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CALEDONIAN AND LATE CALEDONIAN EUROPE: A WORKING HYPOTHESIS INVOLVING TWO CONTRASTED COMPRESSIONAL/EXTENSIONAL SCENARIOS

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RESUMEN

La estructuración tectonomagmática y metamórfica del dominio caledónico europeo sugiere que dos escenarios, compresional y extensional, mutuamente perpendiculares, se desarrollaron durante el Ordovícico-Devónico. Como resultado del esquema compresional del Ordovícico medio (Grampian, caledónico s.s.), en el O de Europa continental se desarrolló una provincia extensional localizada al E de la faja de plegamiento caledónica. Esta situación finalizó hacia el Devónico inferior/medio, cuando la convergencia de América del Norte, Báltica y Gondwana dió origen al supercontinente Pangea. Esta colisión generó un ambiente tectónico caracterizado por: 1. plegamiento y plutonismo en Europa continental occidental, y 2. extensión y volcanismo en la parte N de la faja de plegamiento caledónica (Escocia, SO de Noruega y E de Groenlandia). Este evento puede ser tentativamente denominado «Tardicaledónico». En términos globales, la evolución del dominio caledónico puede ser explicada en términos de «tectónica de inversión» (s.l.), esto es, períodos de adelgazamiento cortical (extensionales) seguidos por períodos de engrosamiento cortical (compresionales) y viceversa.

Palabras clave: *Caledónico, Tardicaledónico, provincia extensional, tectónica de inversión.*

ABSTRACT

The tectonomagmatic and metamorphic structuration of the European Caledonian realm suggests that two mutually perpendicular compressional/extensional scenarios developed during the Ordovician-Devonian time-span. As a result of the mid Ordovician Grampian compressional scheme (Caledonian s.s.), a major extensional province developed further east from the Caledonian foldbelt in continental Europe. This scenario ended by early/mid Devonian, with the complete locking of North America, Baltica and Gondwana into a Pangaea supercontinent, thus triggering a contrasted tectonic environment which might be termed «late Caledonian», characterized by compression and plutonism in western continental Europe, and extensional detachment tectonics and volcanism in the northern part of the Caledonian foldbelt (Scotland, southwestern Norway and eastern Greenland). The overall evolution of this realm can be summarized in terms of inversion tectonics (s.l.) processes, with periods of crustal thinning followed by thickenning and vice versa.

Key words: *Caledonian, late Caledonian, extensional province, inversion tectonics.*

Introduction

The western European realm has been traditionally ascribed to either Caledonian (western Scandinavia and most of the British Isles) or Variscan (southern British Isles and western continental Europe) domains. In this sense, the question of Paleozoic pre-Variscan events, particularly within the continental sector, has been a subject of controversy, as illustrated by the fact that no specific differentiation between Caledonian and Variscan cycles exists in some areas.

Another polemical question is related to the age of the final configuration of Pangaea (either Devonian, or Carboniferous/Permian), an issue which is of vital importance for the overall scenario. In this sense, the list of proposals (based on paleomagnetic and/or paleontological data) is very long. The «late

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Pangaea» hypothesis sustained by Perroud and Bonhommet (1981) and Zonenshain *et al.* (1985), among others, proposes that this supercontinent was not consolidated till Carboniferous or Permian time, when the northward drifting Gondwana was finally welded to the septentrional continental mass (Laurentia, Baltica, and Armorica). The alternative «early Pangaea» scheme (McKerrow and Ziegler, 1972; Keppie, 1977; Morel and Irving, 1978; Livermore *et al.*, 1986; Miller and Kent, 1988), suggests a supercontinent configuration by early to mid Devonian time.

In this paper, we will argue that the structuration of the European Caledonian realm is characterized by the following points: 1. An early link between the different continental masses shaping Pangaea in this area. 2. Two contrasted tectonic scenarios, each of them defined by perpendicular deformational trends: Caledonian s.s., and «late Caledonian». 3. A globalized Caledonian cycle ending by late Devonian time, which can be clearly separated from the Variscan one.

The shaping of the European Caledonides

The controversial issue of a Caledonian continental Europe is not new, and in fact, pre-Variscan unconformities, tectono-metamorphic events, and magmatism have long been recognized in this realm (Alvarado, 1980; Autran and Peterlongo, 1980; Behr *et al.*, 1980; Weber, 1984; Serrano Pinto, 1987, among others). However, these phenomena have been mostly regarded as local peculiarities, and no clear relationships to the main Caledonian foldbelt have been established. Additionally, the existence of tectonic events taking place in continental Europe, while the main Caledonian foldbelt was being shaped westward, favours the hypothesis of an early Paleozoic unified and unstable domain in the continental European realm, thus posing serious doubts on the models based on a series of microplates adrift at different paleolatitudes. Prior to the Caledonian cycle, this realm was affected by the Cadomian orogenesis (Precambrian/Cambrian), a scenario which changed in continental Europe with the onset of extensional conditions (Autran and Cogne, 1980) heralding the Caledonian. Sawkins and Burke (1980) suggest that extension continued in continental Europe during more advanced stages of the Caledonian cycle.

Two orogenic events, with associated compressional and extensional provinces, can be recognized in the European Caledonides (figs. 1A and 1B): 1. Caledonian s.s., a mid Ordovician-early Devonian event characterized by compressional conditions in the Caledonian foldbelt (C1), and extension in continental Europe (E1). 2. «Late Caledonian», a post-early Devonian-pre Dinantian episode characterized by extensional conditions in the northern part of the Caledonian foldbelt (E2), and compression in western continental Europe (C2). The first episode (Caledonian s.s.) is defined in continental Europe by extensional conditions, as revealed by the following data: epeirogenic movements, granulite facies metamorphism, basic volcanism, plutonism and crustal thinning-rifting (Behr *et al.*, 1980; Luettig, 1980; Weber, 1984) in Germany; plutonism in France (Cogne and Wright, 1980), particularly within the axis of Moëlan-Lanvaux and Saint-George-sur-Loire, both accompanied by basic and ultrabasic rocks and alkaline intrusions (Zwart and Dornsiepen, 1980); rifting along the so-called blastomylonitic graben in northwestern Spain (accompanied by some Ordovician alkaline granites: Zwart and Dornsiepen, 1980), as well as volcanism, northwest-trending basic dykes (Gumiel, 1982; Hernández, 1984), rifting, block twisting, and peralkaline magmatism in central Spain (Pieren and Dallmeyer, 1989). Metallogenic processes (Sawkins and Burke, 1980) during this first extensional event (E1) gave rise to important ore deposits, such as those of Lahn Dill (volcanogenic BIF facies; Germany) and Almadén (volcanogenic mercury deposits; Spain, Pieren and Dallmeyer, 1989). This extensional event E1 was coeval with metamorphism and nappe tectonics in the Moines region within the main Caledonian foldbelt (Scotland, D1-D2 deformation, M2 metamorphic peak, circa 450 Ma; Soper and Barber, 1982; crustal shortening during Arenigian-Llanvirnian time, Dewey and Shackleton, 1984). This Grampian compressional event (C1) was related to other orogenic movements within other parts of the Caledonian/Appalachian belt (Scandinavia: Finnmarkian; Newfoundland: Humberian; Appalachians of New York and New England: Taconic; Dewey and Shackleton, 1984; Park, 1988). The final configuration of this compressional realm was achieved by late Silurian-early Devonian, when the Iapetus Ocean closed (Dewey and Shackleton, 1984; Miller and Kent, 1988).

The extensional conditions in continental Europe prevailed till early/mid Devonian time, when the onset of the Acadian compressions («late Caledonian» compressional event C2; fig. 1B) induced generalized folding and plutonism in Iberia, France and Germany (Serrano Pinto *et al.*, 1987; Park, 1988). This event probably contributed to release the stresses within the previously overthickened Caledonian foldbelt, thus allowing the gravitational extensional collapse through detachment systems occurring further north (Scotland, southwestern Norway, and southeastern Greenland; McClay *et al.*, 1986), generating a series of northeast to north-south-trending exten-

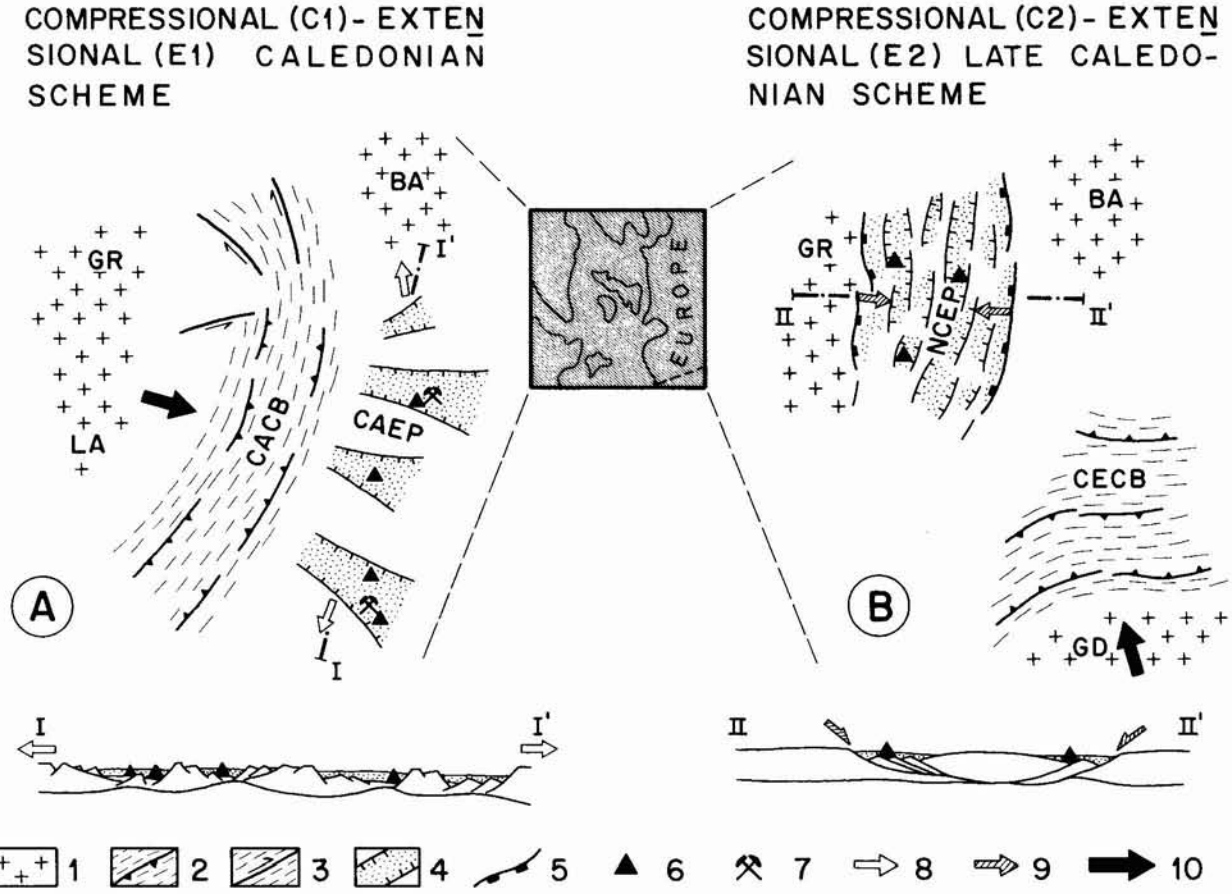

Fig. 1.—Simplified palinspastic sketches and cross-sections depicting the compressional and extensional events characterizing the Caledonian (A) (mid Ordovician to early/mid Devonian) and late Caledonian (B) (post-early Devonian-pre Dinantian) events. CACB: Caledonian compressional belt; CAEP: Caledonian extensional province; CECB: continental Europe compressional belt; NCEP: northern Caledonides extensional province (NCEP and section II-II' simplified and modified after McClay *et al.*, 1986). BA: Baltica; GR: Greenland; LA: Laurentia; GD: Gondwana. 1: cratonic domains; 2: thrust belts; 3: strike-slip zones of deformation; 4: continental rifting areas; 5: extensional detachments; 6: volcanism; 7: volcanogenic mineralizations; 8: direction of regional extension; 9: direction of extensional collapse; 10: direction of regional compression.

Fig. 1.—Esquemas palinspásticos simplificados y secciones mostrando los eventos compresionales y extensionales caledónicos (A) (Ordovícico medio a Devónico inferior/medio) y tardicaledónicos (B) (post-Devónico inferior-Dinantiense). CACB: faja compresional caledónica; CAEP: provincia extensional caledónica; CECB: faja compresional europea continental; NCEP: provincia extensional caledónica norte (NCEP y sección II-II' simplificadas y modificadas de McClay *et al.*, 1986). BA: Báltica; GR: Groenlandia; LA: Laurentia; GD: Gondwana. 1: dominios cratónicos; 2: fajas de plegamiento; 3: zonas de deformación Transcurrentes; 4: zonas de rifting continental; 5: detachments extensionales; 6: volcanismo; 7: mineralizaciones volcanogénicas; 8: dirección regional de extensión; 9: dirección de colápso extensional; 10: dirección regional de compresión.

sional basins in which the Old Red Sandstone facies were deposited and volcanics extruded (extensional event E2). However, the stresses responsible for this collapse were mainly due to intraplate unstable conditions triggered by the previously overthickened orogenic welt. If we assume that an early or mid Devonian Pangaea existed, as suggested by some authors (McKerrow and Ziegler, 1972; Keppie, 1977; Morel and Irving, 1978; Gambles, 1984; Livermore *et al.*, 1986; Miller and Kent, 1988), then the final locking of North America, Baltica and Gondwana (370 Ma, Gambles, 1984) can adequately account for the compressional event C2. Since by Devonian time, the British segment of Iapetus had closed (Dewey, 1982; Dewey and Shackleton, 1984), it is conceivable that the main stress component may have been provided by the northward drifting and collision of Gondwana against Europe by early/mid Devonian time.

Finally, soon after the cessation of this «late Caledonian» scheme, new extensional conditions prevailed during Dinantian time in most of Europe, a si-

tuation which already belongs to the Variscan cycle. During this event the following features developed: the Basin/Block province, volcanism, and the so-called Irish-type ore deposits in Britain and Ireland (Leeder, 1982; Evans, 1987); the «Basin and Swell» zones in Germany (Luettig, 1980); basic and acid volcanism in France (Chauvel and Robardet, 1980); and rifting and bimodal volcanism in southern Portugal and Spain (Swakins and Burke, 1980). To the latter is associated a major volcanosedimentary complex hosting some of the most outstanding massive sulphide deposits of the world (e.g. Aznalcollar, Neves Corvo, Río Tinto). This extensional episode, the first of two during the Variscan cycle (a late Variscan extensional event is also recorded in France, Germany and Spain; Menard and Molnar, 1988; Doblas *et al.*, 1988), ended by late Visean time, when a major Variscan compressional episode induced folding, metamorphism and plutonism throughout continental western Europe (Sudetic phase).

The extensional events: Contrasted genetic models

The case of the «late Caledonian» extensional event (E2; post-early Devonian-pre Dinantian) is analyzed first, as a model has already been proposed to explain it. As suggested by McClay *et al.* (1986), extensional detachment tectonics (as a consequence of the gravitational collapse of a previously overthickened orogenic welt) seems a plausible mechanism to account for the northern Devonian basins in which the Old Red Sandstone facies were deposited during this event. In this sense, the «late Caledonian» Basin and Range-type extensional province thus defined, bears many similarities with southern Spain and northern Africa during late Alpine time (Neogene), when the overthickened Betic-Rif orogenic edifice collapsed through detachment systems (Doblas and Oyarzun, 1989). Even if intraplate stresses arising from a gravitationally unstable crustal welt seem to be the major cause of this extension, the final locking of North America, Baltica and Gondwana (generating a northward-directed compressional stress pattern), may have been the triggering event contributing to release the stresses generated within the Caledonian foldbelt, thus allowing the extensional collapse of its northern sector. By contrast, the Ordovician-early Devonian extensional event (E1) developed as related to different circumstances. Since no previous overthickening can be advocated for continental western Europe, then another cause must account for this extension. In this sense, stresses arising from the building of collisional-type mountain belts are known to trigger extensional provinces in their continental forelands (e.g. Alps, Illies and Greiner, 1978; Himalayas, Tapponnier *et al.*, 1982). Therefore, it can be argued that E1 was a direct consequence of the compressional stresses generated throughout the Caledonian front during the C1 episode. This scheme also provides an adequate explanation for the strike-slip zones of deformation (Dewey, 1982; Dewey and Shackelton, 1984) observed in the northern Caledonian foldbelt (fig. 1A), since is typical of a Himalayan-type collision/indentation model (Tapponier *et al.*, 1982) as the one suggested here. Finally, we suggest that these two Caledonian s.s. compressional (C1) and extensional (E1) domains might have represented unstable intercratonic corridors, differentially deformed in between three major Precambrian shields (Gondwana, Baltica, and Laurentian-Greenland; fig. 2). Moreover, the central bending of the Caledonian compressional belt, and the eastward divergence of the extensional trends in continental Europe, would be a final result of the continued convergence between Laurentian-Greenland, Baltica, and Gondwana.

In conclusion, the Caledonian evolution of the European realm is characterized by two contrasted ex-

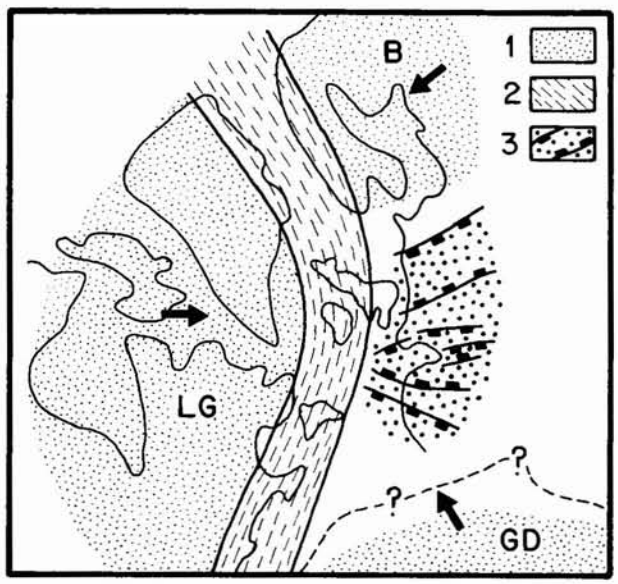

Fig. 2.—Simplified palinspastic sketch representing the Caledonian (s.s.) compressional (C1) and extensional (E1) domains during late Silurian-early Devonian time, as unstable intercratonic areas differentially deformed in between three Precambrian shields. 1: Precambrian shields (Baltica, B; Gondwana, GD; Laurentian-Greenland, LG); 2: Caledonian (s.s.) deformational belt; 3: Caledonian extensional province.

Fig. 2.—Esquema palinspástico simplificado (Silúrico superior-Devónico inferior) representando los dominios caledónicos compresionales (C1) y extensionales (E1) como áreas intercratónicas inestables, deformadas diferencialmente entre tres escudos precámbricos. 1: escudos precámbricos (Báltica, BA; Gondwana, GD; Laurentia-Groenlandia, LG); 2: faja deformacional caledónica; 3: provincia extensional caledónica.

tensional events: 1. Caledonian s.s., with crustal thinning occurring in the foreland realm (E1; fig. 1A), a scenario which can be understood in terms of interplate stresses generated as a result of an Himalayan-type collission/indentation model (Tapponnier *et al.*, 1982); and 2. A «late Caledonian» extensional scheme (E2) related to intraplate stresses, probably resulting from the gravitational collapse of a previously overthickened orogen, a process which might have been initially enhanced by the compressions occurring in western continental Europe (C2; fig. 1B).

Finally, the overall evolution of the European Caledonides can be ascribed to an «inversion-type» (s.l.) tectonic model, in that, regions subject to crustal thickenning were later thinned (e.g. northern Caledonides; C1 followed by E2) and vice versa (e.g. western continental Europe; E1 followed by C2).

References

Alvarado, M. (1980). Espagne. *Géologie des pays européens (Espagne, Grèce, Portugal, Yougoslavie))*. Paris, France, Bordas Editeurs, 1-60.

Autran, A. and Cogne, J. (1980). La zone interne de l'orogene varisque dans l'ouest de la France et sa place dans le développement de la chaîne hercynniene. *Geology of Europe*. Mémoire du Bureau de Recherches Géologiques et Minières 108: 90-111.

Autran, A. and Peterlongo, J. M. (1980). France: Massif Central. *Géologie des pays européens (France, Belgique, Luxembourg)*. Paris, France, Bordas Editeurs, 9-124.

Behr, H. J.; Walliser, O. H. and Weber, K. (1980). The development of the Rheno-hercynian and Saxo-thuringian zones of the mid-European Variscides. *Geology of Europe*. Mémoire du Bureau de Recherches Géologiques et Minières 108: 77-89.

Chauvel, J. J. and Robardet, M. (1980). France: Massif Armoricain. *Géologie des pays européens (France, Belgique, Luxembourg)*. Paris, France, Bordas Editeurs, 125-178.

Cogne, J. and Wright, A. E. (1980). L'Orogène cadomien. Vers un essai d'interprétation paléogéodinamique unitaire des phénomènes orogéniques fini-précambriens d'Europe moyenne et occidentale, et leur signification a l'origine de la croûte et de mobilisme varisque puis alpin. *Geology of Europe*. Mémoire du Bureau de Recherches Géologiques et Minières 108: 29-55.

Dewey, J. F. (1982). Plate tectonics and the evolution of the British Isles. *J. Geol. Soc.* 139: 371-414.

Dewey, J. F. and Shackleton, R. M. (1984). A model for the evolution of the Grampian tract in the early Caledonides and Appalachians. *Nature* 312: 115-121.

Doblas, M. and Oyarzun, R. (1989). Neogene extensional collapse in the western Mediterranean (Betic-Rif Alpine orogenic belt): Implications for the genesis of the Gibraltar Arc and magmatic activity. *Geology* 17: 430-433.

Doblas, M.; Oyarzun, R.; Lunar, R.; Mayor, N. and Martínez, J. (1988). Detachment faulting and late Paleozoic epithermal Ag-base-metal mineralization in the Spanish central system. *Geology* 16: 800-803.

Evans, A. M. (1987). *An introduction to ore geology*. London, Blackwell Scientific Publications, 358 págs.

Gambles, P. (1984). Death of an ancient ocean. *Nature* 312: 400-401.

Gumiel, P. (1982). *Metalogenia de los yacimientos de antimonio de la Península Ibérica*. Unpublished Ph. D. thesis, Universidad de Salamanca. Salamanca. Spain. 324 págs.

Hernández, A. M. (1984). *Estructura y génesis de los yacimientos de mercurio de la zona de Almadén*. Serie resúmenes de tesis doctorales. Facultad de Ciencias. Universidad de Salamanca. no. T-C-370, 64 págs.

Illies, J. H. and Greiner, G. (1978). Rhinegraben and the Alpine system. *Bull. Geol. Soc. Amer.* 89: 770-782.

Keppie, J. D. (1977). Plate tectonic interpretation of Paleozoic world maps. *Nova Scotia Department of Mines*. Paper 77-3, 75 págs.

Leeder, M. R. (1982). Upper Palaeozoic basins of the British Isles-Caledonide inheritance versus Hercynian plate margin processes. *J. Geol. Soc.* 139: 481-494.

Livermore, R.A.; Smith, A. G. and Vine, F. J. (1986). Late Paleozoic to early Mesozoic evolution of Pangaea. *Nature* 322: 162-165.

Luettig, G. W. (1980). Federal Republic of Germany. *Geology of the European countries (Austria, Federal Republic of Germany, Ireland, the Netherlands, Switzerland, United Kingdom)*. Paris, France, Bordas Editeurs, 93-102.

McClay, K. R.; Norton, M. G.; Coney, P. and Davis, G. H. (1986). Collapse of the Caledonian orogen and the Old Red Sandstone. *Nature* 323: 147-149.

McKerrow, W. S. and Ziegler, A. M. (1972). Paleozoic oceans. *Nature* 240: 92-94.

Menard, G. and Molnar, P. (1988). Collapse of a Hercynian Tibetan plateau into a late Paleozoic European Basin and Range province. *Nature* 334: 235-237.

Miller, J. D. and Kent, D. V. (1988). Paleomagnetism of the Silurian-Devonian Andreas redbeds: evidence for an early Devonian supercontinent? *Geology* 16: 195-198.

Morel, P. and Irving, E. (1978). Tentative paleocontinental maps for the early Phanerozoic and Proterozoic. *J. Geol.* 86: 535-561.

Park, R. G. (1988). *Geological structures and moving plates*. New York, Chapman and Hall, 337 págs.

Perroud, H. and Bonhommet, N. (1981). Paleomagnetism of the Ibero-Armorican arc and the Hercynian orogen of western Europe. *Nature* 292: 445-448.

Pieren, A. P. and Dallmeyer, R. D. (1989). Tectonic instability in the Ordovician-Silurian boundary of the Central-Iberian zone (Spain): new stratigraphic and radiometric data. *Southern Appalachian Conference,* P.I.C.G. 233 Terranes in the Circum-Atlantic Paleozoic orogens (poster), Athens, Georgia, July 1989.

Sawkins, F. J. and Burke, K. (1980). Extensional tectonics and mid-Paleozoic massive sulfide occurrences in Europe. *Geol. Rundschau* 69: 349-360.

Serrano Pinto, M.; Casquet, C.; Ibarrola, E.; Corretge, L. C. and Portugal Ferreira, M. (1987). Sintese geocronológica dos granitóides do Maciço Hespérico. In: *Geología de los granitoides y rocas asociadas del Macizo Hespérico*. (F. Bea, A. Carnicero, J. C. Gonzalo, M. López Plaza and M. D. Rodríguez Alonso, Eds.) Madrid, Spain. Rueda Eds., 69-86.

Soper, N. J. and Barber, A. J. (1982). A model for the

deep structure of the Moine thrust zone. *J. Geol. Soc.* 139: 127-138.

Tapponnier, P.; Peltzer, G.; Le Dain, A. Y.; Armijo, R. and Cobbold, P. (1982). Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology* 10: 611-616.

Weber, K. (1984). Variscan events: early Paleozoic continental rift metamorphism and late Paleozoic crustal shortening. *Variscan Tectonics in the north Atlantic region.* (D. H. W. Hutton and D. J. Sanderson, Eds.) Geol. Soc. London, Special Publication 14: 3-22.

Zonenshain, L. P.; Kuzmin, M. I. and Kononov, M. V. (1985). Absolute reconstructions of the Paleozoic oceans. *Earth Planet. Sci. Lett.* 74: 103-116.

Zwart, H. J. and Dornsiepen, U. F. (1980). The Variscan and pre-Variscan tectonic evolution of Central and Western Europe: a tentative model. *Mém. Bureau de Recherches Géologiques et Minières* 108: 226-232.

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