Brittany metamorphic complex is composed mainly of granites and medium to high grade schists and gneisses. Anatectic rocks are dated at c. 380Ma.

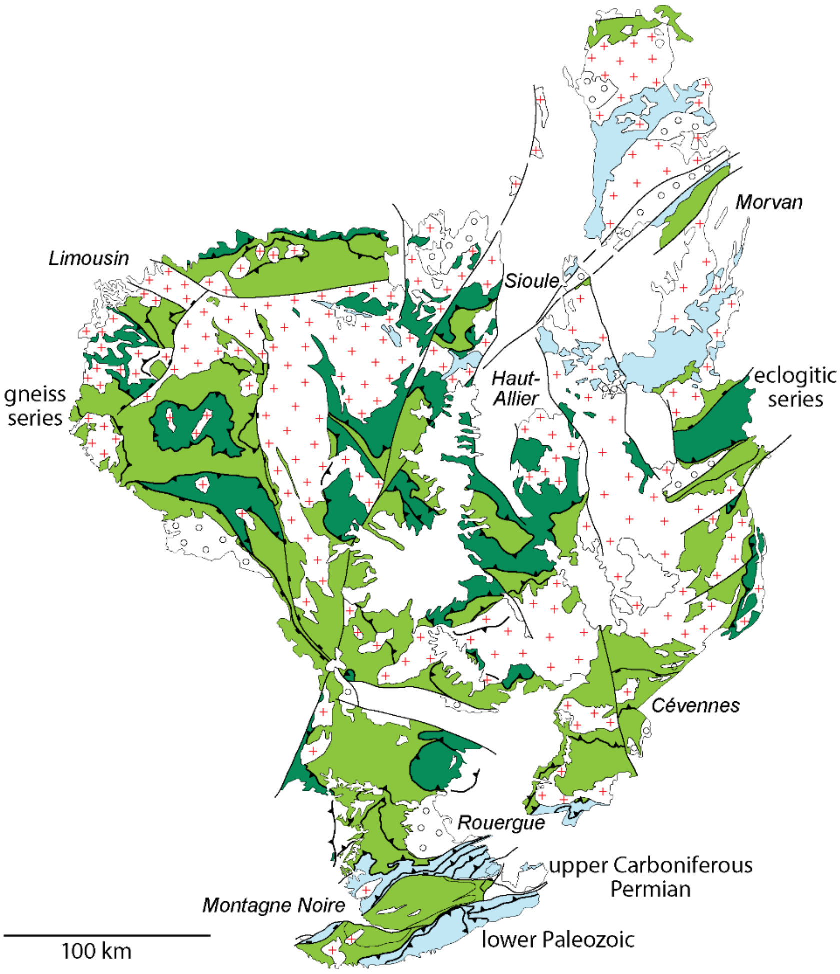


The Groix Island is famous for its blueschist rocks that have a few lateral equivalents both in Spain and in southern Brittany (Vendée). The glaucophane-rich schists have recrystallised in the Silurian (400 to 420 Ma ages). They form one of the far-travelled, rootless klippen in the Ibero-Armorican Syntaxis.

French Massif Central

The French Massif Central exposes over a distance of 400km one of the most complete section on the southern flank of the Variscan Belt, from the foreland Montagne Noire to the hinterland southern margin of the Paris Basin. The main units are separated by major southward thrusts, some of them corresponding to possible oceanic sutures.





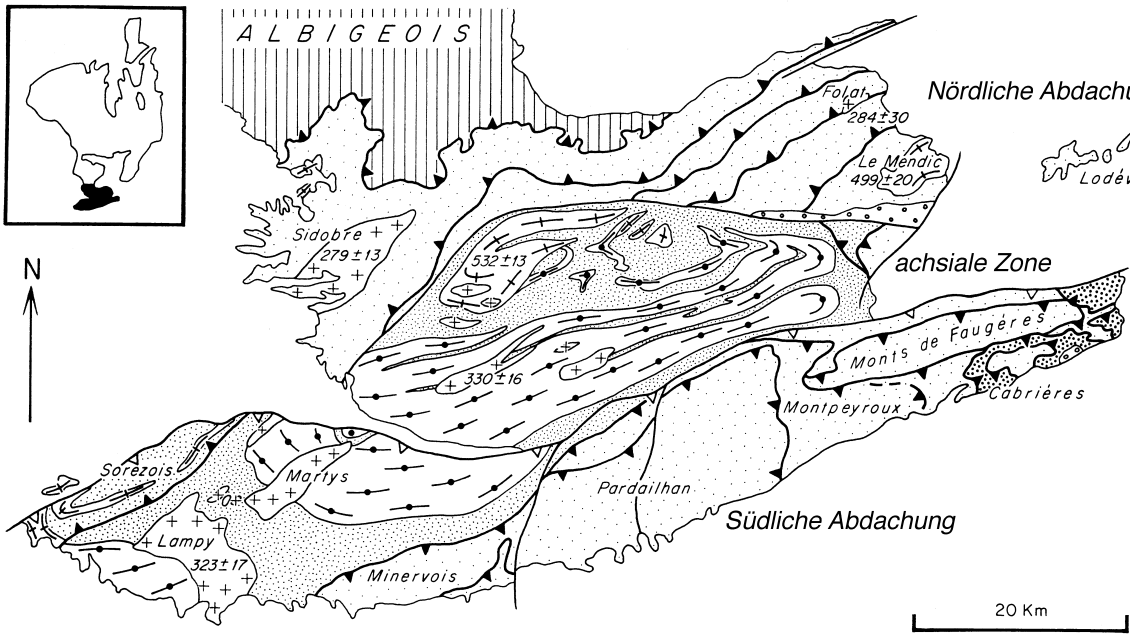
Foreland

The Montagne Noire forms the southernmost rim of the Massif Central and is subdivided into three sub-zones:

- the southern nappes composed of low-grade and unmetamorphosed Paleozoic units.
- the "zone axiale gneissique" comprising mainly middle to high-grade Late Precambrian and Lower Palaeozoic units.
- the northern zone, with low grade, Late Precambrian to Silurian rocks.

The massif of Mouthoumet that forms an isolated outcrop of Paleozoic between the Massif Central and the Pyrenees belongs to the southern zone.

The tectonometamorphic history is well known stratigraphically and by the radiochronology. The main tectonometamorphic events occurred between the Middle and Late Carboniferous.



<u>Lithostratigraphic Sequence</u>

The oldest rocks outcrop in the gneissic axial zone, a large dome-like antiform comprising three main lithologies:

1. Micaschists and pelitic gneiss with some lenses of calc-silicate gneisses and amphibolites represent the deepest structural level presently exposed; locally kinzigitic gneisses and eclogitic lenses occur. The sequence may be of Late Precambrian age.

2. Feldspathic augen gneiss including three main types:

a. orthogneiss with alkaline affinities of Early Paleozoic (530 Ma) age intruding Late Precambrian series with locally some contact aureoles.

b. undated calc-alkaline orthogneiss.

c. augen gneisses with large K-feldspars isolated in a dark biotitic matrix. These rocks could represent metasomatic rocks developed on the borders of the previous orthogneiss.

All around the "zone axiale", a horizon of fine grain feldspathic gneisses may represent rhyodacitic metatuffs at the bottom of the Paleozoic sequence.

3. The Paleozoic autochthonous sequence is tectonically thinned to less than 1000 m in the central part and on the southern slope of the axial zone, below the main basal thrust of the southern nappes.

a. A pelitic rock unit containing some lenses of marble and calc-silicate gneiss is believed to represent Early Cambrian to Early Ordovician because it occurs between the fine grain feldspathic gneisses and the overlying Devonian marbles.

b. The Devonian and carboniferous sequence is fossiliferous and preserved in the inverted limbs of recumbent folds overturned to the south.

A rich fossiliferous sequence from Lower Cambrian to Middle Carboniferous is exposed in the southern nappes.

* The Cambrian, mainly present in the Pardailhan and Minervois nappes and in northern Montagne Noire, comprises three units:

- the lower one with sandstones, schists and limestone lenses contains the oldest Cambrian trilobites;
- the middle one with thick (500 m) limestones and typical violet-green calc-schists. In the northern Montagne Noire, the Cambrian becomes more and more pelitic and the limestones progressively disappear from S to N.
- the upper one (2000 m - 5000 m) is a quartz-rich, turbiditic sequence.

* The Middle and Late Paleozoic are preserved only in the southern Montagne Noire, in the upper Montpeyroux and Mont de Faugères nappes, where a thick (2000 m) monotonous, fossiliferous flysch

sequence of Early Ordovician age is overlain locally, with a slight angular unconformity, by the Early Devonian.
Over this discordance there is:
- a sequence of Devonian limestones (500-100 m), the upper part of which (red nodular) is typical of the southern trough of the Variscan belt;
- a very thick (up to 3000 m) sequence of Early Carboniferous turbidites (Culm facies) beginning with the very persistent horizon of black cherts containing phosphatic nodules.

In summary, the stratigraphical history of the foreland area is that of the north Gondwana passive margin whose evolution is briefly disturbed by epirogenic and extensive movements in the Late Cambrian and Silurian, and interrupted in Tournaisian times. No sedimentation between the Visean and the Stephanian indicate the Variscan deformations. As sediments appear more and more distal northward (more pelitic, less carbonates) we may infer that the sedimentary slope dipped north in the Paleozoic, and that the open ocean was to the north of this area.

Tectonics

The southern Montagne Noire is one of the best examples of fold nappes, comparable to the Helvetic nappes. There is a pile of three main nappes that are from E to W and from the bottom to the top:
- the Mont de Faugères nappe,
- the Montpeyroux nappe, and
- the Pardailhan nappe.

Each of these can be subdivided into 2 to 4 subunits (digitations). The higher a nappe, the more internal it is and the older are the constituent rocks. Two other nappes are exposed at both extremities of the southern Montagne Noire:
- to the west, the Minervois nappe, which lies below the Pardailhan nappe, is considered as an equivalent of the Mont de Faugères nappe despite a slightly different and older Paleozoic sequence.
- To the east, the Cabrières nappe is a superficial décollement unit that shows a Palaeozoic sequence identical to the autochthonous one exposed farther to the south in the Massif de Mouthoumet and known from drilling below the Mesozoic cover. It is thus considered as the most external nappe and is in part an olistostrome emplaced at the frontal autochthonous part before the major deformation.

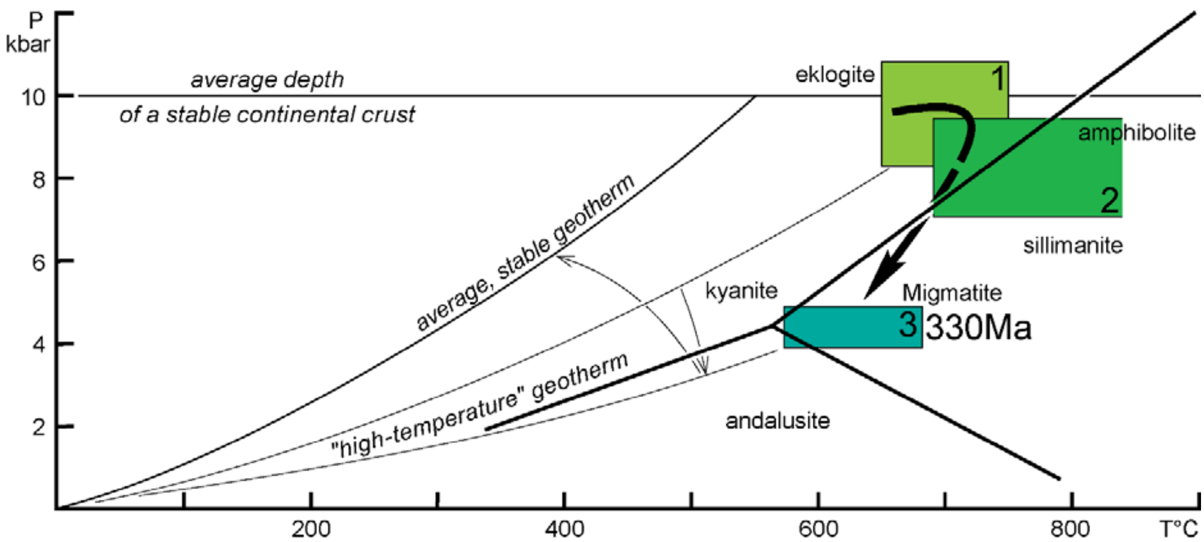
Aside from Cabrières, the nappes are characterised by large inverted limbs (up to 10 km in length) refolded into broad E-W trending antiforms and synforms.
Two main phases of deformation occurred in both the axial zone and the southern Montagne Noire.
* The first phase is related to emplacement of the nappes. The folds had initially horizontal axial planes. They trend roughly E-W and verge to the south. The maximum finite elongation is usually parallel to the fold axes, particularly in the frontal and upper parts of the nappes. In these areas the elongation is weak with an X/Y ratio about 1.5 and the strain ellipsoids fall generally in the flattening field. The parallelism between the direction of maximum finite elongation and the fold axes may be caused by the extension at the outer part of an arcuate fold. In the deeper and inner parts of the nappes, near the basal thrusts, the finite elongation is oblique to the trend of the fold axes and varies from N-S to NE-SW. The transport direction inferred from the dispersion of fold axes is from N to S.
* Shear occurred after recumbent folding because the flat-lying thrusts cut fold hinges and associated cleavage.
* The second phase produced folds with steep axial planes trending N050E to N080E and folding the F_1 structure and producing the gneiss dome of the axial zone, the broad antiforms and synforms folding the nappe pile to the south and large upright folds of the northern Montagne Noire. The southward dip of the thrusts and cleavage is due to this folding phase. Unfolding restores thrusts and cleavage with initial northward dips.

Deformation is post-metamorphic in the Paleozoic cover (crenulation of the slaty cleavage). In the gneiss dome, late folds, though folding the foliation and the metamorphic banding, developed under mesozonal conditions. The second phase of deformation occurred prior to the deposition of Late Carboniferous in the small intramontane basin of Graissesac.

The northern Montagne Noire is separated from the axial zone by a major mylonitic, normal fault. The area is characterised by several E-W to NE-SW trending thrusts dipping N or NW. Kilometre-scale folds parallel to the thrusts are overturned to the south or southwest and show fracture and slaty cleavage.

Metamorphism

Metamorphism increases downwards from the front to the roots of the nappes. In the nappe pile, the metamorphism is epizonal and contemporaneous with the main cleavage. Deformation conditions (250 < T ~ 350°C, 1.2 < P < 2 kbars) have been estimated from fluid inclusions in quartz in the basal thrust of the Pardailhan nappe. Biotite and garnet occur in the autochthonous Devonian and Carboniferous strata. Isograds are centred on the axial zone that contains amphibolite to hornblende granulite facies rocks. Metamorphism is plurifacial with an initial stage of intermediate to high-pressure type (staurolite, kyanite and even eclogites) and a later stage of low-pressure type (cordierite, andalusite, and sillimanite). The Barrovian metamorphism fits with nappe stacking. However, the biotite, garnet, staurolite and sillimanite isograds are crossed along a 2 km section.



PT history of the Montagne Noire axial zone (gneiss dome) in the French Massif Central
from Burg (1992) *Sciences Géologiques*, **44(1-2)**, 105-206

Intermediate fold and thrust regions: Albigeois – Rouergue - Lot - Cévennes

Flat-lying monotonous schists, mica schists, and gneiss showing a complex structural and metamorphic history are thrust over the foreland. Ages are poorly defined owing to the scarcity of fossils.

Lithologic Sequence

Three main lithologic units are separated by major thrusts. From bottom to top they are:

- The lower unit, in the Albigeois area, consists of green sandstones, greywackes and pelites with acid volcanics. The sequence shows the same facies as the lower Cambrian of northern Montagne Noire.
- It is overlain by dark bluish schists with intercalations of basalts, rhyodacites, and it is intruded by gabbros and dolerite dikes. In the Lot-Cévennes area the bluish schists contain Cambro-Ordovician acritarchs.

- The upper unit is a very thick monotonous quartzopelitic series (> 4000 m) in which Early Ordovician microfossils have been found (the Albigeois and Cévennes schists and micaschists). The schists are tectonically covered by more metamorphosed micaschists of probable Late Precambrian age because they are intruded by 540 Ma old quartz metadiorites.

The bulk history is a pelitic sequence deposited during the Paleozoic in a deep, marine environment. The old intrusions indicate extension during the Nord-Gondwana margin evolution.

Tectonics

The intermediate fold and thrust zone is bounded by two main thrusts:
- the southern, sole thrust corresponds is the contact between the Albigeois quartzo-pelitic series onto the Early Paleozoic of northern Montagne Noire.
- the northern, roof thrust corresponds to the base of the leptyno-amphibolites, with a 100 to 150 km throw.

As in Montagne Noire two major phases of deformation exist.
* The first phase caused the general bedding-parallel slaty cleavage. Folds are scarce, very tight and intrafolial and have variable trends. In some areas (Lot and northern Albigeois) the intersections are N-S and parallel to a prominent stretching lineation in particular in the mylonites that mark the sole and roof thrusts. Preferred orientations of quartz axes show that the stretching lineation corresponds to an intense southwards shear.
* The second phase produced upright mesoscopic chevron folds with local crenulation cleavage and large synforms and antiforms (dome and basin structures).

The overall interpretation is a polyphase, imbricate zone whose deformation style, although metamorphic, compares to that of a foreland.

Metamorphism

Metamorphism varies from greenschist to amphibolite facies. It is of intermediate type and the isograds, parallel to the foliation, appear inverted from the low grade, fossiliferous schists to the south up to kyanite mica schists below the roof thrust. Fine-grained biotite-sillimanite paragneisses in tectonic windows correspond to the deepest buried parts of the sequence.

The metamorphic inversion is probably original and contemporaneous with the main thrusting of the leptyno-amphibolites. This intermediate metamorphism is dated around 350 Ma.

Allochthonous, meta-ophiolite-bearing units

The northern part of the Massif Central Français represents the deepest structural levels of this Variscan inlier. Its lower boundary is the major thrust with granulite facies rocks, blue schists and eclogites have overridden the intermediate schists. The name leptyno-amphibolite described the association of quartz-feldspar gneiss with ophiolite-derived basic and ultrabasic rocks.

Lithologies

The high-grade rocks form the leptynite-amphibolite units. Most amphibolites show complex corona reactions resulting from the retrogression of eclogites and/or granulitic pyrigarnites. Acid and mafic granulites and skarns are found in a matrix of fine-grained pelitic and/or feldspathic gneisses. Lenses of marble are rare. Basic rocks are MORB type basalts that represent the crustal part of the oceanic lithosphere whose mantle is seen in the meta-harzburgites that occur in the leptynite-amphibolite units.

The isotopic dates of the leptynite-amphibolite unit yield Paleozoic ages. An eclogitic gabbro and an ortholeptynite give U-Pb ages of 480 Ma. A granulitic orthogneiss gives a whole rock Rb-Sr isochron of 467 Ma. These Ages would correspond to the emplacement of these igneous rocks.

Thick anatexites (>2000 m) are found in large synforms above the leptynite-amphibolite unit. They consist of partially molten, massive paragneisses with large cordierites. The typical paragenesis: orthoclase, plagioclase, biotite, cordierite, sillimanite, almandine has been interpreted in terms of Barrovian prograde metamorphism. Lenses of high-pressure granulites - khondalitic-kinzigitic gneisses - eclogites and garnet peridotites are preserved, with gradational contacts between acid granulites and the anatectic gneisses . These occurrences and relict HP metamorphic minerals imply that the anatectic gneisses are products of melting of granulites.

<u>Tectonics</u>

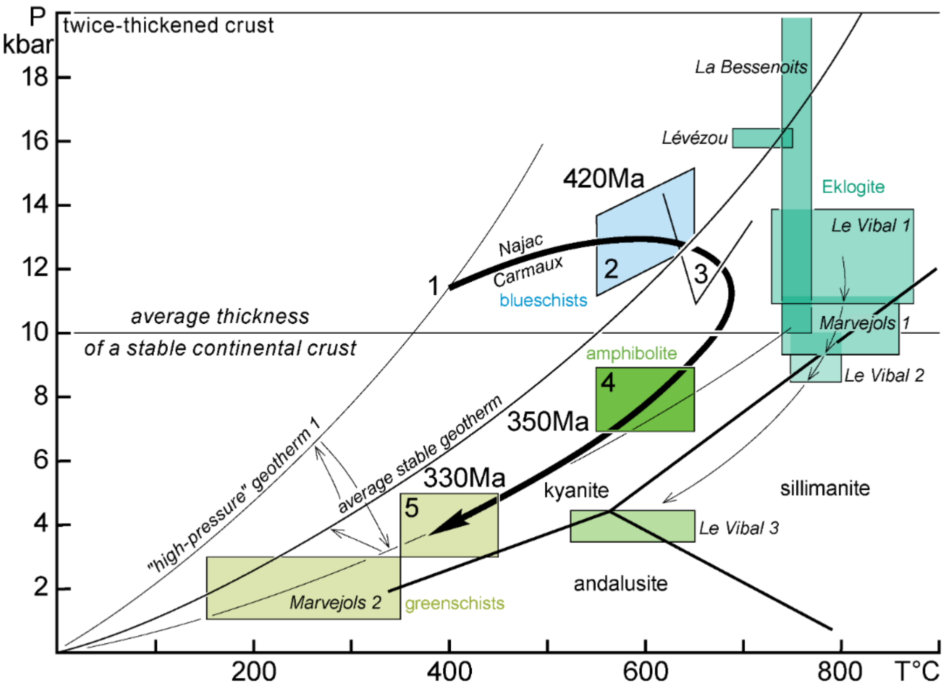
The bulk deformation is polyphased. It is associated with the thrusting of the leptyno-amphibolite units. Underthrusting of the low-grade schists beneath the granulite facies rocks is supposed to have generated sufficient water to retrograde eclogites and granulites to amphibolite facies. The bulk kinematics as from lineations in the mylonites is southward.

The oldest deformation event is preserved in granulitic boudins as ghostly isoclinal folds that are older than a static recrystallisation under the granulite facies conditions. These folds may be contemporaneous with granulite migmatization. The major phase corresponds to the widespread metamorphic foliation that affects pre-Late Devonian rocks. Isoclinal folds are developed on all scales and generally verge to the south.

Southwest-facing chevron folds and upright folds of kilometre scale with variable orientation developed produced dome and basin structures.

<u>Metamorphism</u>

The main deformation is contemporaneous with the widespread amphibolitization (hydration and retromorphism) of granulites and eclogites, during the regional Barrovian metamorphism. Because of the early granulite facies in the overriding rocks, the inverted zonation in the lower units may be the consequence of an “ironing effect” as in the Himalayas, with heat of the already metamorphosed rocks being transferred to the underthrusted sediments.



PT history of allochthonous units in the French Massif Central
from Burg (1992) *Sciences Géologiques*, **44(1-2)**, 105-206

Two U-Pb measurements on the high-pressure rocks yielded upper intercepts of 415 Ma and 410 Ma. These ages represent the HP metamorphism. Barrovian metamorphism occurred before the deposition of the Late Devonian-Early Visean strata i.e. before 340 Ma. Rb-Sr whole rock isochrons on the orthogneiss yield ages circa 360 Ma considered as the climax of agnates.

Granitoids:

For a long time, granitoids have been considered to be a characteristic feature of the Variscides and indeed, a look at any map shows how widespread they are compared to the Alps for example. Three main kinds of granitoids are present are identified on a chemical and age basis:

a. Foliated augen gneiss that have mainly monzogranitic compositions. They are considered either as pre-Variscan granitoids inherited from the establishment of the margin or as syntectonic injections. A difficult geochronology does not provide any conclusive answer.

b. Late granitoids as the Margeride cross cut the main thrusts and associated structures. They are dated at around 330 Ma. They are closely related to metamorphism and anatexis. They originated in the middle part of the crust (high Sr/ Rb ratio) and show a schistose, slightly oriented or unoriented texture depending on their time of emplacement. They commonly are calc-alkaline plutons related to the Visean ignimbritic volcanism.

c. Younger granitoids intruded at around 300 Ma. and have often a deeper origin (lower initial Sr ratio).

Upper, low-grade or non-metamorphosed Devono-Carboniferous cover

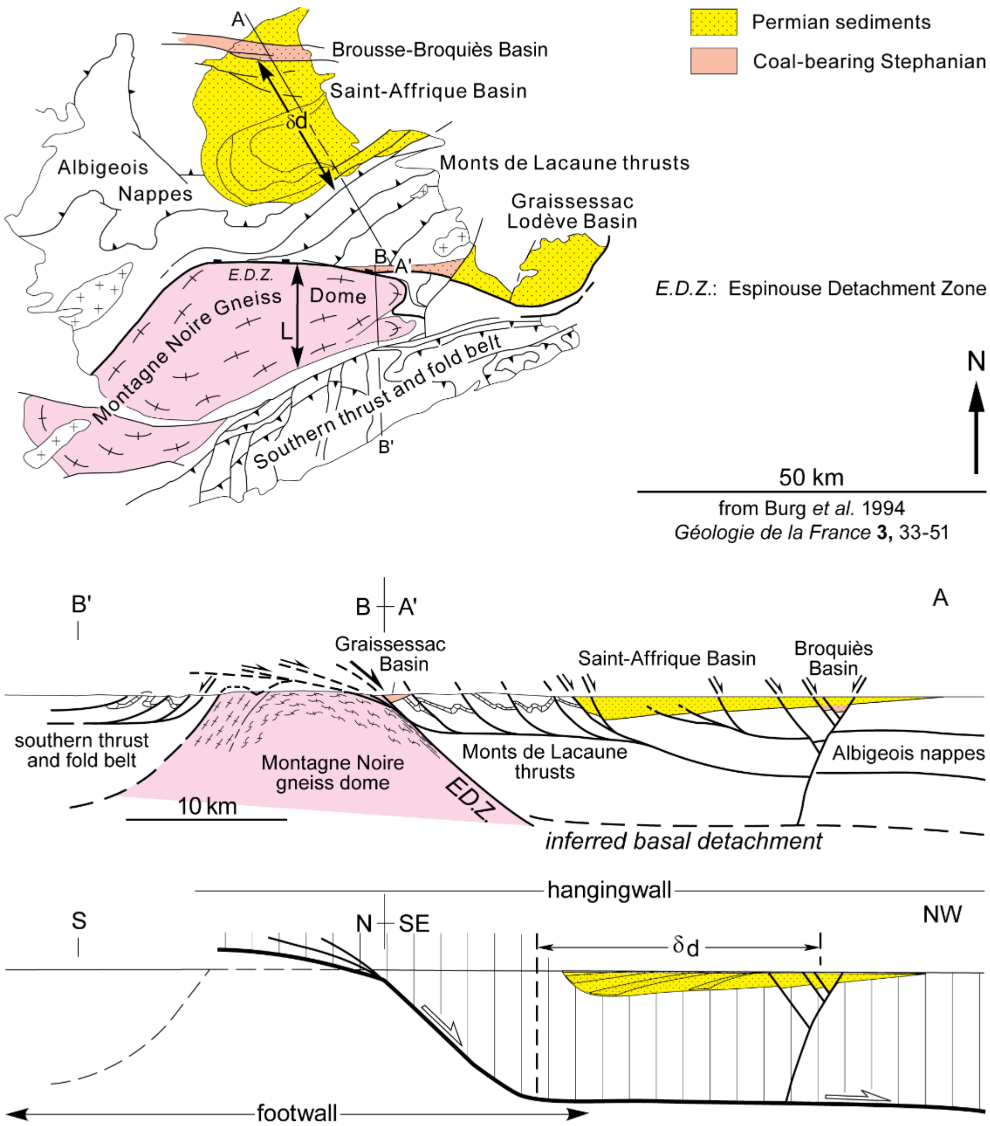
The epizonal to unmetamorphosed Devono-Carboniferous cover is a thick volcanoclastic sequence with abundant keratophyres and spilites (sometimes pillow-lavas) and locally gabbros, norites, serpentinites (possible cumulates). Late Devonian to Early Visean fossils were found in the lower part, which overlies unconformably the anatexites in which 502 Ma orthogneiss are present. The sequence has suffered some deformation (slaty cleavage) and metamorphism (up to amphibolite facies) before the deposition of the unconformable, non-metamorphic and slightly deformed upper unit that consists of shales, sandstones, conglomerates with thin anthracites and a Late Visean flora.

Detachment systems

Much of the plutonism in the Variscides has been caused by late orogenic extension ie. the thickened crust became unstable and extended laterally by gravity spreading. Collapse caused the isotherms to rise and the base of the crust to heat up and melt. Carboniferous to Permian collapse and thinning of the crust caused:

(1) Bimodal volcanism.
(2) Extensional gneiss domes (e.g., Montagne Noire) associated with spreading of the European crust.
(3) Post-orogenic Carboniferous extension in centre of orogen and reusing old tectonic grain.
(4) Supply of high volumes of anatectic material - granites
(5) HT-LP regional metamorphism.

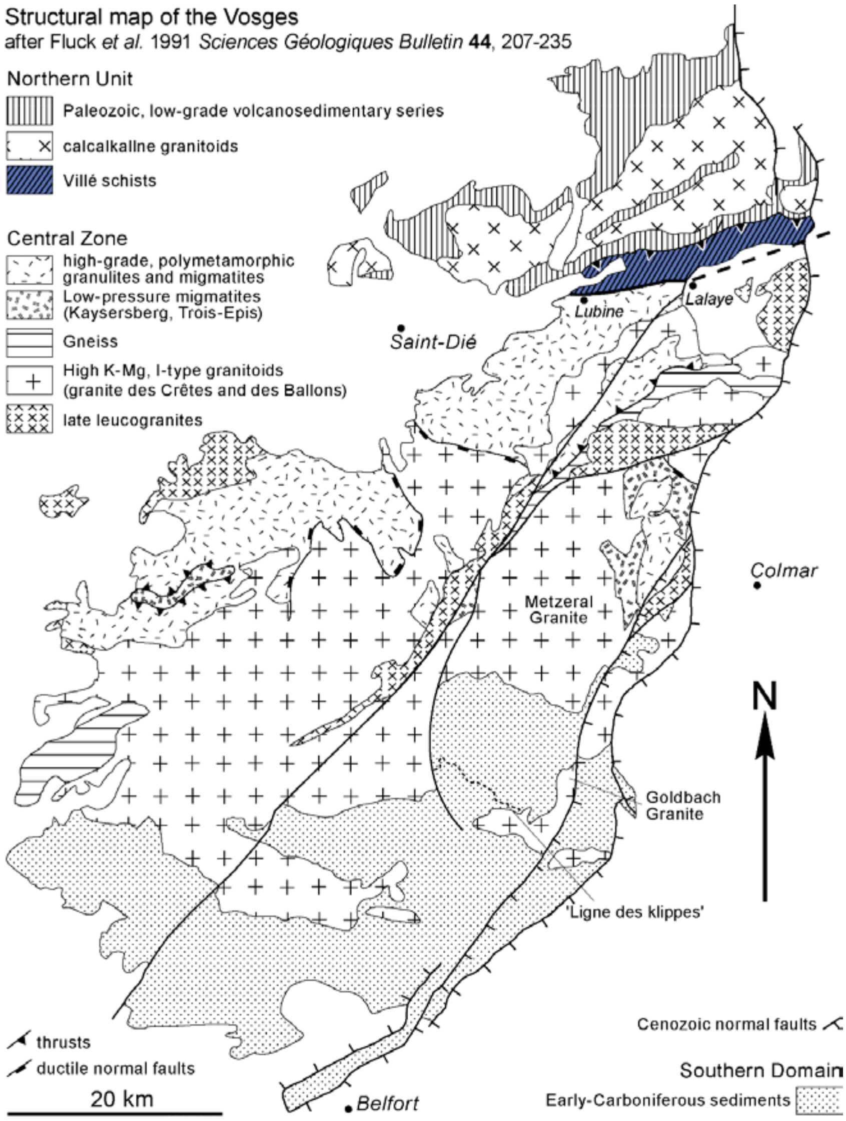
The last two characteristics are of ages 330-290Ma.



In the southern part of the Massif Central, sedimentological and structural investigations of the Saint-Affrique basin have shown that the asymmetry of the basin filling and southward tilt of layers were controlled by a roll-over semi-anticline, which implies that it was in the hangingwall of an extensional detachment system during Late-Stephanian to Permian times. The basin is bounded to the south by a high-angle, northward dipping detachment which supposedly flattens downwards in the brittle ductile transition, resulting in listric geometry at crustal scale. Actual flat lying normal faults associated with this extension system are the reactivated thrusts with northward sense of shear in the underlying "schistes de l'Albigeois". A large part of the hanging wall displacement may be related to the mylonitic detachment seen on the northern slope of the "zone axiale" thus accommodating the exhumation of the Montagne Noire Crystalline Axis in Stephanian to Early Permian times.
Gneisses and migmatites forming the crystalline axis raised by roll-under folding of the footwall which is consistent with early Carboniferous metamorphism and deformation. The Stephanian Graissessac basin deposited on the detachment zone, north of the rising gneiss and migmatites. The average width of denuded ductile crust parallel to the extension direction is ca. 20 km. this event represents the post-thickening event that has stretched the crust by nearly 100%

Vosges Massif

The Vosges Massif consists of three major lithotectonic units: (1) a northern unit consisting of Cambro-Ordovician shales and Upper Devonian to Lower Carboniferous low-grade metamorphic active continental margin sequences, intruded by a calc-alkaline magmatic series ranging from diorites to granites with ages of around 340 and 330 Ma; (2) a central belt composed of granulites and migmatites that were intruded by large granitic bodies; (3) a southern domain consisting of an Upper Devonian and Visean sedimentary basin with volcanic activity between 345 and 340 Ma, and which was intruded by large masses of diorites to granites 342 to 339 Ma ago. The southern domains 2 and 3 are referred to as Moldanubian, whereas the northern zone, separated by a large strike-slip shear zone (LLSZ), belongs to the Saxothuringian domain.



Southern Vosges

The Southern Vosges host a well preserved, Lower Carboniferous sedimentary basin, interpreted as tensional basin formed during syn-convergence extension in the internal part of the orogen. It is bordered by the intrusions of the Ballons and Crêtes granites, the post-Carboniferous sedimentary cover and Tertiary Rhine Graben faults. The basin is subdivided into a southern (more proximal) and a northern, more distal part, the latter called Markstein formation. Both the southern and northern parts of the basin are slightly deformed (slight folding and local thrusting) due to either regional deformation prior to the intrusion of the magmatic rocks and/or due to transtensional tectonics during emplacement.

Lithostratigraphic subdivisions of the basin sediments have been established by detailed mapping and paleontological studies, distinguishing older (pre-Late Visean) and younger (Late Visean) sequences. More recent investigations, however, have suggested that most of the fossil faunas represent reworked mixtures of Tournaisian up to Late Visean age. Schneider (1990) proposed a stratigraphic division based on the depositional facies and temporal evolution of the volcanism in the basin.

Southern part of the basin.

Three consecutive sedimentary units may be distinguished within the southern part of the basin: (1) A Lower Unit (biostratigraphic age: Late Devonian - base of Late Visean): It consists of turbidites that are associated with bimodal volcanic rocks (basalts and low-K rhyolites): the basalts have been diversely interpreted as oceanic arc tholeiites or continental tholeiites.
(2) The Middle Unit (base of the Late Visean) is characterised by marine and mainly turbiditic sediments and by andesitic volcanism, hence a distinct change in the nature of volcanism in the basin.
(3) The Upper Unit (upper Late Visean) displays a volcanic association, which evolved from trachyandesites towards more felsic compositions (latitic rhyolites, rhyodacites and rhyolites) that have a pronounced potassic chemistry. The sedimentation rapidly evolved from marine to terrestrial and involved mainly reworking of volcanic rocks.

Both the Middle and Upper Units were thus deposited during the Late Visean (ca. 340-325 Ma) according to biostratigraphic evidence. The whole sequence was subsequently intruded by trachytes.

Northern part of the basin (Markstein formation)

This up to 4000 m thick marine formation forming the northern part of the basin contains very rare volcanic rocks and has been deposited from Famennian (Late Devonian, ca. 365 Ma) to Late Visean (ca. 340-335 Ma) times. Detailed investigations by pointed out that these strata represent the northern distal equivalent of formations located in the southern part of the basin and that the volcanism of the south is recorded by tuffs and reworked volcanic components in the clastic sediments. A layer containing lenses of high-grade gneisses, serpentinites and mafic rocks with oceanic affinities of unknown age and origin and separating the two basin domains, represents the base of the Markstein formation ("Ligne des Klippes") and has been interpreted as olistostrome. The olistostrome deposition occurred pre-Late Devonian, because it is overlain by Famennian pelites (green and red "Treh shales") and grade upward into turbiditic sequences of alternating conglomerates, sandstones and pelites. This structure has also been considered as a succession of tectonic lenses (the "klippes") marking a south-vergent thrust fault. There is no agreement, whether the "Ligne des Klippes" represents a tectonic or a stratigraphic contact between the two basin domains.

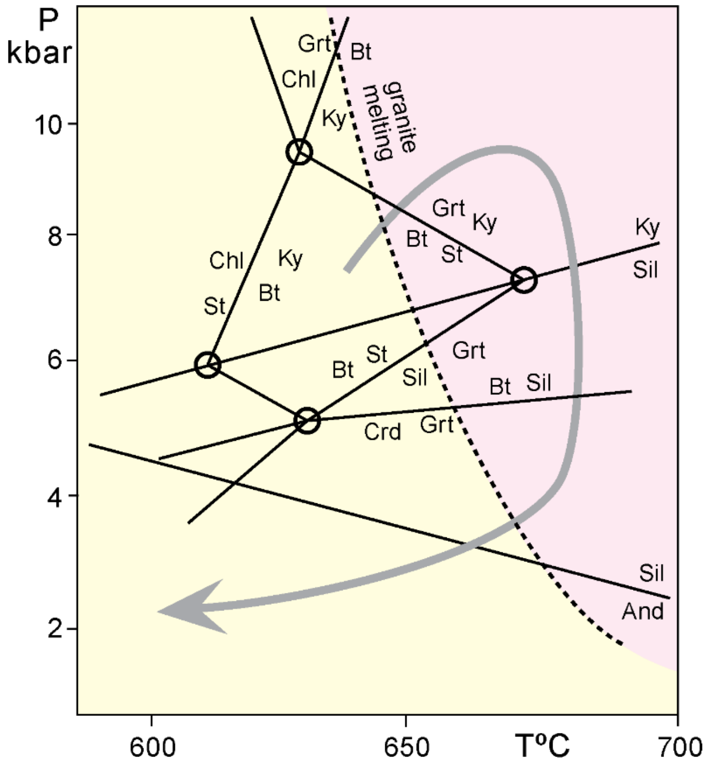
Central Vosges

The central part of the Vosges comprises high-grade gneisses, granulitic rocks and granites that were intruded by numerous granitoid plutons (granodiorites, anatectic granites and late-stage leucogranites). The central zone is separated from the northern basin by a large shear zone (Lalaye-Lubine Shear Zone, LLSZ), which is considered as the ancient collisional suture that has been reactivated during late orogenic strike-slip. The LLSZ juxtaposes very-low-grade metasediments of the northern volcano-sedimentary basin to the high-grade rocks of the axial zone. The southern border of the central zone was obliterated by the intrusion of granitoid rocks. Within the zone, two units may be distinguished:

a) Sainte-Marie-aux-Mines unit (SMM unit)

This unit mainly comprises low-pressure (<10 kbars) mafic to acid granulite-facies rocks from a variety of protoliths (acid igneous rocks, metapelites, calc-silicate rocks) that underwent some retrogression in amphibolite-facies. The acid members include pink granulites of igneous origin (so-called leptynites), concentrated the area around Col des Bagenelles, typically containing layers or boudins of mafic to ultramafic rocks. The main granulitic lithology is of sedimentary origin (so-called kinzigites); retrograded members are sillimanite and biotite bearing gneisses. The granulites host different types of leucosome in highly variable proportions: tonalitic to trondhjemitic veins in mafic granulites, garnet or cordierite-bearing leucosomes in kinzigites.

Textural equilibrium between garnet, mesoperthite and kyanite define granulite facies conditions in acid granulites (leptynites). First melting in granulitic metapelites is marked by the development of large proportions of coarse grained leucosome with garnet and biotite rich salvages indicating dehydration melting of biotite. The degree of melting strongly depends on protolith composition, such as the leptynites do not show textural features of dehydration melting but metapelites in some places exhibit more than 50-70% of garnet rich melt. Thermo-barometric calculations from granulitic metapelites yield temperature estimates of 750-800°C and pressures 7-9 kbar.
Retromorphic evolution of granulites show pressure and temperature decrease via temperatures 580 - 660°C and pressures 6.5 kbar of sillimanite bearing rocks to cordierite bearing migmatites. 39Ar-40Ar age spectra of amphibole and biotite from granulitic schists yielded ages ranging between 357 to 339 for amphibole and 327 for biotite.



PT history of the gneiss in the Vosges
after Rey *et al.* (1991-1992) *Geodinamica Acta* **5**, 17-36

<u>b) Kaysersberg and Trois-Epis units:</u>

Different varieties of cordierite-bearing amphibolite-facies units occur in the south of the SMM zone (villages of Kaysersberg and Trois-Epis). Field observations suggest that the Kaysersberg unit is a homogeneous intrusive granite to granodiorite with abundant enclaves in some places. Enclave-free or -poor portions with 5 cm long k-feldspar phenocrysts and some cordierite are hard to distinguish from other adjacent granites. The Kaysersberg granite is interpreted as a partial melt of a fertile metasedimentary granulite-facies protolith of kinzigite type at conditions of 3-5 kbars and 630-720°C, which intruded into the overlying strata.
The Trois-Epis unit is situated on top of Kaysersberg granite and has been interpreted as thrust-sheet of a granulitic protolith onto non-metamorphic or lower-grade rocks. Field evidence shows no clear separation of two units, but Trois-Epis layers or mega-boudins occur in a matrix of Kaysersberg granite. We interpret the Trois-Epis lithology as layers of former leptynite that have undergone pervasive recystallization, but no remelting due to the lack of hydrous phases. Trois-Epis layers were partly intruded by Kaysersberg granite portions.

Both the Kaysersberg and Trois-Epis units have been formerly interpreted as low-pressure migmatites derived from metasedimentary (Kaysersberg) or metamorphic (remelting of metasedimentary granulite) protoliths.

North/Central European Variscides

Three main zones in Middle Europe are from north to south: The Rhenohercynian, the Saxothuringian and the Moldanubian Zones.

Rhenohercynian Zone

The Rhenohercynian zone is the external zone of Variscides in Europe and extends from Poland, Germany (Rhenish Massif and Harz Mountains), Belgium, NE France and the British Isles. It is more tentatively correlated with the external zone in SW Iberia. The basement consists of Cadomian Precambrian seen in the London-Brabant massif and on mainland Europe (East Avalonia?) but not in Ireland. Upper Paleozoic sedimentary successions at lower greenschist facies were folded, cleaved and thrust. Transport is generally towards the north and deformation migrated northward with time. Its northern margin changes character along strike. In NE France it is a major frontal thrust called the Faille du Midi seen clearly on deep seismic lines. In northern Germany it dies out into a foreland basin as seen on deep seismic. Similar situations occur in the British Isles. There is a foreland basin with coal to the north in Germany, Belgium, France and Wales, not in Ireland but also in the Appalachians.

Devonian sedimentation reflects a clastic influx from the north (Old Red Sandstone continent= Laurussia) in a marine shelf that gave way to hemipelagic sedimentation turbidites, shales and carbonates. From Frasnian onwards a southerly source shed flysch into the basin (mid-German crystalline high). The flysch front advanced northward with time reflecting the advance of the Variscan tectonic front.

The Rhenohercynian became a foreland basin in Namurian to Westphalian times with influx of sediment overcompensating for subsidence so that the environment became coal bearing (Ruhr coal-fields).

Saxothuringian Zone: Slate Belt

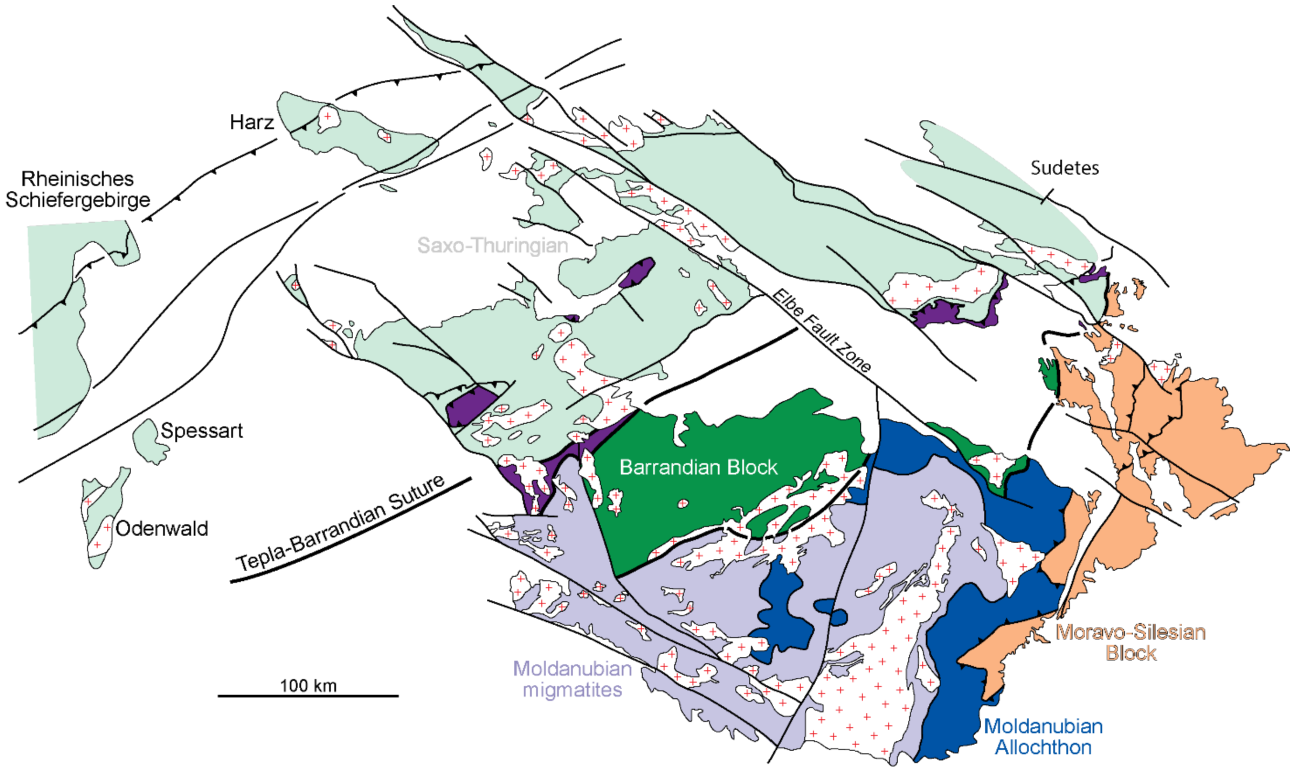
Northwest-directed thrusting and associated folds affected an uninterrupted sequence of Proterozoic through Late Visean sediments with volcanic evidence for Cambro-Ordovician extension of a shelf drown to deep-water conditions in Silurian-Devonian times. Crystalline complexes (Lusatian Block, Erzgebirge, Granulite Massif, Münchberg Gneiss Complex) were thrust on the mostly unmetamorphosed Paleozoic sediments.

Moldanubian Zone

The westward extent of the Moldanubian and Saxothuringian zones relies on geophysical information. To the Southeast, they form the Bohemian inlier.

Bohemian Massif:

High-grade metamorphic nappes were thrust onto both northwestern (Saxo-Thuringian Zone) and southeastern (Moravo-Silesian Zone) foreland units. Large granitoids are mostly of the 340-330 Ma sequence. Late carboniferous basins show that the late extension has here too taken place.



Barrandian: Microcontinent

The Barrandian basement, comprises Late Proterozoic schists overlain by Cambrian to middle Devonian marine sediments. They have been involved in more or less open, south-facing folds during very low grade metamorphism, which means that the region has been little eroded, because it has been little thickened. However, this unit seems to have been thrust southward over the Moldanubian.

Moldanubian Zone

Granulite facies and eclogite units have been thrust over a vast domain of anatexites and granites, the so-called Moldanubian.

The lower unit is composed of para and orthogneisses that have undergone an Early Devonian medium pressure metamorphism, characterised by the inverted, tectonic superposition of metamorphic zones. Eclogites are sporadic. The thrusting event refers to forelandward thrusting predating a widespread low pressure metamorphism that characterises the Moldanubian s.s.

The intermediate unit comprises anatectic gneisses with granulites, serpentinites and other mafic rocks. Southerly directed transport is suggested by vergence of structures and strike of lineations.

The upper, gneiss unit is tectonically separated from the lower and intermediate units by an ophiolite-like association.

Moravo-Silesian Zone: southern continent

The Moravo-Silesian Zone, in southeastern Bohemian Massif includes a Cadomian crystalline basement covered by Silurian to Early Carboniferous shallow water and pelagic sediments (Lower Carboniferous syn-orogenic Culm-type flysch of the Silesian trough) and a Late Carboniferous molasse-type sequence.

The Moravian nappe complex includes Cadomian tectonic elements affected by Variscan amphibolite to greenschist facies metamorphism and associated ductile deformation.

Minor regions

Isolated continental blocks, like the Corso-Sardinian or Balearic blocks, as well as the whole Alpine belt, also include a Variscan basement. In general, these comprise highly metamorphic and granitic, externally located zones which are largely similar in composition to the Moldanubian Zone.

Tectonic models

Since the advent of plate tectonics, an awareness of the orogen as a whole has developed. The two broad regions of the European Variscides need separate descriptions.

- The western Variscides.
- The Central Variscides.

Western Variscides: southern suture zone

The western Variscides of Europe show the following characteristics:

- Large thrusts reaching 200 km of displacement and great recumbent folds verging to the inner foreland of the Ibero Armorican Arc. Thrust sheets include ophiolites and rocks of Lower Paleozoic passive margins, from both sides of the remnant ocean. Tectonic imbrication originated from the north- to west-dipping subduction and closure of the "Proto-Tethys" Ocean.
- Polyphase Variscan metamorphism located in the central crystalline part of the orogen close to the supposed main suture zone with an early high-pressure stage around 400 Ma followed by intermediate to low pressure stages between 370 to 330 Ma.
- Decreasing age (migration) of the tectonometamorphic events from the internal crystalline parts (380-400 Ma) towards the external basins (330-300 Ma) with simultaneous changes in deformation style from deeper levels (ductile thrusts and recumbent folds) to the higher levels (superficial decollement thin-skin tectonics). The autochthonous regions consist of Lower Paleozoic shallow-water sediments deposited on the margin of Gondwana.
- The generation of two main types of granitic magmas during and following the main tectonometamorphic climax:

Aluminous intrusions, generally leucogranites and subordinate monzogranites and diorites are more or less related to the metamorphism and produced by wet anatexis of Paleozoic and Precambrian sediments in the middle part of the crust. These granitoids show high initial Sr isotopic ratio (0,710 to 0,720). They were emplaced between 360 and 310 Ma.

Calc-alkaline granodiorites with low initial Sr ratio originated by melting of the lower part of the crust. Some of these granitoids were emplaced early (330-340 Ma) but most of them are late (300-280 Ma) with respect to the main tectonometamorphic event. The most probable mechanism of this post-collisional magmatism is extensional decompression after crustal thickening leading to melting of the deep continental root.

The Iberian section includes, to the south, a segment of the Central Variscides.

Central Variscides: northern suture zone

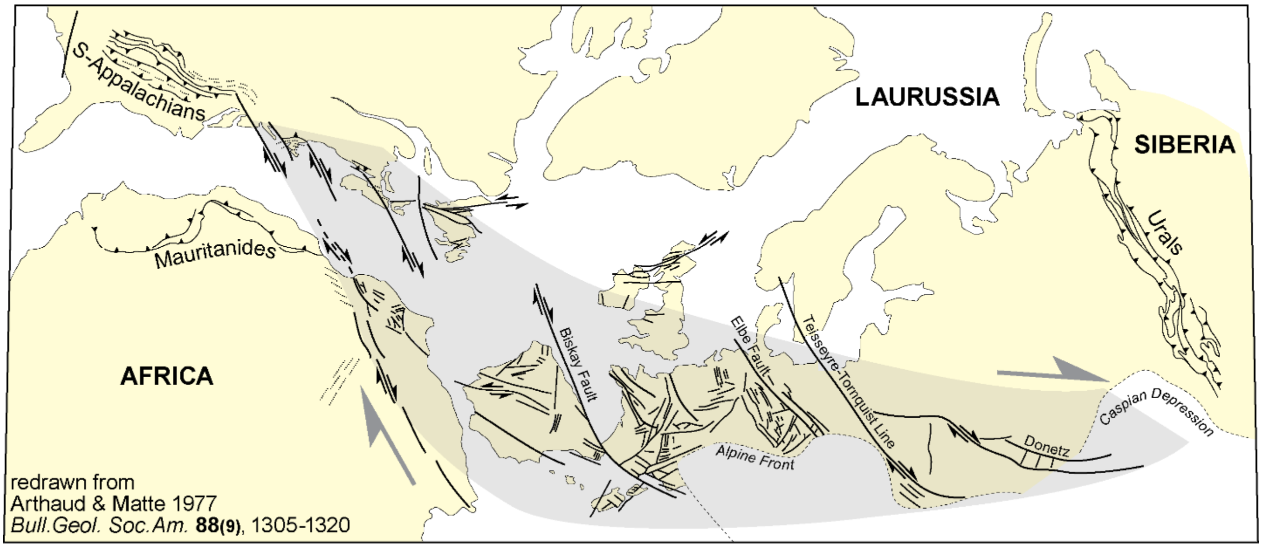
Convergence between Laurussia and Gondwana may have opened the Avalonia–Armorica boundary, creating the narrow Rheno-Hercynian oceanic (back-arc?) basin whose remains are traced from southern Portugal through Wales and the Rhenish Massif into Moravia.

In consistency with structural vergence, the Rheno-Hercynian Ocean subducted towards the south. Collision between the Armorican and Avalonian terranes (Saxo-Thuringia, Bohemia, and Moldanubia) with Laurasia took place in Late Devonian times.

Variscan deformation is essentially Early Carboniferous, with thrusting typically involving the collided continental lithospheres and migrating towards the forelands filled with syn-orogenic clastic debris. Final erosion of the mountain system during the late Carboniferous fed clastic sedimentation in shallow-marine to fluvial environments under the tropical climate that generated the wide coal basins of Europe.

Late shear zones, indentation model and intrusion of granites

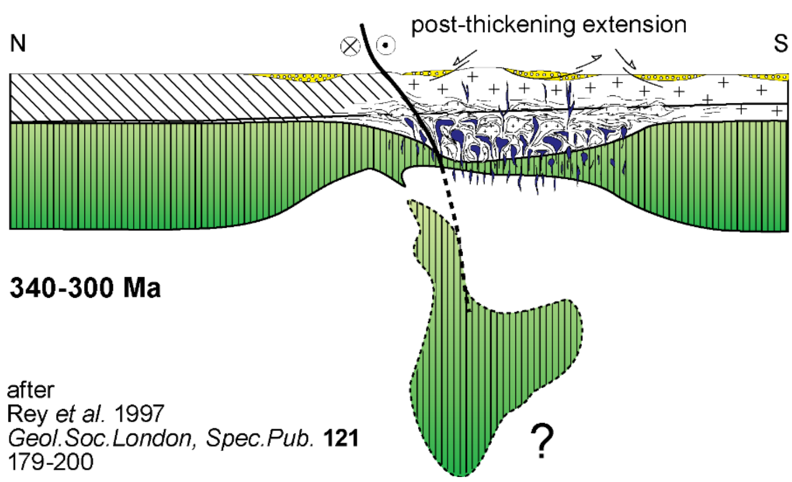
Strike-slip faulting dominated the late Paleozoic history of southern Europe and northern Africa. It is ascribed to a general dextral wrenching induced by the relative motion of the northern part of Pangea (Canadian Shield, Greenland and stable Europe) with respect to the southern part (Africa, India, Australia). The relative movement of these two sub-plates was transformed into shortening at both ends of the wrench zone and led to the formation of the Urals to the east and the southern Appalachians to the west. Transcurrent shearing in the continental lithosphere has controlled ascent, emplacement and site of granitoids. Two possibilities are either the deep reaching shear zones have provided a pathway for the granites to ascend or frictional heating within the shear zone would has generated temperatures high enough to cause anatexis. Arguments have been raised against frictional heating on the basis of inadequate rock viscosities, rates of movement and duration of movement.



Late Variscan strike slip faults interpreted as a Riedel shear system in a general dextral wrench zone between Africa and Laurussia, with shortening in the compressional Appalachian and Urals quadrants.

Late extensional collapse

Much of the granitoid plutonism in the Variscides is related to late orogenic extension i.e. the thickened crust became unstable and extended laterally by gravity spreading. Consequent thinning caused the isotherms to rise and for the base of the crust to heat up and melt.



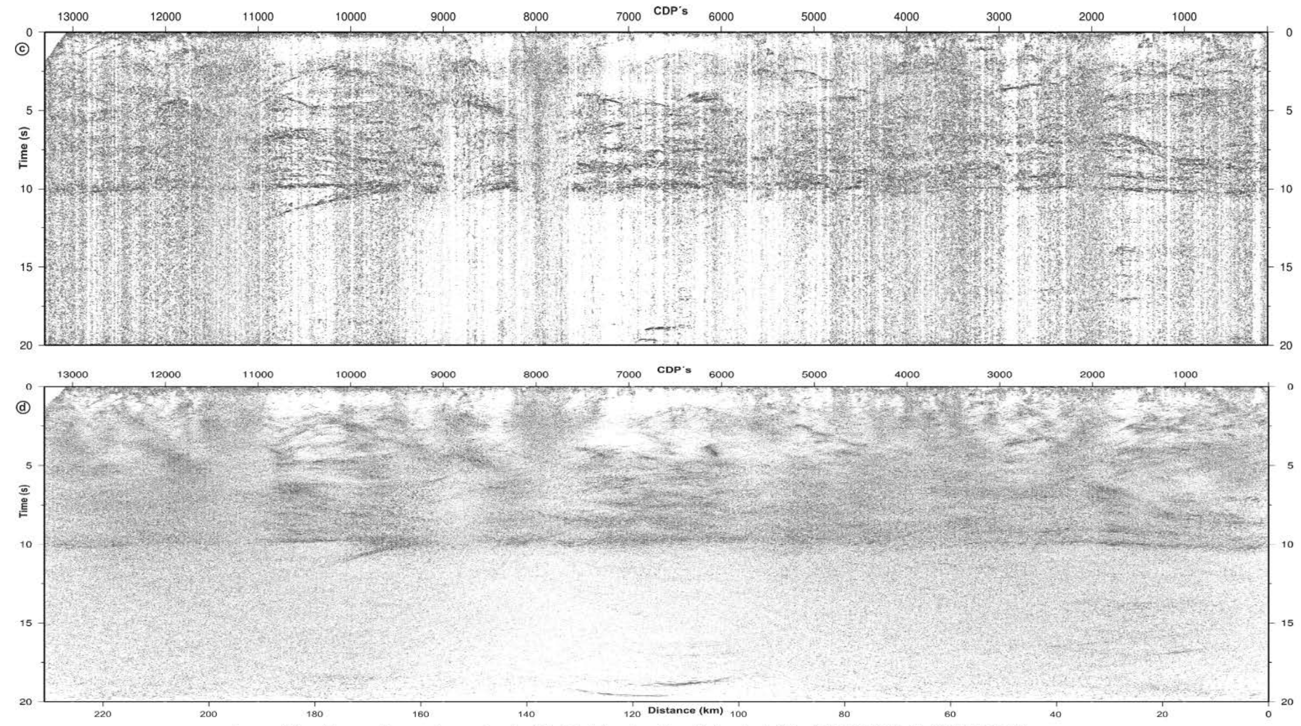
Carboniferous orogenic collapse and Permian extension (330-290Ma) caused:
- Extensional gneiss domes (e.g., Montagne Noire) associated with spreading of the European crust.

- HT-LP regional metamorphism.
- Supply of high volumes of anatectic material (leucogranites).
- Bimodal volcanism.

Consequences are that pre-extension thrust displacements were not as large and the Variscan Belt not as wide as estimated from maps.Pangea was formed with the Tethys oceanic bay in its eastern center. Due to Late Carboniferous and Permian dextral shear between Gondwana and Eurasia, the Tethys Ocean widened into a large bay extending from the proto-Pacific Ocean towards the west, and rifting started again. Late Paleozoic transgression prograded westwards forming a Tethyan shelf and reached the area of the future Alps, where corresponding deposits postdate formation of the Variscan basement, in the Late Carboniferous.

Lower crust of Europe

Deep seismic reflection profiling in several European countries has identified a highly reflective, high velocity lower crust. These mostly subhorizontal, dense reflectors are variously attributed to a strong fabric and sill intrusions Xenoliths in Tertiary volcanic rocks of Europe are natural samples of this few km thick “layered” lower crust. Petrology has described a wide range of rock types, including eclogites, mafic garnet-bearing and garnet-free granulites, through felsic granulites to high-grade metasediments. Zircon ages from crustal xenoliths are often younger than exposed rocks. This suggests that magmatic underplating has added much material to the base of variscan crust during rifting and orogenic collapse.



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Uralides

The Ural Mountains represent a Late Paleozoic collisional orogen which developed between Fennosarmatia and Paleozoic Altaid island arc complexes. A section exposes from west to east: (1) a wide Permian peripheral foreland basin (pre-Uralian foredeep) which developed on the Paleozoic cover of Fennosarmatia; (2) the Suvanyak accretionary wedge; (3) the Zilair and Maksutovo nappes and complexes and (4) several island arc complexes including the Magnitogorsk island arc. The Magnitogorsk island arc monitors Devonian to Early Carboniferous subduction of an oceanic basin separating the arc from the Laurussian continent. The Maksutovo island arc comprises high-pressure rocks which formed within the subduction zone during continent-island arc collision.

Conclusion

All geological characters of Variscan regions are those of collision belts.
Two major plates: Laurussia in the north (with newly accreted Caledonian terranes along its southern margin) and Gondwana in the south (mainly Africa) converge with several microplates in between. Sequential collisions produced the huge landmass of Pangea.
Late Devonian and Early Carboniferous: Gondwana moved north and rotated clockwise. Laurussia moved north at a faster rate and began to rotate anticlockwise.
Late Carboniferous: major changes in plate movements as South America collided with southern North America. Gondwana began to rotate anticlockwise and "collided" with Laurussia, squeezing and rotating micro-plates caught in between.
The major thrusts with mafic-ultramafic rocks and HP metamorphism are superposed onto suture zones. One suture continues to the west of Galicia and perhaps in the Badajoz-Cordoba shear zone as the roots of the western Galician ophiolitic nappes.
Collision led to a fan-like profile with folds and thrusts facing outward toward the foreland basins.
The Variscan events may be explained by a logical sequence including:

- Consumption of an Early Paleozoic ocean during Late Ordovician and Silurian by intra oceanic subduction towards the NW (synthetic with the large thrust system) leading to obduction (Silurian, Early Devonian). The sense of subduction is inferred from vergence and nappe displacements.
- Collision during Middle to Late Devonian and progressive underthrusting of a southern (Gondwanian) salient below a northern continent during Early-Middle Carboniferous. Evidence for remnants of oceanic lithosphere is provided by geochemistry. Retrogression of initial high-pressure assemblages into intermediate and Barrovian type metamorphism and formation of anatectic granites occurred at this stage.

- Increasing intracontinental deformation took place while rising anatectic granites accompanied high temperature metamorphism. Migration of metamorphism and deformation from internal to external zones and the rise of many granitoids from the deeper parts of the thickened continental crust was pervasive. The arcuate form of the belt is acquired after collision by progressive impingement of the southern continental promontory into the northern continent. Intracontinental deformation results from the blocking of the subduction zone by underthrusting of continental crust.
- Continental thickening was followed by extension, marking a transition with opening of the Tethys Ocean.

Pangea with the Tethys oceanic bay in its eastern center. Due to Late Carboniferous and Permian dextral shear between Gondwana and Eurasia, the Tethys Ocean widened into a large bay extending from the proto-Pacific Ocean towards the west, and rifting started again. Late Paleozoic transgression prograded westwards forming a Tethyan shelf and reached the area of the future Alps, where corresponding deposits postdate formation of the Variscan basement, in the Late Carboniferous

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