Ber. Inst. Erdwiss. K.-F.-Univ. Graz	ISSN 1608-8166	Band 23	Valencia 2017
International Conodont Symposium 4	Valencia, 25-30th June 2017		

Geological features of Variscan Pyrenees

Pilar Clariana[1]

[1]Instituto Geológico y Minero de España, Unidad de Zaragoza; c/ Manuel Lasala 44, 9ºB; E-50006 Zaragoza, Spain; p.clariana@igme.es

Introduction

The Pyrenees are an ESE – WNW trending, Alpine cordillera built after the collision between the Iberian and Euro-Asian plates from Late Cretaceous to Early Miocene. This mountain belt extends 450 km between the Mediterranean Sea and the Atlantic Ocean but from a geological point of view the Pyrenean Orogen extends for more than 1000 km from Provenza (France) to the Cantabrian Mountains and their continental platform under the Cantabrian Sea (Alonso et al., 1996; Pulgar et al., 1996, 1997; Gallastegui, 2000). Neo-proterozoic to Cenozoic, rocks appear in this Alpine orogen. The pre-Cambrian and Paleozoic rocks are affected by variscan deformation and metamorphism and are outcropping in a large belt in the core of the cordillera. These rocks are flanked to the south and to the north by large outcrops of Mesozoic and Cenozoic rocks. The Alpine deformation gave rise to the development of E – W trend thrusts, which involved previously deformed pre-Cambrian and Paleozoic basement rocks. These thrusts caused shifts and rotations of large blocks of basement rocks with an Alpine deformation restricted to narrow bands and the development of a tectonic foliation represented mainly to west of the Pyrenees (Choukroune & Seguret, 1973; Autran y García-Sansegundo, 1996; Izquierdo-Llaval, 2014). This situation makes necessary to carry out a revision about main features of the Alpine Orogen as well as of Paleozoic of the Pyrenees and The Variscan Orogen of which pre-Mesozoic rocks were part.

The Variscan Orogen in the Iberian Peninsula

The European Variscan belt extends from the North of Bohemia (Bohemia Massif) in the East to the Iberian Peninsula in the west (Iberian Massif) and is interrupted by the Alpine orogenic front in both limits. Nevertheless, evidences about a greater extension of this belt have been found from The Urals in the east to the Appalachians – Mauritanides in the west (Julivert, 1983, 1996). The Variscan belt resulted from the collision between two supercontinents (Laurussia and Gondwana) giving rise to Pangea supercontinent later. This Cordillera has a bilateral geometry, which can be recognized when the Appalachians and The Iberia Massif are connected. In the most eastern part of the Iberian massif branch the thin-skinned tectonic is predominant and affect non-metamorphic rocks or low-grade metamorphic rocks ranging in age from Cambrian to Carboniferous. This branch borders with the orogen core area on the west where most granitoids and metamorphic rocks are located (Julivert, 1996; Pérez-Estaun et al., 2004).

Due to the opening of the Bay of Biscay some Western European outcrops of the Variscan orogen are included in the basement of more recent orogens, for example in the Pyrenees, or splited from the original position as the Iberian Massif, which exposed the most complete section of the European Variscan belt. Six tectonostratigraphic zones are distinguished in the Iberian Massif (Lotze, 1945; Matte, 1968; Julivert et al., 1972; Robardet, 1976; Farias et al., 1987; Arenas et al., 1988). These zones show an arched geometry continuing to the north of the Bay of Biscay in the Armorican Massif forming the Ibero-Armorican Arc. The inner core of the arc is formed by regions initially located in the most external parts of the belt, that is, the foreland, represented by the Cantabrian Zone, whereas the outer part of the arc consists of hinterland regions (West Asturien-Leonese Zone and Central-Iberian Zone) (Fig. 1). Different authors have proposed different hypothesis to explain the genesis of this arc (Brun y Burg, 1982; Martínez-Catalán, 1990; Ribeiro et al., 1995), which has been classified as a secondary orogenic arc or orocline according to Weil and Sussman (2004) classification (Gutiérrez-Alonso et al., 2008; Martínez-Catalan, 2011; Pastor-Galán, 2012). So, in this zone, the Variscan belt got their curvature after Variscan Orogeny. The Variscan basement of the Pyrenees and Catalonian Coastal Ranges would be the prolongation of the northern branch of the arc.

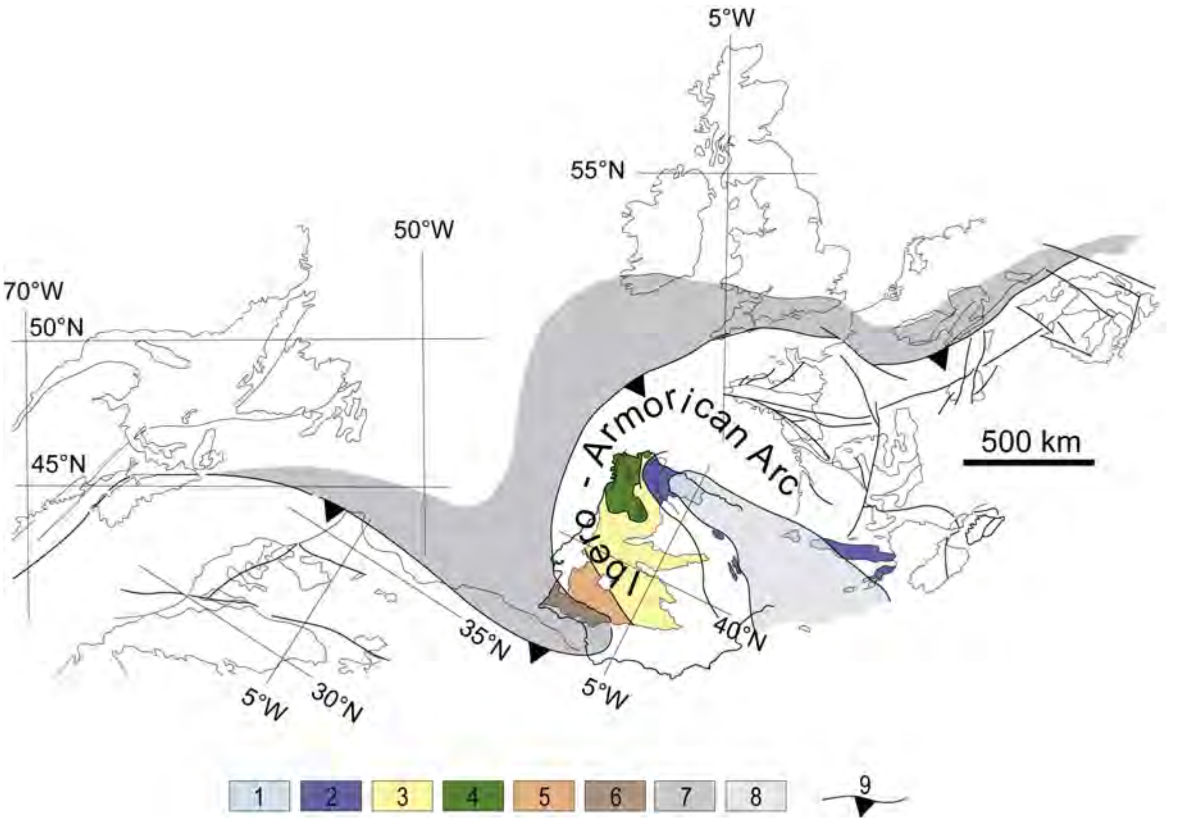


Figure 1. Location of the six tectonostratigraphic zones of the Iberian Massif whitin the Variscan Orogen in western Europe and North America (reconstruction of the Pangea in the area surrounding Iberia after Lefort, 1989). (1) Cantabrian Zone, (2) Western Asturian-Leonese Zone, (3) Central-Iberian Zone, (4) Galicia – Tras Os Montes Zone, (5) Ossa-Morena Zone, (6) Sudportuguesa Zone, (7) accretionary prism, (8) foreland fold and thrust belt & (9) Variscan front. Modified from Alonso et al. (2009). (Clariana, 2015).

The rocks that crop out in the northern branch of the arc formed by the Iberian Massif were deposited on the old continental margin of Gondwana. Nevertheless, in the southern part of the arc, within the Central-Iberian Zone, mafic and ultramafic rocks and ophiolites are represented constituting the Allochthonous Units which overthrust onto the Gondwana margin during the Variscan orogeny (Ries & Shackleton, 1971; Bard et al. 1980; Iglesias et al., 1983; Bastida et al., 1984; Vogel, 1984; Arenas et al., 1986; Matte, 1991). These features allowed Farias et al. (1987) to separate these rocks from the Central-Iberian Zone and to define the Galicia-Tras-os-Montes Zone (Fig. 1). According to Matte (1991) this zone represents fragments of the opposite continental margin involved in the Variscan orogeny. The root of this Allochthonous Complex could be located to the west of Galician coast and would be the prolongation of Badajoz – Córdoba Shear Zone.

Variscan Orogeny mainly produces the structure of Iberian Massif and other neighbouring variscan massifs but previous deformations have also been recognized. That is, the Pre-Cambrian rocks were deformed before development of basins and deposit of Paleozoic formations (Pérez-Estaun et al., 2004). The Pre-Variscan tectonic is recognizable in different areas of the Iberian Massif, Iberian Ranges and in the Pyrenees. Different unconformities have been observed in the Iberian Massif. A Lower Cambrian unconformity known in the regional geological literature as the "Cadomian or Asyntic Unconformity" (De Sitter, 1961; Matte, 1968; Marcos, 1973) which was also identified in the Iberian Ranges by Liñan & Tejero (1988). A Lower Ordovician unconformity (Díez-Balda et al., 1990; Pérez-Estaun et al., 1991) coeval to Lower Ordovician magmatic episode (Valverde-Vaquero & Dunning, 2000; Montero et al., 2007; Diez-Montes et al., 2010; Navidad y Castiñeiras, 2011) and finally the Late Ordovician Unconformity recognized both in the Iberian Massif and in the Pyrenees. This unconformity in the Pyrenees has been related to an extensional event (García-Sansegundo et al., 2004, 2011; Clariana, 2015). This extensional event is also supported by the presence of normal late Ordovician faults in the Eastern Pyrenees (Casas, 2010; Casas & Fernández, 2007).

The Paleozoic of the Pyrenees, The Pyrenean Axial Zone

The Paleozoic rocks of the Pyrenees crop out mainly in the Axial Zone which extends in East – West trend between the Cap de Creus to the East and Hecho and Aspe Valleys in the western Pyrenees where are covered by Mesozoic rocks. Moreover, the Paleozoic rocks also crop out in the North-pyrenean Massifs which are involved in alpine thrusts in the northern part of the cordillera, in the Nogueras Units in the southern part and in the Basques Massifs, which represent the westernmost Paleozoic rocks. The Axial Zone constitutes the basement of the Alpine Pyrenean Orogen. This basement was incorporated in alpine thrust sheets south-directed which also produced their uplift and rotation of previous variscan structures (García-Sansegundo, 2004). However, alpine age structures (folds and faults) are restricted to narrow bands. So, the structures observed in the Pyrenean Axial Zone are mainly of Variscan age (García-Sansegundo, 2004; Gil-Peña, 2004).

The stratigraphic succession of the Pyrenean Axial Zone spans from the Neoproterozoic to the Carboniferous although some isolated Permo-Triassic and Mesozoic rocks also occur. The pre-Cambrian, Cambrian and Ordovician rocks are characterized by siliciclastic successions that crop out normally in large-scale structures, such as gneiss metamorphic domes (Gil-Peña & Barnolas, 2004). These domes are affected by HT – LP metamorphism and can reach high-grade metamorphism conditions. Above, the Silurian shows homogeneous features throughout the Axial Zone while the Devonian exhibit significant facies variations. Both are frequently located in narrow E – W trend synclines and present low-grade metamorphism conditions. The Carboniferous is represented by varied lithology, so that the carbonate successions were deposited during the lower Carboniferous whereas the upper Carboniferous is characterized by sands and conglomerates which represent the Variscan syn-orogenic successions. Moreover, the late orogenic succession contains volcanic rocks that are considered post-orogenic by some authors (Mey et al., 1968). Finally, during the post-orogenic Permian, the sediments were deposited in small, isolated continental basins, which are bounded by extensional faults. Thus, the Permian rocks are heterogeneous and alternate with levels of volcanic rocks. As well as sedimentary rocks, Ordovician orthogneisses (Laumonier, 2004) and variscan granitoids are located in the Pyrenean Axial Zone (Fig. 2).

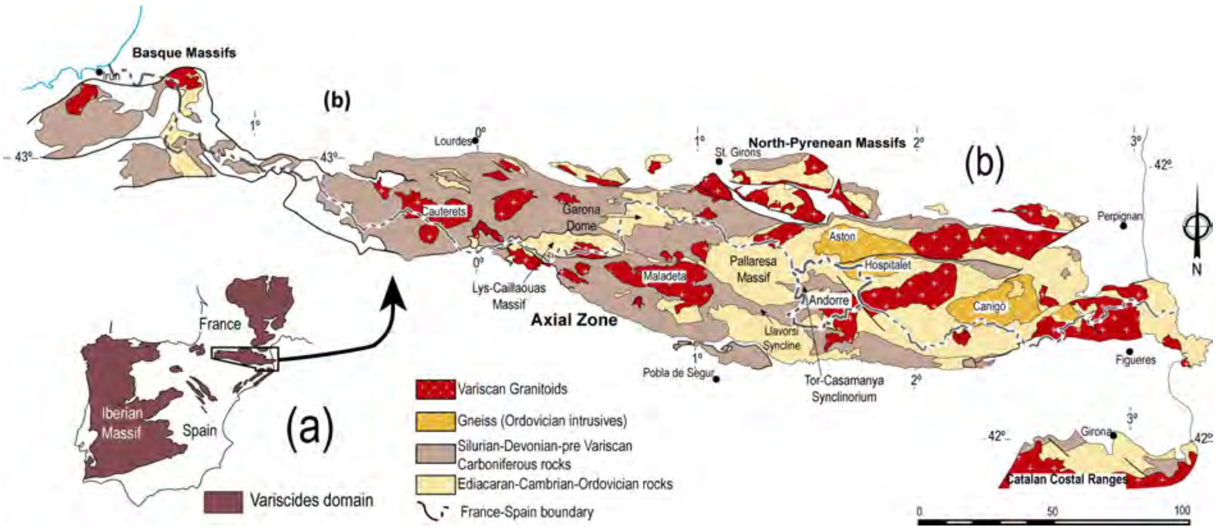


Figure 2. (a) Variscan outcrops of the Iberian Peninsula and southern France. (b) Geological map of the Paleozoic rocks of the Pyrenees.

The main lithostratigraphic features of the Upper Proterozoic and Paleozoic rocks that crop out in the Central Pyrenees are briefly described below.

The pre-Caradoc Succession

The pre-Upper Ordovician rocks consist mainly of monotonous alternation of quartzites and slates with some intercalations of limestone or microconglomerate without fossil remains. In the Pyrenean Axial Zone, Laumonier et al. (2004) studied the Cambro-Ordovician stratigraphy using the stratigraphic section of Cavet (1957) in the eastern Pyrenees. Laumonier et al. (2004) subdivided the pre-Caradoc succession of the eastern Pyrenees into two units. (i) The Canaveilles Group, which is the oldest stratigraphic unit and is built of a schis-greywacke sequence with interbedded limestones and volcanic rocks. The volcanic levels were dated at 580 Ma (Ediacaran age) using U – Pb radiometric data from zircons (Cocherie et al. 2005). (ii) The Jujols Group, which basically consists of an alternation of slate, sandstones and quartzites. Its base contains two olistostromes (Formation Tregura) related to a fast eustatic fall. Both Canaveilles and Jujols are short of fossils. In the central part of the Axial Zone (Pallaresa Massif, La Massana – Ribera de Cardos Anticline, Aston and Hospitalet Domes) the Canaveilles Group is only present bellow the Aston gneissic Dome and most outcrops correspond to the lower part of the Jujols group which was separated into three formations: (i) *Alos de Isil Fm*. characterized by an alternation of white grey sandstone and dark-grey slates with quartzitic horizons 10 to 20 m thick; (ii) *Lleret-Bayau Fm*. consisting of white limestones and black slates; (iii) *Alins Fm.* characterized by alternating white quarztzites and greenish grey slates (Laumonier et al. 2004). The Jujols group is assigned to Cambrian and Early – Middle Ordovician age (Laumonier et al. 2004).

The Late Ordovician

Upper Ordovician rocks lie unconformable on older pre-Caradoc succession (Santanach, 1972; Den BroK, 1989; García-Sansegundo & Alonso, 1989; García-Sansegundo et al. 2004; Muñoz & Casas, 1996; Casas & Fernández, 2007). Hartevelt (1970) made the first detailed stratigraphic study on the Upper Ordovician succession in the Segre Valley. Later, other authors described these rocks in different localities of the central Pyrenees (Van den Eeckhout, 1986; García-Sansegundo & Alonso, 1989; García-Sansegundo et al. 2004; Poblet, 1991; Palau, 1998; Gil-Peña et al. 2000). Many of these authors took as a reference the most complete Upper Ordovician succession described by Hartevelt (1970). This author distinguished from bottom to top, the following stratigraphic formations: (1) the *Rabassa Fm.* characterized by conglomerates with sandstone and slate levels intercalated; (2) *Cava Fm*. consisting of alternating greywackes and slates with volcanic intercalations, dated as Late Caradoc – Ashgill on the basis of brachiopods data (Gil-Peña et al., 2004); (3) *Estana Fm*. composed of calcareous shales, limestones and nodular limestones; Middle Ashgill age according to Sanz-López & Sarmiento (1995); (4) *Ansovell Fm*. characterized by poorly bedded dark slates with scarce siliciclastic levels, dated as Middle - Upper Asghill because of its stratigraphhical position between the dated under-and –overlain formations; (5) *Bar Fm*. consists of quartzites with late Asghill age (Hartevelt, 1970). In some regions not all these formations occur and in others the lower part of the Upper Ordovician succession is basically a package of siliciclastic levels denominated La Massana Fm. by Van den Eeckhout (1986).

Silurian

The Silurian is represented by black shales passing into limestones beds and nodules in the upper part. The maximum thickness of this unit is uncertain because of the frequent occurrences of décollement structures, which often add or subtract sections. Degardin (1988) made a biostratigraphic and paleogeographic study of the Pyrenean Silurian identifying more than eighty species corresponding to thirteen genera of graptolites which represent most of the biozones from Llandovery to Early Ludlow. To the top, the conodonts found in the limestone levels yielded a Telychian – Lochkovian age. Thus, a reasonably complete Silurian succession has been preserved in the Pyrenees. Although the Ordovician – Silurian boundary is not defined clearly because the lower Rhuddanian has not identified by paleontological data and the lowermost part of the black shales is frequently tectonized. Nevertheless, in the central Pyrenees the typical Hirnantian glaciomarine sediments could correspond to a stratigraphic unconformity and the uppermost Ordovician and the Bar quartzite could contain the Ordovician – Silurian boundary (Gil-Peña, 2001). On the other hand, in the central Pyrenees the Silurian – Devonian boundary is rather precisely defined by conodont assemblages (Valenzuela-Ríos, 1994).

Devonian

The Devonian rocks in the central Pyrenees exhibit significant facies variations across the different structural units. The first systematic stratigraphic studies of Devonian system in this zone were made during the sixties and seventies by geologists of Leiden University (summarized by Zwart, 1979 and references therein). These authors defined *facies areas* characterized by different stratigraphic successions for all Pyrenean Devonian. The initial areas defined and the different modifications introduced by the Dutch geologists can be observed in Figure 3.

AUTHORS	DEVONIAN OF THE PYRENEES FACIES AREAS						
Mey, 1967	Southern Facies Area	Sierra Negra Subfacies Area Baliera Subfacies Area Renanué Subfacies Area Compte Subfacies Area	Central Facies Area	Valle de Aran Subfacies Area Pla dels Estanys Subfacies Area	Northern Facies Area	Westhern - Northpyrenean Facies Area	North Subarea Central Subarea Southwest Subarea
Boersma, 1973	Southern Facies Area	Sierra Negra s.l. Subfacies Area (Sierra Negra s.s. Area; Baliera Area) Renanué Subfacies Area Compte Subfacies Area	Central Facies Area		Northern Facies Area	Westhern - Northpyrenean Facies Area	
Zwart, 1979	Southern Facies Area	Sierra Negra s.l. Subfacies Area (Sierra Negra s.s. Area; Baliera Area) Compte Subfacies Area	Central Facies Area		Northern Facies Area	Westhern - Northpyrenean Facies Area	

Figure 3. Comparison table of the Devonian facies areas defined by the Leiden geologist in the Pyrenean Axial Zone (modified from Clariana, 2015).

Most of these *facies areas* are bounded by both variscan and alpine tectonic accidents restraining their stratigraphic regional utility. This fact together with biostratigraphic advances led some authors to an attempt of integrating the different stratigraphic successions in correlation diagrams (García-Alcalde et al. 2002; Sánz-López, 2004; Valenzuela-Ríos & Liao, 2006). Recent studies (García-Sansegundo et al. 2011) have distinguished three main Devonian – Carboniferous (pre-Stephanian) domains. *A Devonian northern and eastern domain* characterized by limestones, slates and marls, with development of nodular limestone in the Middle and Late Devonian. This domain represents setting with hemipelagic rocks deposited in moderately deep platform and includes *the Compte Facies*, *the Northern Facies* and *the Northpyrenean Facies* defined by Zwart (1979). *The Devonian* *western and southern domain* shows Lower Devonian rocks consist of shales, marls and limestones with local intrusions of hypabyssal rocks. Reefal limestone to the west and black shales to the east characterize the Middle Devonian and the Upper Devonian rocks consist of limestones. This domain includes the *Sierra Negra Facies* and *Baliera Facies* defined by Mey (1967) and can be interpreted as deposited in a shallow platform. Finally, the third domain is located between previous domains and corresponds to *the Central domain* which shows a thick siliciclastic succession of Middle and Late Devonian age. This domain is represented by the Central Facies defined by Kleinsmiede (1960) and corresponds to an elongated and deep region within the central part of the Devonian platform filled in by turbidites.

Carboniferous

When the pre-Stephanian Carboniferous sequence is more complete, it is composed of a lower part characterized by nodular red limestones and cherts underlying black limestones that reach Bashkirian ages (Perret, 1993). The upper part corresponds to Culm facies (synorogenic succession), formed of mainly terrigenous turbidite deposits (sandstones, greywackes, slates and conglomerates). In the Central and Western Pyrenees, the Culm facies deposited contemporaneously with the black limestones.

The Stephanian Carboniferous rocks occur in scattered outcrops and lie unconformable over eroded older rocks through a marked angular unconformity (Colmenero et al. 2002). These rocks consist of breccias, volcanic rocks, shales, conglomerates, sandstones and some coal and limestone beds intercalated. This succession was deposited in alluvial and lacustrine environments within transtensional basins that were bordered by volcanic cones (Lucas & Gisbert-Aguilar, 1995).

Structural features of the Pyrenean Axial Zone

The structures of the Paleozoic rocks of the central Pyrenees and their origin have been a matter of debate between geologists from different schools. According to most authors the Variscan orogeny gave rise to a polyphasic deformation and some of the structures recognized in the Paleozoic rocks were formed during the superimposed Alpine orogeny. However, the number of variscan deformation phases and the representation of alpine structure are controversial aspects nowadays (Seguret & Proust, 1968, Zwart, 1979; Matte, 1969; Clint et al., 1970; Muller & Roger, 1977; Soula, 1982; Soula et al., 1986; Vissers, 1992). Two structural domains have been classically distinguished in the Pyrenean Axial Zone according to their different main Variscan cleavage disposition and metamorphic grade: “infrastructure” and “suprastructure” (Zwart, 1963). Most authors agree that in the “infrastructure” the main cleavage is subhorizontal and usually associated with high temperature metamorphism, whereas in the “suprastructure”, the cleavage is subvertical and was generated under low-grade metamorphic conditions. However, the relative age of the main structures characterizing each domain and their main structural features has been extensively discussed (Seguret & Proust, 1968; Matte, 1969; Van den Eeckhout & Zwart, 1988; Vissers, 1992). Moreover, the geological setting invoked to explain the origin of variscan structures, metamorphism and magmatism is also a controversial matter (Wickham & Oxburgh, 1985; 1986; Soula et al., 1986; Matte & Mattauer, 1987; Van den Eeckhout & Zwart, 1988; Pouget et al., 1989; Pouget, 1991; Vissers, 1992; Poblet & Casas, 1993). In the Central Pyrenees structural units belonging to both domains “infrastructure” (Aston, Hospitalet, Garona domes) and “suprastructure” (Tor-Casamanya syncline, La Massana anticline, Llavorsí syncline, Vall d’Aran syncline, Segre unit) are present, inclusive the transitional zone between both domains can be observed. The structural studies made the last years in the Central Pyrenees have allowed proposing a deformation sequence for this zone and to explain the distinction between domains, as well as interpret them within the Variscan belt frame.

Geological mapping together with meso and microstructural studies have allowed the recognition of a slaty cleavage (S_E), only present in the pre-Caradoc rocks although folds associated with this cleavage have not been identified (García-Sansegundo & Alonso, 1989; García-Sansegundo et al., 2004; Clariana & García-Sansegundo, 2009; Clariana & García-Sansegundo, 2016). These data together with other from different Paleozoic sectors of the Pyrenees, which support an extensional event before and during the Upper Ordovician, for example: (i) the existence of an angular unconformity, the late Ordovician rocks lie unconformable on the underlying series (Domo del Garona), (ii) Zn-Pb stratiform or stratabound ore deposits of late Ordovician – early Devonian age, related to a continental pre-Variscan extension (Lys-Caillaouas massif), and (iii) the presence of late Ordovician volcanic rocks (Casas, 2010; Navidad et al. 2010), allowed to consider the S_E cleavage as pre-variscan and related to an extensional origin.

Besides, three main variscan deformation events have been identified in Central Pyrenees (D1, D2 y D3) (García-Sansegundo et al., 2011; Clariana, 2015; Clariana & García-Sansegundo, 2016). The *deformation event D1* is characterized by E – W trending, recumbent to inclined north verging folds which are developed at all scales (Casas & Poblet, 1989; García-Sansegundo & Alonso, 1989; Casas et al., 1989; Cirés et al. 1990; García-Sansegundo 1990, 1992, 1996; Poblet, 1991; Clariana & García-Sansegundo, 2009, 2016; Clariana, 2015). These folds are well developed and tighter in some regions (Garona Dome, Lys-Caillaouas massif, Pallaresa massif, Aston and Hospitalet domes) where pre-Silurian rocks which can be affected by high-grade metamorphism crop out. In these zones, an axial plane foliation is associated with D1 folds (S1) and is the dominant foliation. In pre-Ordovician rocks, S1 cleavage consists of a crenulation cleavage of the pre-Variscan cleavage. In low-grade metamorphic regions, S1 corresponds to slaty cleavage and it may even be absent. The *deformation event D2* includes E – W trending upright or south verging folds developed from millimetre to kilometre scale (Casas & Poblet, 1989; Casas et al., 1989; Cirés et al. 1990; García-Sansegundo 1990, 1992, 1996; Poblet, 1991; Clariana & García-Sansegundo, 2009, 2016; Clariana, 2015). D2 folds verge to the south and exhibit a subvertical to moderately north dipping axial plane cleavage (S2) which is the main cleavage in low-grade metamorphic areas (Valle de Aran syncline, Tor-Casamanya Syncline, Llavorsí Syncline, Segre Unit) and corresponds to a crenulation cleavage, deforming S1. However, D2 structures are scarce in areas composed of high-grade metamorphic rocks. During the D2 event, E – W trending, south-directed thrusts were developed. The oldest thrusts merge into detachment levels located within the Silurian shales, and the youngest, out of sequence thrusts, with deeper detachments located within pre-Caradoc rocks. The crosscutting relationships between them and D2 folds have allowed interpreting both structures as approximately coeval. The existence of two detachment levels gives rise to a more gradual transition from deeper levels where subhorizontal structures are predominant to superficial levels characterized by subvertical structures (Clariana, 2015; Clariana & García-Sansegundo, 2016). This is a coherent explanation about the gradual transition between “infrastructure” and “suprastructure” proposed by previous authors for the Central Pyrenees. Finally, the *deformation event D3* is characterized by ductile shear structures. These structures are restricted to the contact metamorphic aureoles and in some areas, for example the Hospitalet Dome, the crystallization – deformation relationships indicate that the D3 event was coeval with the main metamorphic episode which happened during late stages of Variscan orogeny. Moreover, this metamorphic episode would be linked to the intrusion of igneous masses, for example the Ax-les-Thermes granite dated at 306,2 ± 2,3 Ma (Denèle et al., 2014).

The structural and metamorphic features exposed above suggest that the Variscan deformation in the Central Pyrenees mostly occurred during a compressional tectonic setting in which folds and thrusts systems developed giving rise to the crustal thickening of the Variscan cordillera in this region. Subsequently, in the last stages of the Variscan deformation, an extensional deformation event, whose effects are only observed close to the gneissic domes or igneous masses, occurred which is probably related to emplacement of late granites in this zone (Clariana, 2015).

Some structures affecting the Paleozoic rocks formed during the Alpine orogeny of Late Mesozoic – Tertiary age that is responsible for the formation of the Pyrenees. So, some thrusts, folds and associated crenulation cleavages affect both Paleozoic and post-Paleozoic rocks. On the other hand, the Alpine orogeny produced reactivation of thrusts and faults originated during the Variscan orogeny or the Mesozoic extensional stage. In addition, there is a “progressive” tilting of the S2 cleavage from steeper attitudes to the north to gentler dips in the southern part consistent with the overall geometry of the Pyrenean belt (Parish, 1984).

The structural, metamorphic and magmatic features of Variscan age recognized in the Paleozoic rocks of the Central Pyrenees have allowed proposing a zonation for he Pyrenean Axial Zone (foreland southwards of the hinterland) (García-Sansegundo et al., 2011). So, this proposal supports that the Pyrenean Axial Zone can be related to the north branch of the Ibero-Armorican or Asturian Arc.

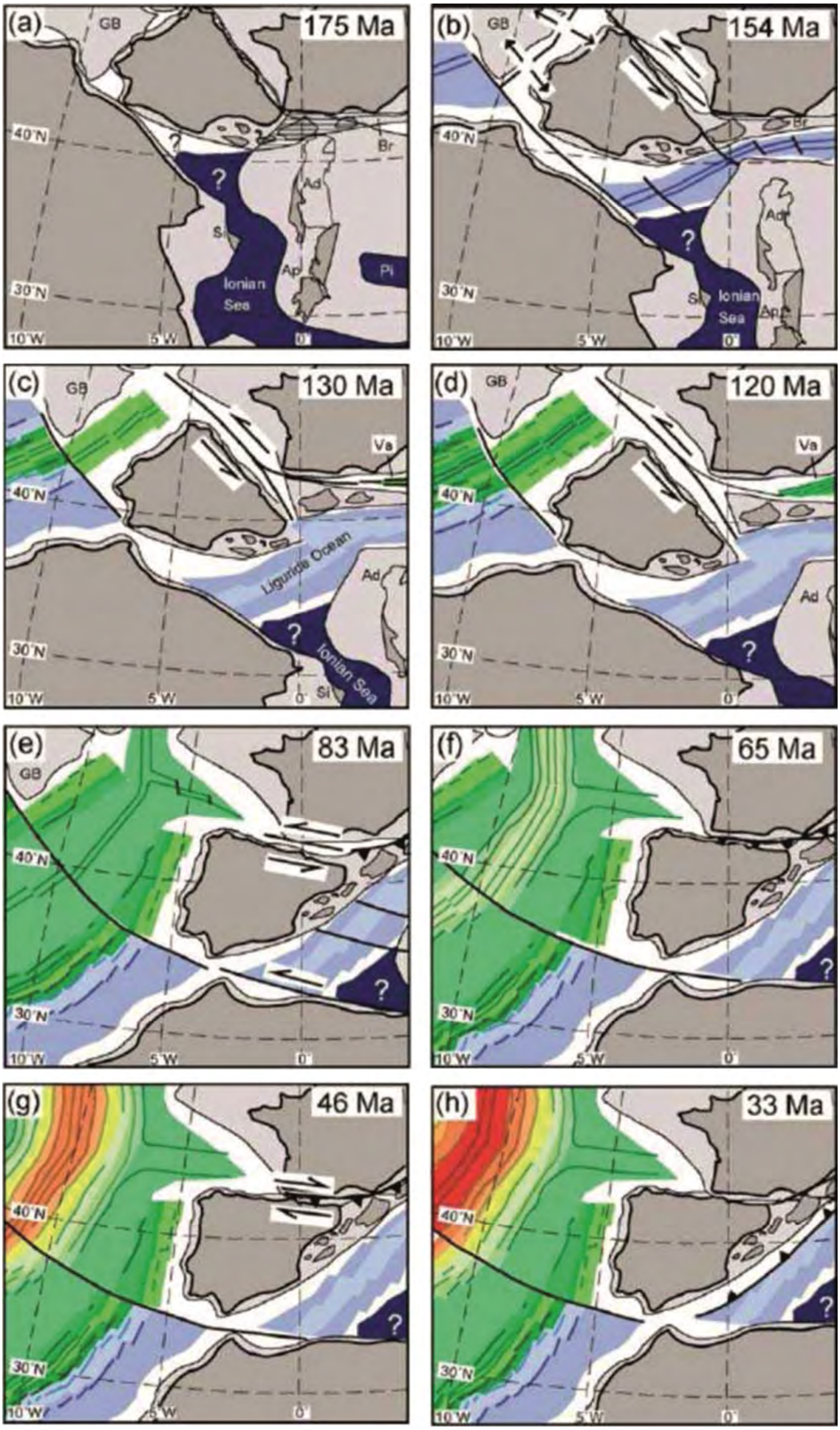
The Pyrenean Orogen

The Pyrenees represents an example of continental collisional orogen characterized by a folds and thrusts system and without development of typical hinterland where deformations linked to metamorphism and magmatism can be developed. Consequently, pre-alpine features have been preserved. This Orogen resulted from Mesozoic-Cenozoic interaction between the Iberian and Euro-Asian plates. A Key aspect and closely related to the origin and evolution of the Pyrenean Orogen was the opening of the Bay of Biscay linked to the north Atlantic opening and the subsequent rotation of the African plate during Cretaceous and Tertiary times producing a general compression along the Tethys margins (Fig. 4). In this setting, the tectonic inversion of the Triassic-Cretaceous extensional to transtensional rift systems took place.

The Pyrenees constitutes an asymmetric double verging orogen, which has been classically divided into three ONO – ESE trending zones (Mattauer, 1968): *North-Pyrenean Zone*, *Axial Zone* and *South-Pyrenean Zone*. The *North-Pyrenean* and *South-Pyrenean zones* are mainly composed of Mesozoic and Cenozoic rocks and the *Axial Zone* consists of Paleozoic rocks, which form the core of the mountain range. In the *North-Pyrenean Zone* north-directed thrusts involve basement and cover rocks. Variscan basement forms outcrops as the North Pyrenean massifs and Basque Massifs and the cover is represented by thick successions of Mesozoic rocks. Its northern limit is established in the *North-Pyrenean frontal thrust,* which covers Cenozoic sediments of the Aquitania basin. The southern border of this zone corresponds to the *North Pyrenean Fault*. The area of the *North Pyrenean Fault* is characterized by thermal metamorphism affecting pre-Albian rock, presence of mantle rocks (lherzolites) and Cretaceous magmatism and constitutes the boundary with the *Axial Zone*. This last zone is the vast outcrop of uplifted Variscan basement with south verging structures, related to Alpine thrusting which produced an antiformal stack (Fisher, 1984: Déramond et al. 1985; Willians, 1985; Muñoz, 1992; Vergés et al., 1995; Teixell, 1998). These Alpine thrusts overlap the previous Variscan structures bring about greater structural complexity to rocks of the Axial Zone. Post-variscan successions lie unconformable on Paleozoic basement rocks and extend south to the *South Pyrenean frontal thrust* located in the border with the Ebro basin. These cover rocks constitute the *South-Pyrenean Zone*. In this zone south-directed thrusts involved basement and, mainly, Mesozoic and Cenozoic rocks. The South-Pyrenean Zone is divided into Eastern, Central and Western Zones delimited by structural alignments (Segre, Cinca and Pamplona). *The Eastern South-Pyrenean Zone* is located between the Mediterranean Sea and the Segre river structural alignment. Here the South-Pyrenean Zone is composed of a narrow band of Mesozoic and Cenozoic rocks; the *Central South-Pyrenean Zone* is situated between the Segre river and the Cinca river structural alignments. Three main thrust sheets characterized this Zone (Bóixols, Montsec and Sierras Marginales). Finally, the *Western South-Pyrenean Zone* includes the Jaca-Pamplona Basin bounded by Pamplona fault (to the W) and the Cinca structural alignment (to the E). This zone is mainly constituted by sin-orogenic sequences of the Jaca-Pamplona basin (Barnolas & Pujalte, 2004).

The crustal and lithospheric structures of the Pyrenees have been constrained by different geophysical techniques standing out the deep seismic reflection profiles, mainly the ECORS Pyrenees profile (ECORS – Pyrenees, Choukroune et al., 1989; ECORS – Arzacq, Daignières et al., 1994) and the ESCIN programme (ESCIN – 2, Pulgar et al., 1996). The main result of these seismic surveys is the demonstration of the subduction of the Iberian plate below the European plate.

Figure 4. WesternTethys reconstruction since Middle Jurassic using rotation parameters for Africa, Iberian and Europe (after Rosenbaum et al., 2002 and references therein).



(a)
175 Ma
GB
40°N
Br
Ad
Si
Ap
Pi
Ionian Sea
30°N
10°W
5°W
0°
(b)
154 Ma
GB
40°N
Br
Ad
Si
Ionian Sea
Ap
30°N
10°W
5°W
0°
(c)
130 Ma
GB
Va
40°N
Liguride Ocean
Ad
Ionian Sea
Si
30°N
10°W
5°W
0°
(d)
120 Ma
GB
Va
40°N
Ad
30°N
10°W
5°W
0°
(e)
83 Ma
GB
40°N
30°N
10°W
5°W
0°
(f)
65 Ma
40°N
30°N
10°W
5°W
0°
(g)
46 Ma
40°N
30°N
10°W
5°W
0°
(h)
33 Ma
40°N
30°N
10°W
5°W
0°

In the Central Pyrenees the ECORS – Pyrenees profile shows an antiformal stacks compose of three thrust sheets: Nogueras, Orri and Rialp sheets (Muñoz, 1992) (Fig. 5). This thrusting throughout the crust and upper mantle generated the thickening of the Pyrenean crust and uplifting of Paleozoic basement in the Axial Zone and a fan-like thrust pattern in the crust. From ECORS – Pyrenees section a total shortening of 100 km (Roure et al., 1989) and 150 – 165 km (Muñoz, 1992; Beaumont et al., 2000) was proposed. This disparity is due to diverse interpretations regarding the subcrop of the Mesozoic cover below the South-Pyrenean basement thrusts.

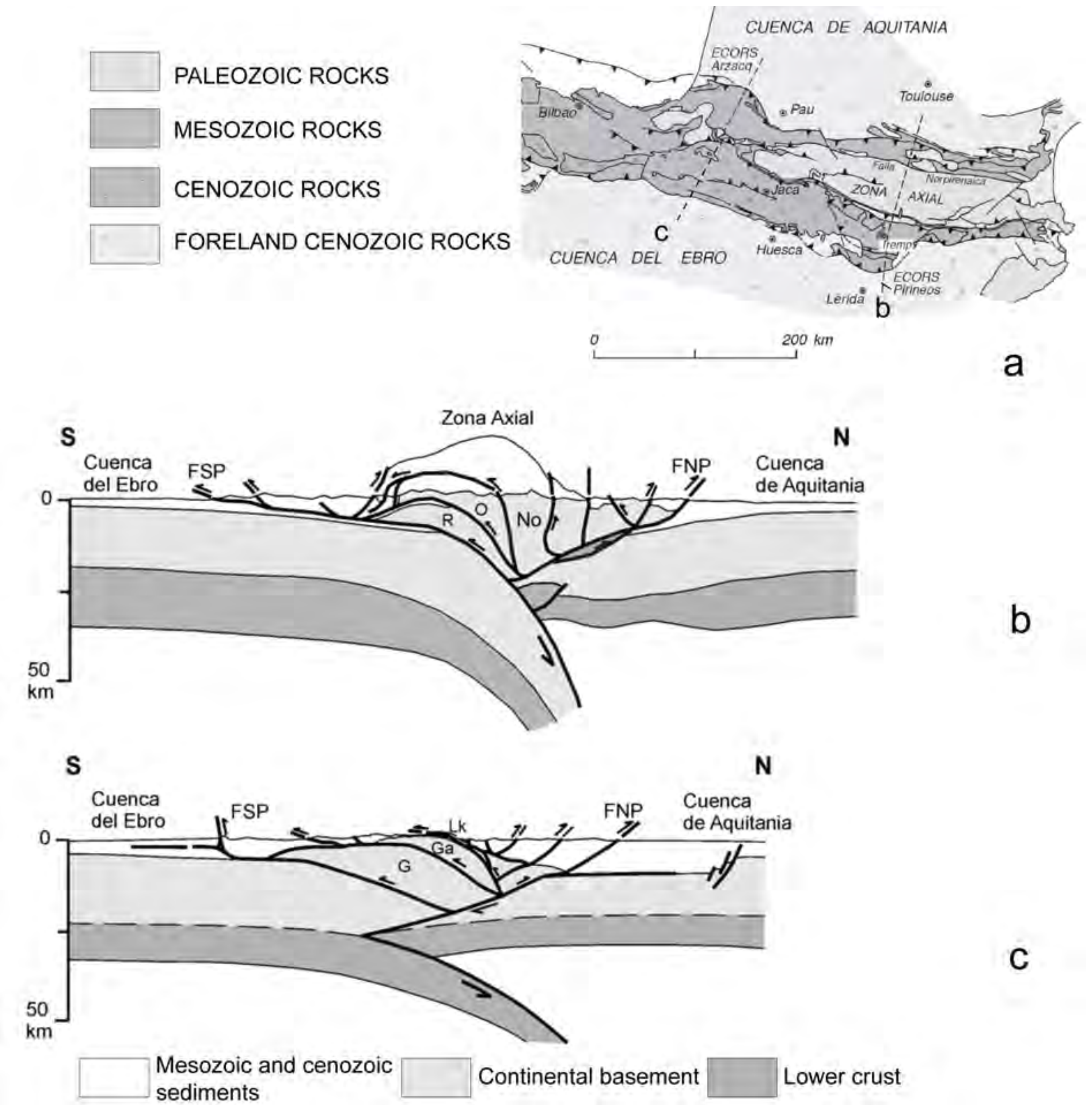


Figure 5. (a) Structural sketch of the Pyrenees with location of two crustal-scale cross sections of the Pyrenees based on seismic data combined with gravity (modified from Teixell, 2000). (b) ECORS-Pyrénées (Muñoz, 1992; Berástegui et al. 1993). R, O, No: Rialp, Orri and Nogueres sheets. (c) ECORS-Arzacq (Teixell,1998). G, Ga, Lk: Guarga, Gavarnie and Lakora sheets.

References

ALONSO, J.L., PULGAR, J.A., GARCÍA-RAMOS, J.C. & BARBA, P. (1996): Tertiary basins and Alpine tectonics in the Cantanbrian Mountains (NW Spain) - In: FRIEND, P.F. & DABRIO, C.J. (eds): Tertiary Basins of Spain. The Stratigraphic Record of Crustal Kinematics. - Cambridge University Press, Cambridge: 214-227.

ARENAS, R., GIL IBARGUCHI, J.I., GONZÁLEZ LODEIRO, F., KLEIN, E., MARTÍNEZ CATALAN, J.R., ORTEGA GIRONES, E., PABLO MACÍA, J.G. DE & PEINADO, M. (1986): Tectonostratigraphic units in te complexes with mafic and related rocks of the NW of the Iberian Massif. - Hercynica, 2: 87-110.

ARENAS, R., FARIAS, P. & GALLASTEGUI, G. (1988): Características geológicas y significado de los dominios que componen la Zona de Galicia-Tras-Os-Montes. - Congreso Geológico de España, Granada, 2: 75-84.

AUTRAN, A. & GARCÍA-SANSEGUNDO, J. (1996): Tectonique hercynienne. Carte structurale. - In: BARNOLAS, A. & CHIRON, J.C. (eds): Synthèse géologique at géophysique des Pyrénées, vol 1. BRGM - ITGE, Orléans - Madrid.

BARD, J.P., BURG, J.P., MATTE, Ph. & RIBEIRO, A. (1980): La Chaine Hercynienne d'Europe occidentale en termes de Tectonique des Plaques. - In: Géologie de l'Europe, du Précambrien aux basins sédimentaires post-Hercyniennes. - Mémories du Bureau de Recherches Géologiques et Minières, 108: 233-246.

BARNOLAS, A. & PUJALTE, V. (2004): La Cordillera Pirenaica. Definición, límites y división. - In: VERA, J.A. (ed.): Geología de España. SGE - IGME, (Madrid): 233-341.

BASTIDA, F., MARCOS, A., MARQUÍNEZ, J., MARTÍNEZ-CATALÁN, J.R., PÉREZ-ESTAÚN, A. & PULGAR, J.A. (1984): Mapa y memoria de la hoja nº 1 (La Coruña) del Mapa Geológico de España a escala 1:200000. - IGME. Madrid.

BEAUMONT, C., MUÑOZ, J.A., HAMILTON, J. & FULLSACK, P. (2000): Factors controlling the Alpine evolution of the Central Pyrenees inferred from a comparison of observations and geodynamical models. - Jour. Geophys. Res. 105(B4): 8121-8145.

BRUN, J.P. & BURG, J.P. (1982): Combined thrusting and wrenching in the Ibero-Armorican Arc – A corner effect during continental collision. - Earth and Planetary Science Letters, 61(2): 319-332.

CASAS, J.M. (2010): Ordovician deformations in the Pyrenees: new insights into the significance of pre-Variscan ("sardic") tectonics. - Geol. Mag., 147: 647-689.

CASAS, J.M. & POBLET, J. (1989): Essai e restitution de la déformation dans une zone avec plis et chavauchements: le "synclinal de Llavorsí dans les Pyrénées centrales (Espagne). - C. R. Acad. Sci. Paris, 308, II: 427-433.

CASAS, J.M., DOMINGO, F., POBLET, J. & SOLER, A. (1989): On the role the Hercynian and Alpine thrusts in the Upper Paleozoic rocks of the Central and Eastern Pyrenees. - Geodinamica Acta, Paris, 3, 2: 135-147.

CASAS, J.M. & FERNÁNDEZ, O. (2007): On the Upper Ordovician unconformity in the Pyrenees: New evidence from the La Cerdanya area. - Geologica Acta, 5, 2: 193-198.

CAVET, P. (1957): Le Paléozoïque de la zone axiale des Pyrénées orientales françaises entre le Roussillon et l'Andorre (étude stratigraphique et paléontologique). - Bull. Serv. Carte géol. France, Paris, 254, 55: 303-518.

CHOUKROUNE, P. & SEGURET, M. (1973): Carte structurale des Pyrénées, 1/500000. Université de Montpellier – ELF Aquitaine.

CHOUKROUNE, P. & ECORS TEAM (1989): The ECORS deep seismic profile reflection data and the overall structure of an orogenic belt. - Tectonics, 8: 23-39.

CIRÉS, J., ALÍAS, G., POBLET, J. & CASAS, J.M. (1990): La estructura del anticlinal de La Massana (Hercínico del Pirineo central). - Geogaceta, 8: 42-44.

CLARIANA, P. (2015): Estratigrafía, estructura y su relación con el metamorfismo de la Zona Axial pirenaica en la transversal del Noroeste de Andorra y comarcas del Pallars Sobirá y el Alt Urgell (Lleida). - Tesis doctoral, Universidad de Oviedo: 190 pp.

CLARIANA, P. & GARCÍA-SANSEGUNDO, J. (2009): Variscan structure in the Eastern part of the Pallaresa massif Axial Zone of the Pyrenees (NW Andorra). Tectonic implications. - Bull. Soc. géol. France, 180: 501-511.

CLARIANA, P. & GARCÍA-SANSEGUNDO, J. (2016): Caracterización de la transición estructural entre unidades metamórficas y no metamórficas en el Paleozoico del Noroeste de Andorra, parte central de la Zona Axial pirenaica. - Geotemas, 16(1): 45-48.

CLIN, M., HEDDEBAUT, C., MIROUSE, R., MULLER, J., ROGER, P. & WATERLOT, M. (1970): Le cycle hercynien dans les Pyrénées. - Annales de la Société Géologique du Nord: 253-276.

COCHERIE, A., BAUDIN, T., AUTRAN, A., GUERROT, C., FANNING, M.C. & LAUMONIER, B. (2005): U-Pb zircon (ID – TIMS and SHRIMP) evidence for the early Ordovician intrusion of metagranites in the late Proterozoic Canaveilles Group of the Pyrenees and the Montagne Noire (France): new U-Pb zircon datings. - Bull. Soc. géol. France, 176: 269-282.

COLMENERO, J.R., FERNÁNDEZ, L.P., MORENO, C., BAHAMONDE, J.R., BARBA, P., HEREDIO, N & GONZÁLEZ, F. (2002): Carboniferous. - In: GIBBONS, W & MORENO, M.T. (eds): The Geology of Spain. - Geological Society, London: 93-116.

DE SITTER, L.U. (1961): Le Précambrien dans la chaîne cantabrique. - Compte Rendu sommaire de séances de la Société Géologique de France, 9: 253-254.

DEGARDIN, J.M. (1988): Le Silurien des Pyrénées. Biostratigraphie. Paléogéographie. - Soc. Geol. Nord, publ. 15: 355 pp.

DAIGNIÉRES, M., SEGURET, M., SPECHT, M. & ECORS TEAM (1994): The Arzacq – Western Pyrenees ECORS Deep Seismic Profile. - In: MASCLE, A. (ed.): Hydrocarbon and petroleum geology of France Springer: 199-208.

DEN BROK, S.W.J. (1989): Evidence for pre – Variscan deformation in the Lys Caillaouas area, Central Pyrenees, France. - Geologie en Mijnbouw, 68: 377-380.

DENÈLE, Y., LAUMONIER, B., PAQUETTE, J.L., OLIVIER, P., GLEIZES, G. & BARBEY, P. (2014): Timing of granite emplacement, cristal flow and gneiss dome formation in the Variscan segment of the Pyrenees. - In: SCHULMANN, K., MARTÍNEZ-CATALÁN, J.R., LARDEAUX, J.M., JANOUSÊK, V. & OGGIANO, G. (eds): The Variscan orogeny: Extent, Timescale and the Formation of the European Crust. - Geol. Soc. London Spec. Pub., 405: 265-287.

DERAMOND, J., GRAHAM, R.M., HOSSACK, J.R., BABY, P. & CROUZET, G. (1985): Nouveau modèle de la chaîne des Pyrénées. - C. R. Acad. Sci., Paris, 301: 1213-1216.

DÍEZ BALDA, M.A., VEGAS, R. & GONZÁLEZ-LODEIRO, F. (1990): Central-Iberian Zone. Autochtonous sequences. Structure. - In: DALLMEYER, R.D. & MARTÍNEZ-GARCÍA, E. (eds): Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin: 172-188.

DIEZ-MONTES, A., MARTÍNEZ-CATALÁN, J.R. & BELLIDO MULAS, F. (2010): Role of Ollo de Sapo massive felsic volcanism of NW Iberia in the Early Ordovician dynamics of northern Gondwana. - Gondwana Research, 17(2-3): 363-376.

FARIAS, P., GALLASTEGUI, G., GONZÁLEZ-LODEIRO, F., MARQUÍNEZ, J., MARTÍN-PARRA, L.M., MARTÍNEZ-CATALAN, J.R., PABLO-MACÍA, J.G. & RODRÍGUEZ-FERNÁNDEZ, L.R. (1987): Aportaciones al conocimiento de la litoestratigrafía y estructura de Galicia Central. - Mem. Mus. Lab. Min. Geol. Fac. Ciencias do Porto, 1: 411-413.

FISCHER, M.W. (1984): Thrusts tectonics in the north of the Pyrenees. - Jour. Structur. Geol., 6(6): 721-726.

GALLASTEGUI, J. (2000): Estructura cortical de la Cordillera y Margen Continental Cantábricos: Perfiles ESCI-N. - Trabajos Geol. Univ. Oviedo, 22: 9-234.

GARCÍA-ALCALDE, J.L., CARLS, P., PARDO ALONSO, M.V., SANZ-LÓPEZ, J., SOTO, F., TRUYOLS-MASSONI, M. & VALENZUELA-RÍOS, J.I. (2002): Devonian. - In: GIBBONS, W & MORENO, M.T. (eds): The Geology of Spain. - Geological Society, London: 67-91.

GARCÍA-SANSEGUNDO, J. (1990): Structure of the Paleozoic in the Aran Valley, Axial Zone, central Pyrenees. - Bull. Soc. géol. France, Paris (8), VI, núm. 2: 229-239.

GARCÍA-SANSEGUNDO, J. (1992): Estratigrafía y estructura de la Zona Axial pirenaica en la transversal del Valle de Aran y de la Alta Ribagorça. - Publicaciones especiales del Boletín Geológico y Minero, 167 pp.

GARCÍA-SANSEGUNDO, J. (1996): Hercynian structure of the Axial Zone of the Pyrenees: the Aran Valley cross-section (Spain - France). - J. Struct. Geol., 18: 1315-1325.

GARCÍA-SANSEGUNDO, J. (2004): Estructura varisca en los Pirineos. - In: VERA, J. (ed.): Geología de España, SGE-IGME. Madrid: 254-258.

GARCÍA-SANSEGUNDO, J. & ALONSO, J.L. (1989): Stratigraphy and structure of the southeastern Garona Dome. - Geodinámica Acta, Paris, 3, 2: 127-134.

GARCÍA-SANSEGUNDO, J., GAVALDÁ, J. & ALONSO, J.L. (2004): Preuves de la discordance de l' Ordovicien supérieur dans la Zone Axiale des Pyrénées: exemple du Dôme de la Garonne (Espagne, France). - Comptes Rendus Geosciences, 336: 1035-1040.

GARCÍA-SANSEGUNDO, J., POBLET, J., ALONSO, J.L. & CLARIANA, P. (2011): Hinterland – foreland zonation of the Variscan orogen in the Central Pyrenees: comparison with the northern part of the Iberian Variscan Massif. - In: POBLET, J. & LISLE, R.J. (eds): Kinematic Evolution and Structural Styles of Fold-and-Thrust Belts. - Geological Society, London, Special Publications, 349: 169-184.

GIL-PEÑA, I. (2004): Estructura alpina de la Zona Axial. - In: VERA, J. (ed.): Geología de España, SGE-IGME. Madrid: 241.

GIL-PEÑA, I., SANZ LÓPEZ, J., BARNOLAS, A. & CLARIANA, P. (2000): Secuencia sedimentaria del Ordovícico Superior en el margen occidental del domo del Orri (Pirineos Centrales). - Geotemas, 1(2): 187-190.

GIL-PEÑA, I., BARNOLAS, A., SANZ-LÓPEZ, J., GARCÍA-SANSEGUNDO, J. & PALAU, J. (2001): Discontinuidad sedimentaria del Ordovícico terminal en los Pirineos centrales. - Geogaceta, 29: 57-60.

GIL PEÑA, I. & BARNOLAS, A. (2004): Introducción al ciclo Varisco en los Pirineos. - In: VERA, J. (ed.): Geología de España, SGE-IGME. Madrid: 241.

GIL-PEÑA, I., BARNOLAS, A., VILLAS, E. & SANZ-LÓPEZ, J. (2004): El Ordovícico Superior de la Zona Axial. - In: VERA, J. (ed.): Geología de España, SGE-IGME. Madrid: 241.

GUTIÉRREZ-ALONSO, G., MURPHY, J.B., FERNÁNDEZ-SUÁREZ, J. & HAMILTON, M.A. (2008): Rifting along the northern Gondwana margin and the evolution of the Rheic Ocean: A Devonian age for the El Castillo volcanic rocks (Salamanca, Central Iberian Zone). - Tectonophysics, 461, 1-4: 157-165.

HARTEVELT, J.J.A. (1970): Geology of the upper Segre and Valira valleys, central Pyrenees, Andorra/Spain. - Leidse Geol. Med., 45: 167-236.

IGLESIAS, M., RIBEIRO, M.L. & RIBEIRO, A. (1983): La interpretación aloctonista de la estructura del Noroeste Peninsular. Libro Jubilar J.M. Ríos "Geología de España, Volumen I". IGME, Madrid: 459-467.

IZQUIERDO-LLAVAL, E. (2014): Variaciones longitudinales en la estructura de la Zona Axial Pirenaica: aportaciones de la fábrica magnética, el paleomagnetismo, la paleotermobarometría y la modelización analógica. – Ph.D. thesis, Univ. de Zaragoza, 354 pp.

JULIVERT, M., FONTBOTÉ, J.M., RIBEIRO, A. & CONDE, L. (1972): Mapa tectónico de la Península Ibérica y Baleares. - Instituto Geológico y Minero de España, Madrid.

JULIVERT, M. (1983): Los tiempos Precámbricos y Paleozoicos; El ciclo Hercínico; Generalidades. - In: Libro Jubilar, J.M. Ríos, Geología de España, Tomo I, Ins. Geol. Min. España, Madrid: 59-71.

JULIVERT (1996): Place de la chaîne hercynienne des Pyrénées dans le cadre Varisque. - In: BARNOLAS, A. & CHIRON, J.C. (eds): "Synthèse géologique et géophysique des Pyrénées". Edition BRGM – ITGE – Volume 1: 586-587.

KLEINSMIEDE, W.F.J. (1960): Geology of the Valle de Arán (Central Pyrenees). - Leidse Geol. Meded., 25: 129-245.

LAUMONIER, B. (2004): Serie pre-Caradoc de la Zona Axial. - In: VERA, J. (ed.): Geología de España, SGE-IGME. Madrid: 241-244.

LAUMONIER, B., AUTRAN, A., BARBEY, P., CHEILLETZ, A., BAUDIN, T., COCHERIE, A. & GUERROT, C. (2004): Conséquences de l'absence de socle cadomien sur l'age et la signification des séries pré-varisques (anté-Ordovicien supérieur) du sud de la France (Pyrénées, Montagne Noire). - Bull. Soc. géol. France, t. 175, nº 6: 643-655.

LIÑAN, E. & TEJERO, R. (1988): Las formaciones precámbricas del antiforme de Paracuellos (Cadenas Ibéricas). - Boletín de la Real Sociedad Española de Historia Natural, 84: 39-49.

LOTZE, F. (1945): Zur Gliederung der Variszidenn in der Iberischen Meseta. - Geotektonische Forschungen, 6: 78-92.

LUCAS, C. & GISBERT-AGUILAR, J. (coords) (1995): Carbonifère Supérieur-Permien. - In: BARNOLAS, A. & CHIRON, J.C. & GUÉRANGÉ, B. (eds): Synthèse Géologique et Géophysique des Pyrénées – Volume1: Introduction. Géophysique Cycle hercynien. - BRGM and IGME, Orléans and Madrid: 339-359.

MARCOS, A. (1973): Las series del Paleozoico inferior y la estructura herciniana del occidente de Asturias (NW de España). - Trabajos de Geología, Universidad de Oviedo, 6: 1-113.

MARTÍNEZ-CATALÁN, J.R. (1990): A noncylindrical model for the northwest Iberian allochthonous terranes and their equivalents in the Hercynian belt of Western-Europe. - Tectonophysics, 179, 3-4: 253-272.

MARTÍNEZ-CATALÁN, J.R. (2011): Are the oroclines of the Variscan belt related to late Variscan strike-slip tectonics? - Terra Nova, 23: 241-247.

MATTAUER, M. (1968): Les traits structuraux essentiels de la chaîne pyrénéenne. - Rev. Géogr. Phys. et Géol. Dyn., 2è sér.,10, 1: 3-12.

MATTE, Ph. (1968): La structure de la virgation hercynienne de Galice (Espagne). - Revue de Gélogie Alpine, 44: 1-128.

MATTE, Ph. (1969): Le problème du passage de la schistosité horizontale à la schistosité verticale dans le dôme de Garonne (Paléozoïque des Pyrénées Centrales). - C. R. Acad. Sc. Paris, 268: 1841-1844.

MATTE, Ph. (1991): Accretionary history and crustal evolution of the Variscan belt in Western Europe. - Tectonophysics, 196: 309-337.

MATTE, Ph. & MATTAUER, M. (1987): Hercynian orogeny in the Pyrénées was not a rifting event. - Nature, 325: 739-740.

MEY, P.H.W. (1967): The Geology of the Upper Ribagorzana and Baliera valleys, Central Pyrenees, Spain. - Leidse Geol. Meded., 41: 153-220.

MEY, P.H.W., NAGTEGAAL, P.J.C., ROBERTI, K.L. & HARTEVELT, J.J.A. (1968): Lithostratigraphic subdivision of post-hercynian deposits in the South-Central Pyrenees. Spain. - Leids, Geol. Meded., 41: 221-228.

MONTERO, P., BEA, F., GONZÁLEZ-LODEIRO, F.G., TALAVERA, C. & WHITEHOUSE, M.J. (2007): Zircon ages of the metavolcanic rocks and metagranites of the Ollo de Sapo Domain in central Spain: implications for the Neoproterozoic to Early Paleozoic evolution of Iberia. - Geological Magazine, 144: 963-976.

MULLER, J. & ROGER, Ph. (1977): l' evolution structural des pyrénées (domaine central et occidental). le segment hercynien, la chaîne de fond alpine. - Géologie alpine, 53: 149-191.

MUÑOZ, J.A. (1992): Evolution of a continental collision belt: ECORS – Pyrenees crustal balanced cross – section. - In: MCCLAY, K.R. (ed.): Thrust Tectonics. Chapman & Hall, London: 235-246.

MUÑOZ, J.A. & CASAS, J.M. (1996): Tectonique préhercynienne. - In: CARRERAS, J. & DEBAT, P. (eds): Chapitre: tectonique Hercinien, Synthèse géologique et géophysique des Pyrénées. Edition BRGM – ITGE – Volume 1: 587-589.

NAVIDAD, M., CASTIÑEIRAS, P., CASAS, J.M., LIESA, M., FERNÁNDEZ-SUÁREZ, J., BARNOLAS, A., CARRERAS, J. & GIL-PEÑA, I. (2010): Geochemical characterization and isotopic age of Caradocian magmatism in the northeastern Iberian Peninsula: insights into the Late Ordovician evolution of the northern Gondwana margin. - Gondwana Research, 17: 325-337.

NAVIDAD, M. & CASTIÑEIRAS, P. (2011): Early Ordovician magmatism in the northern Central Iberian Zone (Iberian Massif): New U-Pb (SHRIMP) ages and isotopic Sr-Nd data. - In: GUTIÉRREZ MARCO, J.C., RÁBANO, I. & GARCÍA-BELLIDO, D. (eds): 11th International Symposium on the Ordovician System, Alcalá de Henares, Ordovician of the World: 391-398.

PALAU (1998): El magmatisme calcoalcalí del massis de Maimanya i les mineralizacions As-Au-W asociades. Monografies 4. Institut Cartografic de Catalunya, 340 pp.

PARISH, M. (1984): A structural interpretation of a section of the Gavarnie nappe and its implications for Pyrenean Geology. - Jour. Struct. Geol., Oxford, 6: 247-255.

PASTOR-GALÁN, D. (2012): Evolución geodinámica del oroclinal Ibero-Armoricano, geología structural, modelización. - Ph.D. thesis, Univ. de Salamanca, 187 pp.

PÉREZ-ESTAÚN, A., MARTÍNEZ CATALAN, J.R. & BASTIDA, F. (1991): Crustal thickening and deformation sequence in the foorwall to the suture of the Variscan belt of northwest Spain. - Tectonophysics, 191: 243-253.

PÉREZ-ESTAÚN, A., BEA, F., BASTIDA, F., MARCOS, A., MARTÍNEZ-CATALÁN, J.R., MARTÍNEZ-POYATOS, D., ARENAS, R., DÍAZ-GARCÍA, F., AZOR, A., SIMANCAS, J.F. & GONZÁLEZ-LODEIRO, F. (2004): La Cordillera Varisca Europea: El Macizo Ibérico. - In: VERA, J. (ed.): Geología de España SGE-IGME. Madrid: 21-25.

PERRET, M.F. (1993): Recherches micropaléontologiques et biostratigrafiques (conodontos - foraminifères) dans le Carbonifère Pyreneen. - Strata, 2(21): 1-597.

POBLET, J. (1991): Estructura herciniana i alpina del Vessant sud de la zona Axial del Pirineu Central. - Ph.D. thesis, Univ. de Barcelona, Inédita, 604 pp.

POBLET, J. & CASAS, J.M. (1993): Variscan extension in the Pyrenees (comment). - Tectonics, 12: 1479-1481.

POUGET, P., LAMOUROUX, C., DAHMANI, A., DEBAT, P., DRIOUCH, Y., MERCIER, A., SOULA, J.C. & VEZAT, R. (1989): Typologie et mode de mise en plance des roches magmatiques dans les Pyrénées hercyniennes. - Geologische Rundschau, 78: 537-554.

POUGET, P. (1991): Hercynian tectonometamorphic evolution of the Bossots dome (French – Spanish central Pyrenees). - Journal of the Geological Society, London, 148: 299-314.

PULGAR, J.A., GALLART, J., FERNÁNDEZ-VIEJO, G., PÉREZ-ESTAUN, A., ÁLVAREZ-MARRÓN, J. & ESCIN GROUP (1996): Seismic image of the Cantanbrian Mountains in the western extensión of the Pyrenees from integrated ESCIN reflection and refraction data. - Tectonophysics, 264: 1-19.

PULGAR, J.A., PÉREZ-ESTAUN, A. GALLART, J., ÁLVAREZ-MARRÓN, J., GALLASTEGUI, J., ALONSO, J.L. & ESCIN GROUP (1997): The ESCI-N2 deep seismic reflection profile: a traverse across the Cantabrian Mountains and adjacent Duero basin. - Rev. Soc. Geol España, 8(4): 383-394.

RIBEIRO, A., DIAS, R. & SILVA, J.B. (1995): Genesis of The Ibero-Armorican Arc. - Geodinamica Acta, 8, 4: 173-184.

RIES, A.C. & SHACKLETON, R.M. (1971): Catazonal complexes of north-western Spain and north Portugal; remmants of a hercynian thrust plate. - Natural and Physical Science, 234: 65-69.

ROBARDET, M. (1976): L' originalité du segment hercynien sud ibérique au Paléozoïque inférieur: Ordovicien, Silurien et Dévonien dans le nord de la province du Séville (Espagne). - C. R. Acad. Sci. Paris, 283, Serie D: 999-1002.

ROURE, F., CHOUKROUNE, P., BERASTEGUI, X., MUÑOZ, J.A., VILLIEN, P., MATHERON, P., BAREY, M., SEGURET, M., CÁMARA, P & DERAMOND, J. (1989): ECORS Deep Seismic data and data and balanced cross-sections: Geometric constrains on the evolution of the Pyrenees. - Tectonics, 8: 41-50.

SANTANACH, P. (1972): "Sobre una discordancia en el Paleozoico inferior de los Pirineos orientales". - Acta Geol. Hisp., 7(5): 129-132.

SANZ LÓPEZ, J. & SARMIENTO, G.N. (1995): Asociaciones de conodontos del Ashgill y del Llandovery en horizontes carbonatados del valle del Freser (Girona). - XI Jornadas de Paleontología, Tremp: 157-160.

SANZ-LÓPEZ, J. (2004): Silúrico, Devónico y Carbonífero pre- y sin-varisco de los Pirineos. - In: VERA, J. (ed.): Geología de España; SGE-IGME. Madrid: 250-254.

SEGURET, M. & PROUST, F. (1968): Tectonique hercynienne des Pyrénées Centrales: signification des schistosités redressées, chronologie des deformations. - CR Acad. Sci. Paris, 266: 984-987.

SOULA, J.C. (1982): Characteristics and mode of emplacement of gneiss domes and plutonic domes in central-eastern Pyrenees. - Jour. Struct. Geol., 3: 313-342.

SOULA, J.C., DEBAT, P., DERAMOND, J. & POUGET, P. (1986): A dynamic model of the structural evolution of the Hercynian Pyrenees. - Tectonophysics, Amsterdam, 129: 115-147.

TEIXELL, A. (1998): Crustal structure and orogenic material budget in the west central Pyrenees. - Tectonics, 17: 395-406.

VALENZUELA-RÍOS, J.I. (1994): Conodontos del Lochkoviense y Praguiense (Devónico inferior) del Pirineo Central español. - Memorias del museo paleontológico Univ. Zaragoza, nº5: 142.

VALENZUELA-RÍOS, J.I. & LIAO, J.-C. (2006): Annotations to Devonian Correlation Table, R 357-360 di-ds 06: Spanish Central Pyrenees, southern part. - Senckenbergiana lethaea, 86(1): 105-107.

VALVERDE-VAQUERO, P. & DUNNING, G. (2000): New U-Pb ages for Early Ordovician magmatism in Central Spain. - Jour. Geol. Soc., 157: 15-26.

VAN DEN EECKHOUT, B. (1986): A case study of a mantled gneis antiform, the Hospitalet massif Pyrenees (Andorra, France). - Geologica Ultraiectina, 45: 1-193.

VAN DEN EECKHOUT, B. & ZWART, H.J. (1988): Hercynian crustal scale extensional shear zone in the Pyrenees. - Geology, 16: 135-138.

VERGES, J., MILLÁN, H., ROCA, E., MUÑOZ, J.A., MARZO, M., CIRÉS, J., DEN BEZEMER, T., ZOETEMEIJER, R. & CLOETHING, S. (1995): Eastern Pyrenees and related foreland basins: Pre-, syn-, and post-collisional crustal scale cross-sections. - Mar. Pet. Geol., 12: 903-915.

VISSERS, R.L.M. (1992): Variscan extensión in the Pyrenees. - Tectonics, 6: 1369-1384.

VOGEL, D.E. (1984): Cabo Ortegal, mantle plume or double klippe. - Geologie en Mijnbow, 63: 131-140.

WEIL, A.B. & SUSSMAN, A.J. (2004): Classifying curved orogens based on timing relationships between structural development and vertical-axis rotations. - In: SUSSMAN, A.J. & WEIL, A.B. (eds): Orogenic curvature: integrating paleomagnetic and structural analyses. - Geological Society of America: 1-16.

WICKHAM, S.M. & OXBURGH, E.R. (1985): Continental rifts as a setting for regional metamorphism. - Nature, London, 318: 330-333.

WICKHAM, S.M. & OXBURGH, E.R. (1986): A rifted tectonic setting for Hercynian high-thermal gradient metamorphismin the Pyrenees. - Tectonophysics, Amsterdam, 129: 53-69.

WILLIANS, G.D. (1985): Thrust tectonics in the south central Pyrenees. - J. Struct. Geol., Oxford, 7, 1: 11-17.

ZWART, H.J. (1979): The Geology of the Central Pyrenees. - Leidse Geol. Med., 50, 1: 74 p.