Syn- to post-thickening extension in the Variscan Belt of Western Europe: Modes and structural consequences*

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L'extension syn- à post-épaississement de la chaîne varisque en Europe occidentale : modalités et conséquences

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Mots-clés : Extension tectonique, Orogénie hercynienne, Carbonifère, Permien inférieur, Faille de transfert, Effondrement (Effondrement extensif), Europe Ouest.

Abstract

Two extension patterns are identified in the Western European Variscides. Late-Visean-Westphalian extension is nearly parallel to the belt and took place during escape tectonics controlled by still active compression forces. Late-Stephanian to Early-Permian extension implies complex changes in extension direction induced by the gravitational collapse of the entire chain after continental convergence. Variations in the direction and the finite amount of extension are accommodated by crustal-scale transfer faults.

A quantitative and theoretical analysis guided by real geological examples in the Southern Massif central permits some rules to be established for intepreting the extended orogen. Several 10 % of transverse extension are inferred in regions strongly affected by the later event, thus exaggerating the length of regional sections. We have removed this effect on synthetic sections accross the Iberian, Massif central and Bohemian segments of the Variscan belt. We show that the early displacement of collision-related thrusts was significantly less and therefore, mechanically more plausible than figures commonly proposed. We also argue that a large part of the lower orogenic crust was tectonically transferred to higher crustal levels during late-orogenic processes.

Résumé (étendu)

Deux périodes extensives sont reconnues dans l'évolution finale de la chaîne varisque d'Europe occidentale. Pour résumer et simplifier cette histoire, l'étirement est surtout parallèle à la chaîne du Viséen au Westphalien. Il devient ensuite moins organisé, mais il implique une plus grande quantité d'extension, pendant le Stéphano-Permien.

Du Viséen au Westphalien, l'extension est diachronique et commence dans les zones axiales, peut-être les plus épaisses de l'orogène. Elle accompagne la fin de la convergence continentale et ajuste le jeu de zones décrochantes qui réutilisent éventuellement les chevauchements hérités de la collision dévonienne. Les zones décrochantes traduisent l'échappement latéral de blocs continentaux en front de l'orogène. L'enregistrement sédimentaire différencie de façon marquée les régions montagneuses, profondément érodées, et les avant-pays où de grands bassins fluvio-deltaïques témoignent d'une ambiance tectonique calme. Bien que la convergence continentale soit encore active, l'extension est dénotée par des bassins volcano-sédimentaires contemporains d'un volcanisme acide, souvent de type explosif. Le plutonisme abondant, dérivé de la fusion crustale et qui caractérise la chaîne hercynienne, est attribué au début de la relaxation thermique de la croûte épaissie. Cet épisode extensif n'implique pas un important amincissement de la croûte mais atténue les effets de l'épaississement pendant une tectonique intracontinentale dominée par l'échappement de blocs continentaux.

Du Stéphanien supérieur à l'Autunien, l'extension, surtout transverse à la chaîne, traduit un effondrement foncièrement radial. Cependant, des variations complexes en direction et quantité d'étirement interviennent par endroit. L'enregistrement sédimentaire ne permet plus de discerner les régions montagneuses et les avant-pays. La forte acti-

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vité tectonique et volcanique d'un environnement extensif partout dans la chaîne varisque, et en particulier dans sa branche sud, est marquée par les nombreux bassins dont les sédiments d'origine proximale proviennent des reliefs des failles bordières, des coulées volcaniques et des caldeiras. Les discordances entre le Stéphanien et le Permien inférieur dépendent des vitesses relatives de subsidence et de sédimentation ainsi que des variations locales de la direction d'extension. La chaîne varisque d'Europe occidentale enregistre alors un métamorphisme de basse pression et est affectée par des failles de détachement tandis que l'exhumation de la croûte ductile est amplifiée par la formation de dômes de granites et migmatites. L'extension stéphano-autunienne est induite par l'effondrement gravitaire, après la convergence continentale, de tout le domaine épaissi.

Elle permet un amincissement rapide à la suite duquel la croûte retrouve une épaisseur normale d'équilibre isostatique. Deux explications sont possibles : le volume du domaine épaissi est devenu suffisant pour produire des forces de corps, verticales, supérieures aux forces compressives, horizontales, dues à la convergence ; la chaîne se répand alors latéralement vers les avant-pays. L'alternative, que nous préférons, implique un changement dans la cinématique des plaques au Stéphano-Permien ; la modification de la géodynamique globale a provoqué le déclin des forces horizontales le long des limites de l'orogène, permettant la croûte épaissie en cours de relaxation thermique de s'effondrer vers une bordure libre.

Les variations de direction et quantité d'étirement de l'extension stéphano-autunienne sont accommodées par des failles de transfert d'échelle crustale. Il s'agit de discontinuités majeures qui séparent des régions où l'extension est essentiellement transverse à la chaîne des zones adjacentes où l'extension fait un angle moins fort par rapport à la chaîne. Le Sillon Houiller et la faille Nord-Pyrénéenne en sont probablement les meilleurs exemples. Nous proposons que la lithosphère européenne a hérité de cet événement extensif les grandes failles qui seront encore actives pendant le Mésozoïque et le Cénozoïque. D'un point de vue géodynamique, les directions d'extension tardi-hercyniennes sont cohérentes avec le mouvement relatif dextre connu pour cet époque entre Gondwana et Laurentia.

Une réflexion théorique et quantitative basée sur des expériences analogiques nous permet de quantifier l'étirement dû aux détachements crustaux. En appliquant ces techniques semi-quantitatives à l'extension stéphano-permienne, celle qui a les effets les plus marqués sur la structure de la chaîne varisque, nous montrons qu'elle a notablement exagéré la flèche des grands chevauchements collisionels. Par exemple, la flèche pré-extension des nappes d'éclogites et granulites du Massif central oriental est réduite de près de 200 km à environ 100 km, une différence qui souligne l'importance des processus extensifs dans les grands systèmes de nappes. En corollaire, la largeur originale de la chaîne était pour beaucoup plus étroite que celle observée sur les cartes géologiques actuelles. En particulier, le Massif central oriental a été nettement plus élargi que le Massif central occidental et la Bretagne méridionale. En ajoutant en base de croûte des coupes restaurées les quantités de matériel enlevées aux coupes corrigées de l'étirement tardi-orogénique, on s'aperçoit que l'extension syn- à post-épaississement est un mécanisme tectonique essentiel dans le transfert de croûte inférieure vers la croûte supérieure.

Nous montrons donc que l'effondrement d'un orogène varie d'un segment à l'autre en âge et en direction. Il n'est pas nécessairement sub-perpendiculaire à la chaîne ; il commence dès les derniers stades de la convergence en s'associant à une tectonique d'échappement de blocs continentaux. De grandes failles décrochantes créées pendant l'effondrement post-épaississement sont des failles de transfert qui accommodent des variations latérales de direction et d'intensité de l'extension.

Introduction

One of the chief concerns of structural geologists is the study of regional structures and tectonics in relation to orogenesis. A prevailing technique has been extrapolation of a model based on field work and synthesis within one orogen to other orogenic areas. Predominant means of communication have been synthetic profiles illustrating the relationships of geologic structures across. In this article, we investigate the geometrical and structural consequences of syn- to post-thickening extension on orogenic belts. We use the West-European Variscides as an example. Indeed, high-temperature-low-pressure regional metamorphic terrains and considerable volumes of anatectic, igneous material are so notable in the Variscan Belt that they have been taken as a distinctive feature of the "Hercynotype" (Zwart, 1967). Mineral assemblages of the high-temperature terrains imply that over wide areas the crust became pervasively hot at shallow depth, developing exceptionally high temperature gradients in the upper crust. Granite and high-temperature metamorphism ages ranging between 330 and 290 Ma indicate that the Hercynotype took place after the 390-360 Ma old collision and crustal thickening (Bard *et al.*, 1980; Duthou *et al.*, 1984; Matte, 1986). Hence, it has been proposed that the Variscan Belt presents an older equivalent of the Basin and Range province (Lorenz and Nicholls, 1976; 1984) with a likely orogenic sequence of thickening followed by extension and coeval crustal thinning. The analogy is supported by bimodal compositions of the Carboniferous volcanism (Bébien, 1976) and by the extensional history of the continental crust all over Europe that formed deeply eroded metamorphic and granitic rocks surrounded by contemporaneous and younger Carboniferous and Permian sedimentary basins (Ménard and Molnar, 1988).

Much work on post-thickening extension has concentrated on factual extensional features and on thermo-mechanical models of the thinning lithosphere. Much less has been devoted to the structural consequences of large-scale strain in extended areas, in particular those with early, thickening-related structures. We attempt, by means of quantitative, theorical analysis guided by real geological examples, to establish some rules for interpreting extended oro-

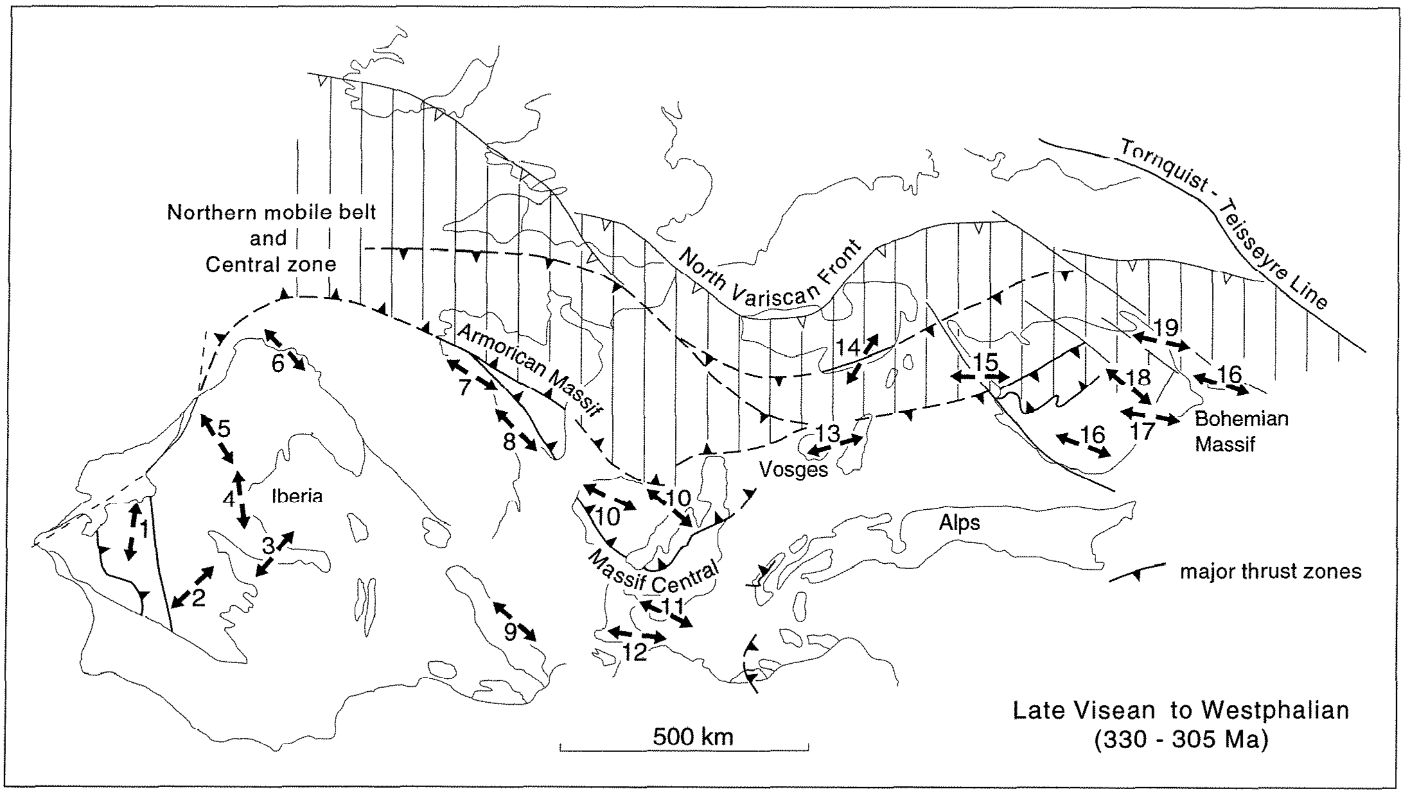

Fig. 1. – Extension direction during Late-Visean to Westphalian times in the Variscan Belt of Western Europe. Data from: 1: (Iglesias Ponce de León and Ribeiro, 1981b), 2: (Azor *et al.*, 1993); 3: (Doblas et *al.*, 1994a); 4: (Díez-Balda *et al.*, 1992; Díez-Balda *et al.*, 1994); 5: (Ribeiro *et al.*, 1990); 6: (Pérez-Estaún et al., 1991); 7: (Gapais *et al.*, 1993); 8: (Goujou, 1992); 9: (Vissers, 1992); 10: (Faure, 1989; Faure *et al.*, 1990); 11: (Faure *et al.*, 1992); 12: (Van Den Driessche and Brun, 1991-1992); 13: (Wickert *et al.*, 1990); 14: (Oncken, 1988); 15: (Hofmann, 1962); 16: (Schulmann *et al.*, 1993); 17: (Melka *et al.*, 1992); 18: (Pitra *et al.*, 1994); 19: (Rajlich, 1990).

Fig. 1. – Directions d'extension du Viséen supérieur au Westphalien dans la chaîne Varisque d'Europe Occidentale. Données de : 1 : (Iglesias Ponce de León et Ribeiro, 1981) ; 2 : (Azor et al.*, 1993) ; 3 : (Doblas* et al.*, 1994a) ; 4 : (Díez-Balda et al., 1992 ; Díez-Balda* et al.*, 1994) ; 5 : (Ribeiro* et al.*, 1990) ; 6 : (Pérez-Estaún* et al.*, 1991) ; 7 : (Gapais* et al.*, 1993) ; 8 : (Goujou, 1992) ; 9 : (Vissers, 1992) ; 10 : (Faure, 1989 ; Faure* et al.*, 1990) ; 11 : (Faure* et al.*, 1992) ; 12 : (Van Den Driessche et Brun, 1991-1992) ; 13 : (Wickert* et al.*, 1990) ; 14 : (Oncken, 1988) ; 15 : (Hofmann, 1962) ; 16 : (Schulmann* et al.*, 1993) ; 17 : (Melka* et al.*, 1992) ; 18 : (Pitra* et al.*, 1994) : 19 : (Rajlich, 1990).*

gens. This approach is intended to emphasise the limitations of present information and knowledge on old collisional systems.

General framework and extensional patterns

Field evidence and extension pat terns lead us to identify two main extensional events in the Variscides of Western Europe. Our simplifying, two-fold classification is generally acceptable, although not clear-cut since time variations exist from place to place. However, the bulk superposition of two main events with capital differences in direction seems valid everywhere: A still insufficiently documented, syn-orogenic extensional event is basically nearly parallel to the orogenic trend. It is followed by a better controlled post thickening extension that shows regional changes in extension direction and quantity.

Early (predominantly Late Visean-Westphalian) extension

The sedimentary record indicates clearly differentiated mountain domains undergoing deep erosion in the axial zones of the belt from foreland areas where large, fluvio-deltaic basins were established in the north (Courel, 1987; Donsimoni, 1981) and the inner parts of the Ibero-Armorican Arc (Heredia *et al.*, 1990). This implies fast uplift of the ranges was taking place while forelands were relatively stable. Although continental convergence was still operative (e.g. Van der Voo, 1982) extensional regions in the Variscides (fig. 1) are locally documented by coeval volcano-sedimentary basins and subaerial, often silicic and explosive volcanism of Visean to Westphalian age. Voluminous, crustal derived plutonism suggests that thermal relaxation was already taking place, magma filling tectonically controlled space whether in extensional or contractional bulk regime (Hutton, 1988).

Iberian Peninsula

An example of a continental crust subjected to thickening and subsequently thinned is recognised in northeastern Portugal (Ribeiro *et al.*, 1990) and Central Spain (Doblas, 1991; Doblas *et al.*, 1994a) with progressive transition from middle Devonian compression to Permian extension. Localised extension appeared as early as the Devonian (Doblas *et al.*, 1994a; Martínez Catalán and Arenas, 1992) but the major period of LP-HT metamorphism and massive plutonism took place in Visean times (Dallmeyer *et al.*, 1993), with a maximum transgression in the Late Visean rapidly followed by regression and emergence in the Early Namurian (Quesada *et al.*, 1990). Plutonism temporally coincides with active transcurrent shear (Castro, 1986). Extension was coeval with compression in Eastern Central Spain (Díez-Balda *et al.*, 1992; Díez-Balda *et al.*, 1994; Escuder Viruete *et al.*, 1994) and in Ossa Morena, producing fault controlled, intramontane basins. In North-Western Spain, extension occurred in the ductile Vivero fault and adjacent areas during the late stage of crustal shortening (Arungen and Tubia, 1992). The detachment faults, metamorphic core complexes, and basins (Doblas, 1991; Doblas *et al.*, 1994a; Hernàndez Enrile, 1991) are interpreted as a Basin-and-Range-type extension (Doblas, 1991).

Brittany

Gapais *et al.* (1993) have argued that most ductile stretching, LP-HT metamorphism and related two-mica granites in southern Brittany are Carboniferous extensional features. In Vendée, pervasive, syn-metamorphic deformation of early-Palaeozoic sequences is better interpreted in terms of Carboniferous extension during plutonism in a foreland area (Goujou, 1992). Extension is nearly parallel to the belt, actually implying important wrenching. Extension related wrenching is consistent with intracontinental tholeiicic magmatism and strongly subsiding, lower Carboniferous pull-apart basins (namely Châteaulin, Laval, Morlaix and Ancenis) formed on the Precambrian continent of Central Brittany (Rolet *et al.*, 1986).

French Massif central

Since 1989, Faure and collaborators have persistently shown that the Namuro-Westphalian granitoids of the French Massif central have a magmatic fabric that indicates a bulk NW-SE to E-W magmatic stretching attributed to crustal thinning of the thickened Variscan belt (Faure, 1989; Faure *et al.*, 1990; Dumas *et al.*, 1990; Faure and Pons, 1991; Faure *et al.*, 1992; Faure and Becq-Giraudon, 1993). The best documented structure is a symmetrical dome in Limousin that implies 3 to 8 % extension (Faure and Pons, 1991). In addition, some of the widespread E-W stretching lineations (e.g. Brun and Burg, 1982) may be related to this extension (Mattauer *et al.*, 1988; Faure and Becq-Giraudon, 1993). This may be true in the close surrounding of the plutons only because ages show that metamorphic minerals defining the regional lineation pattern were cooled by ca., and before, 350 Ma (Costa, 1991-1992).

Vosges-Black Forest

Late Carboniferous extension in the Vosges and the Black Forest was first reported by Eisbacher *et al.* (1989) who also noticed that it began while compression still dominated in the Rheno-Hercynian foreland wedge. Detailed study in the Vosges has shown that south-westward detachment faults and associated NNE-SSW transfer faults were developing between 330 and 310 Ma (Rey, 1992; Rey *et al.*, 1991-1992). Extension was accompanied by nearly-isothermal decompression (suggesting nearly 15 km crustal thinning) and granite intrusion. A similar deformation pattern is identified in the southern Black Forest for the same period (Echtler and Chauvet, 1991-1992). The fast exhumation event is probably responsible for the Late Visean emersion and erosion reported in the southern Vosges volcanic province (Schneider, 1990).

Bohemian Massif

Several lines of evidence show that post-thickening extension has taken place but has yet to be documented. A close relationship between compression and extension is recorded in the Early Carboniferous Culmian basins (Rajlich, 1990). Large, low-angle normal faults are suspected around gneiss domes (Mlcoch and Schulmann, 1992) and dominate highly extended terranes (Pitra *et al.*, 1994). Also, low-pressure, regional metamorphism post-dates intermediate and high-pressure metamorphism (e.g. Blümel and Schreyer, 1976; Cháb and Suk, 1978). Orientation data are inferred from fold measurements (Rajlich, 1990) and lineations in leucogranites (Melka *et al.*, 1992).

Alps

The Briançonnais Westphalian basin records the distal accumulation of a huge amount of sediments within a quiet and vast deltaic domain (Courel *et al.*, 1986). In the Southern and Eastern Alps, a synorogenic, foredeep basin was filled with shallow- to deep-marine sediments (Krainer, 1993) that were folded during the Westphalian (Castellarin and Vai, 1981). Intrusion of large volumes of mafic to acid rocks culminates at ca. 330 Ma (von Raumer and Neubauer, 1993). No information is available on the granite related deformation.

Stephanian/Early Permian extension

The "Basin and Range Province of the Permo-Carboniferous Europe" was by name identified in 1976 (Bébien, 1976; Lorenz and Nicholls, 1976). The sedimentary record does no longer permit to discern the range from the foreland. Thick, fault controlled basins indicate widespread tectonic activity and extensional environment throughout the Variscan Belt, in particular its southern branch (fig. 2), foreshadowing the Permian "Variscan" province of (Falke, 1976). Sediments have a proximal origin linked with local, fault related topographic highs. Lava flows and caldeiras depict a strong volcanic activity. Contrarily to previous interpretations, we consider that no major break, from both tectonic and sedimentological point of view, separates the Stephanian and the Early Permian. Whether an unconformity exists depends on variable subsidence and sedimentation rates and/or extension direction during a single extensional event, an argument that can be extended to the so-called Asturian and Saalian phases.

Iberian Peninsula

Continental, clastic to shallow marine sediments and bimodal volcanism deposited in fault controlled, intermontane basins with distinctive half-graben shapes (Virgili *et al.*, 1976). They are attributed to "aborted rifting" in Cantabria (Martínez García, 1990). Terrestrial fills record the Early-Autunian arrival of Gondwanian flora in Europe (Quesada *et al.*, 1990). In Central Spain, no major change occurred between the Early Car-

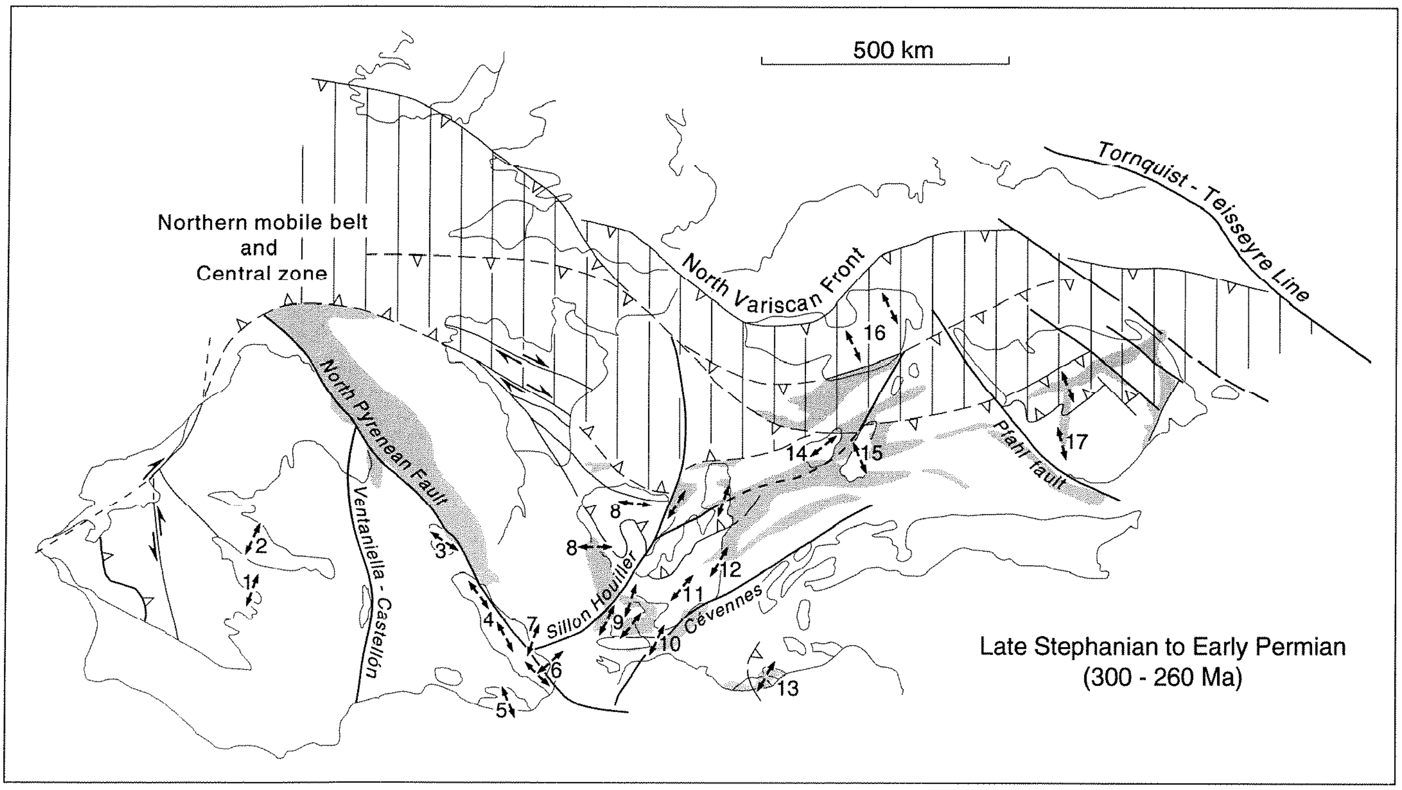

Fig. 2. – Extension direction during Late-Stephanian to Early-Permian times in the Variscan Belt of Western Europe. The main basins are shadowed. Data from: 1: (Azor *et al.*, 1993); 2: (Lillo, 1992); 3: (Hernández Enrile, 1991); 4: (Doblas *et al.*, 1994a); 5: (Martínez García, 1990); 6: (Bixel and Lucas, 1983); 7: (Vissers, 1992); 8: (Lucas, 1987); 9: (Bouhallier *et al.*, 1991); 10: (De Saint Blanquat *et al.*, 1990); 11: (Blès *et al.*, 1989); 12: (David, 1985; Santouil, 1980); 13: (Van Den Driessche et Brun, 1991-1992); 14: (Vergely and Blanc, 1981); 15: (Malavieille *et al.*, 1990); 16: (Toutin-Morin *et al.*, 1993); 17: (Wickert *et al.*, 1990); 18: (Echtler and Chauvet, 1991-1992); 19: (Oncken, 1988); 20: (Holub, 1976; Pesek, 1987).

Fig. 2. – Directions d'extension du Stéphanien supérieur au Permien inférieur dans la chaîne varisque d'Europe Occidentale. Les bassins principaux sont grisés. Données de : 1 : (Azor et al., *1993) ; 2 : (Lillo, 1992) ; 3 : (Hernández Enrile, 1991) ; 4 : (Doblas* et al., *1994a) ; 5 : (Martínez García, 1990) ; 6 : (Bixel et Lucas, 1983) ; 7 : (Vissers, 1992) ; 8 : (Lucas, 1987) ; 9 : (Bouhallier* et al., *1991) ; 10 : (De Saint Blanquat* et al., *1990) ; 11 : (Blès* et al., *1989) ; 12 : (David, 1985 ; Santouil, 1980) ; 13 : (Van Den Driessche et Brun, 1991-1992) ; 14 : (Vergely et Blanc, 1981) ; 15 : (Malavieille* et al., *1990) ; 16 : (Toutin-Morin* et al., *1993) ; 17 : (Wickert* et al., *1990) ; 18 : (Echtler et Chavet, 1991-1992) ; 19 : (Oncken, 1988) ; 20 : (Holub, 1976 ; Pesek, 1987).*

boniferous and the Early Permian extensional events (Doblas *et al.*, 1994b). Extension was paroxysmal during the Stephanian - Early Permian times, resulting in detachment faulting and exhumation of core complexes (Doblas *et al.*, 1994a).

Brittany

The extensional pattern parallel to the orogen persisted up to Stephanian times (Goujou, 1992) while ductile deformation involved synkinematic intrusions as young as 290 Ma (Peucat, 1983; Vidal, 1980). Narrow and small limnic basins are related to wrenching along the South Armorican Shear Zone (Rolet, 1984).

French Massif central

Crustal thinning led to the formation of metamorphic core complexes bound by detachment faults which controlled the opening of throughs where clastic sediments accumulated. Periglacial deposits suggest mountain altitudes of 5 000 m (Becq-Giraudon and Van Den Driessche, 1994). The Stephanian-Autunian extension is characterised by directions sub-perpendicular to the Variscan belt in Eastern Massif central. Important crustal thinning is emphasised by rapid uplift to the ductile, mid-level crust below detachment systems (Echtler and Malavieille, 1990; Malavieille *et al.*, 1990; Van Den Driessche and Brun, 1991-1992; Lagarde *et al.*, 1993). Basins developed in the hangingwall of the detachment systems and mostly display asymmetric patterns (Santouil, 1980; Legrand *et al.*, 1994).

Pyrenees

Stephano-Permian basins are half grabens filled with continental alluvium materials and volcanites (Bixel and Lucas, 1983; Lucas, 1987). They are associated with an E-W sinistral transcurrent fault in the north-western Pyrenees, and controlled by N-S fractures in the south-eastern Pyrenees (ibid.). Extension developed in two different manners: South of the present North Pyrenean fault, both patterns of basement ductile deformation and basin infilling indicate E-W extension (Lucas, 1987; Vissers, 1992), i.e. parallel to the orogen trend. In contrast, extension is roughly N-S, north of the North Pyrenean fault and east of the Sillon Houiller (De Saint Blanquat *et al.*, 1990; Bouhallier *et al.*, 1991).

Vosges - Black Forest

Structural data are lacking but as young as Late-Stephanian/Early-Permian sedimentation is taking place in nearly E-W trending, narrow basins, suggesting a nearly N-S extension, a direction supported by stress tensor calculations from striated planes in granites (unpublished reconstitution, Maurin, pers. comm. 1994).

Bohemian Massif

The Carboniferous/Permian boundary is in place continuous and elsewhere marked by an unconformity (Holub, 1976). Rapidly subsiding, intramontane basins that began to form in Westphalian times are associated with volcanism that culminated in the Autunian. The limno-deltaic and fluvial sediments are localised into long and narrow half-grabens faulted on their eastern boundary (Svoboda, 1966). In the basement, low-pressure anatectic rocks are dated Late Carboniferous suggesting here also exhumation of mid-crustal crust (e.g. Grauert *et al.*, 1974).

Alps

Thick continental and shallow marine shelf sediments and volcanic rocks of Late Carboniferous to Early Permian age were deposited in fault-controlled, intramontane basins (Krainer, 1993). Late plutonism took place by ca. 295 Ma; (von Raumer and Neubauer, 1993). Later Alpine deformation hampers the definition of transtensional or transpressional frameworks.

Sardinia

Although figure 2 does not include Sardinia because of its poorly constrained position in the belt, it is noteworthy that two extension directions are observed (Musumeci, 1992; Carmignani *et al.*, 1994). The first is parallel to the strike of the belt and has been ascribed to ductile wrenching, synchronous with HT-LP metamorphism, partial melting and plutonism. The second corresponds to orogen-orthogonal extension within more or less brittle detachment zones that rework previous ductile fabrics. Both stretching events make a striking comparison with what is described above. They have been ascribed to strain partitioning during post-thickening extension (Musumeci, 1992).

Transfer fault zones

Two striking observations stem from the pattern of the Stephanian-Permian extension directions (fig. 2): (1) There are zones with extension essentially transverse to the orogenic belt adjacent to zones with extension sub parallel to it, and (2). It can be readily seen on the figure that domains with different bulk extension directions are separated by major fault zones. Two examples are the Sillon Houiller and the North Pyrenean Fault, which appears as major discontinuities created during extension between zones with differing extension directions.

Sillon Houiller

Concerning the Sillon Houiller, we proposed this hypothesis as an explanation for the puzzling small strike-slip offset 70 to 100 km (Grolier and Letourneur, 1968) on a several hundred kilometres long fault, compared with several hundred kilometre movements along large continental strike slip faults as in Asia, for example (Tapponnier and Molnar, 1977; Tapponnier *et al.*, 1990). In our model (Burg *et al.*, 1990) this coal-basin related fault separates a zone of transverse, large extension to the east, comparable to that of the north-Western America Province, from a zone extended nearly parallel to the orogen to the west. Maximum extension is expected in the former area where, interestingly, largest areas of low-pressure terranes and gneiss domes are known (Chenevoy and Ravier, 1971).

North Pyrenean Fault

The Variscan orocline is interpreted by a simple kinematic relationship between relative plate motions of Gondwana indenting Laurussia (Bard *et al.*, 1980; Brun and Burg, 1982; Matte, 1991) which does not predict the origin and location of the North Pyrenean fault within the Iberian indenter. We admit that the thermal structure of the Variscan crust in the Pyrenees is dominated by an extension regime associated with strike-slip movements (Wickham and Oxburgh, 1985). This interpretation is consistent with thick sequences of carboniferous and Permian sediments on the northern side of this fault (Paproth, 1987) and provides and elegant explanation for the 150-200 km shift of the Iberian Peninsula along the North Pyrenean zone (Arthaud and Matte, 1977). Accordingly, we believe that the right lateral displacement is due to oblique extension including pull-apart segments of transforms before inception of the relative sinistral movement of Iberia with respect to Europe during the Mesozoic. The two sub orthogonal directions of extension identified in the Pyrenees (fig. 2) emphasise the necessary occurrence of a North Pyrenean, transform-like fault to accommodate differential strain patterns within neighbouring areas. This would provide and explanation for the location of this major fault created within the Ibero-Armorican arc whilst it would seem easier to reactivate the parallel suture zones in South Armorica and in Iberia the Coimbra-Cordoba shear zone. The possible transfer character of the South Armorican Shear Zone has been evoked by (Gapais *et al.*, 1993).

Other probable transfer faults

Extending similar arguments to large and long fault systems of late Variscan age in Europe, several appear transfer faults. For example, the Ventaniella-Castellón fault (Juliver, 1983; Sopeña *et al.*, 1988) separates in Spain a NE region with EW extension from a SW region with NS extension. A difference in extension styles may be more dramatic with the Cévennes fault zone from southern France to its northeastward continuation beyond the Alps and Jura Belts. It controls Stephanian to Permian half-grabens and seems to have played a prominent role in the Permian, separating the Variscan from the Verucano provinces (Falke, 1976). In the Vosges, the Ligne des Crêtes fault contains a leucogranite and separates domains with SW-SE carboniferous extension (Rey, 1992) from the eastern part where extension is dominantly NW-SE (Krohe and Eisbacher, 1988). Finally, the western and eastern boundaries of the Bohemian Massif (the Pfahl fault-Franconian line and Elbe and Tornquist-Teisseyre lines, respectively) controlled large Carboniferous basins and Upper-Carboniferous half-grabens (Pozaryski and Radwanski, 1979).

Global scheme

As a working hypothesis, the chief features of late to post Variscan extension tectonics may be summarised as follows:

Predominantly Late Visean-Westphalian

Early extension took place during the waning continental convergence. It is recorded in granites and volcano-sedimentary basins corresponding to variable amount (often less than 10 %) of extension nearly parallel to the belt, which is emphasised by wrenching tectonics reactivating thrust zones. Extension is diachronous, beginning in the inner, thickest parts of the belt. It does not induce much thinning of the crust but rather attenuates crustal thickening by lateral extrusion and/or escape tectonics during continental convergence.

The following scenario may be written. As a consequence of combined buoyancy forces in the thickened and thermally relaxing crust formed by the Early Devonian collision (Matte, 1983; Burg *et al.*, 1987; Matte, 1991) and still active compression forces. Depending on the amount of crustal thickening and the time required for subsequent thermal relaxation, body forces had increased sufficiently and the lithosphere weakened enough during Late Visean-Westphalian times to let the thickened and thermally relaxing crust spread under its weight. The still overwhelming compressive, tectonic forces drove the chain to spread laterally. Such a process results in the limitation of crustal thickening in the internal parts of the chain and favours propagation of crustal thickening towards more external areas, a foreland migration recorded also by plutonism in the French Massif Central (Duthou *et al.*, 1984). Rapid uplift in locally extending mountains and transition from marine to continental sedimentation was induced by crustal isostatic rebound eventually induced by thermal thinning of the mantle lithosphere (Gaudemer *et al.*, 1988) or gravitational detachment (delamination of Bird, 1979, as inferred by Lorenz and Nicholls, 1984). It is noteworthy that extension coeval with lateral crustal extrusion seems to happen only where continental collision comprises an arcuate geometry. For example, orogen-parallel extension has not been described in the rectilinear, western North American Cordillera whose generalised orogen-orthogonal extension developed during the Tertiary. In contrast, syn-convergence, orogen-parallel extension is reported in both the Alps (e.g. Ratschbacher *et al.*, 1989) and the Himalayas, including the Tibetan Plateau (Molnar and Tapponnier, 1975; e.g. Armijo *et al.*, 1986). Orogenic syntaxis may be essential for compensating crustal shortening by escape tectonics.

Stephanian to Early Permian

Stephanian to Early Permian extension implies complex changes in extension direction with respect to the orogen trend and several tens % stretching and correlative thinning of the crust. The European Variscides are then characterised by low-pressure metamorphism (Wickham and Oxburgh, 1985), detachment faulting and consecutive ductile crust exhumation resulting in granite-migmatite-gneiss extensional domes and rifted continental crust (see references above). This event is induced by the gravity collapse of the entire thickened domain after continental convergence, independently of its thickening stage. The tectonic process results in rapid thinning allowing the crust to recover a "normal" thickness but enlarging initial width of the belt.

The origin of Stephanian-Permian extension meets two explanations: First, the width of the thickened domain may have been sufficient to produce vertical, buoyancy forces able to overwhelm the horizontal, compressive forces due to plate convergence. The entire thickened belt would spread sideways, forelandward, except within the Ibero-Armorican arc whose arcuation constrained ductile flow toward the less resistant boundaries of the collisional system. The alternative, which we prefer because we do not see any oscillating balance between buoyancy and convergence forces, is to consider a major change in plate kinematics during the Stephanian to Early Permian. It resulted in the decline of horizontal compressive forces along the orogen boundaries, subsequently allowing the thickened and thermally relaxing crust to collapse. Comparatively, the Basin and Range province has a free continental boundary along the Pacific side. Changes in convergence rate along the western edge of North America may have also caused extension in the Basin and Range (e.g. Coney, 1987). In the Variscan case the "unknown plate" advocated by Arthaud and Matte (1977) south of the dextral shear system (their figure 9) is, therefore, not necessary. At this state of knowledge, both hypothesis are left opened.

Extension estimates; experimental approach

For simple geometric reasons, the Visean-Westphalian event implying extension parallel to the belt had little effect on the thrust structures imaged by cross-sections. How important the Stephanian-Permian extension is has to be addressed, in particular where extension is transverse to the belt. On a rheological point of view, the time between convergence and the syn- to post-orogenic extension was long enough for thermal relaxation to evolve in the thickened crust (England and Thompson, 1984, 1986; Sonder *et al.*, 1987), producing in effect the huge amount of late Variscan granites. Hence, we have to take into consideration a rheologically two-layer system. Depending on the thermal gradient, there is a 10-20 km thick, brittle, upper crust above a 30-40 km thick, ductile lower crust that may be very weak if it is partially molten and granites are abundant (Kusznir and Park, 1987; Meissner and Kusznir, 1987). From these considerations and in order to estimate the amount of extension, we have developed structural methods based on experimental extension of two-layer brittle/ductile analogue models. The results must be considered to be approximated by a minimum 20 % error.

Principles of modelling

Extension of two-layer brittle/ductile systems has been investigated through laboratory experiments on analogue models where the brittle upper crust is represented by a sand layer, a Mohr-Coulomb material with a mean 30° friction angle, and the behaviour of the ductile lower crust is simulated by silicone putty, a Newtonian fluid of 10^4 Pa.s viscosity at room temperature. The experimental procedure, validity of the scaling including for gravity forces, detailed discussion of the physical properties and the geological relevance of such models can be found in several works (e.g. Faugère and Brun, 1984; Vendeville *et al.*, 1987; Davy and Cobbold, 1991). It is worth noting that in any experiment faults initiate as steeply-dipping normal faults (60°) defining a limited number of grabens and tilted blocks in the brittle layer. During the progressive extension, they commonly rotate to lower dips, implying rotations of initially flat lying markers during progressive extension. As a direct consequence, extension of two-layer systems does not occur everywhere but instead takes place in regularly spaced sites, leaving virtually undeformed areas between the extending sites, looking like a mechanical instability naturally represented by boudinage (Faugère and Brun, 1984; Vendeville *et al.*, 1987; McClay *et al.*, 1991). This large scale behaviour explains how regions (equivalent to the boudins) that have preserved dominantly convergence structures are identified between (necking) regions dominated by extensional deformation.

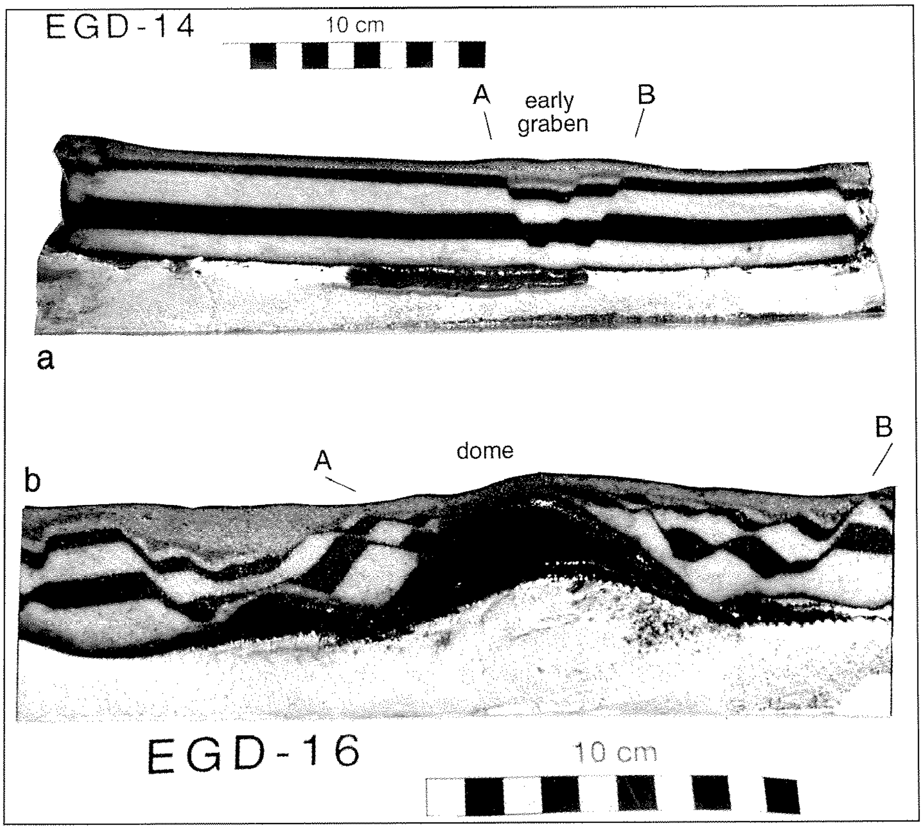

Fig. 3. – Analogue experiment of a detachment system with associated core complex (after Brun *et al.*, 1994). a) initial setting representing brittle-ductile rheological layering in a thickened crust after thermal relaxation: 1/3 = upper layer of sand over 2/3 = a silicone ductile layer. A low-viscosity heterogeneity (dark) was introduced within the ductile layer, modelling a zone of partial melting or granite intrusive. EGD 14: initial stage (bulk extension = 10 %) shows that extremities of the low viscosity body (point of strongest rheological heterogeneity) localise the site where extension of the brittle layer takes place during gravity collapse. EGD 16: amplified domal structure localised by the less viscous body and associated detachment sytem after 100 % bulk extension. Note strong rotation of layers on the dome limbs. A and B are initial, marking faults.

Fig. 3. – Expérience analogique d'un système de détachement et d'un dôme associé (d'après Brun et al.*, 1994). a) Le stade initial comprend un littage rhéologique fragile-ductile d'une croûte épaissie après la relaxation thermique : 1/3 = de croûte supérieure fragile simulée par du sable sur 2/3 en épaisseur de silicone ductile. Une hétérogénéité de faible viscosité (sombre) est introduite dans la couche ductile pour simuler une zone en fusion partielle ou un granite. EGD 14 : stade initial (extension = 10 % environ) montrant que les extrémités du corps à faible viscosité (point de plus forte hétérogénéité rhéologique) localise le site où l'extension de la couche fragile apparaît. EGD 16 : structure en dôme amplifié localisé par le corps à faible viscosité après 100 % d'extension. Noter la forte rotation des couches dans les flancs du dôme. A et B sont des failles repères.*

Dimensions of extension-related domes of ductile crust: detachment faults and core complexes; roll-under structure

Experimental result and extension calculation

Localised extension results in a main, upward convex detachment fault allowing the ductile layer to raise whilst heterogeneous deformation of the brittle crust is accommodated by a pervasive flow of the ductile crust (fig. 3b). No fault offsets the initial brittle-ductile interface along which shear due to relative displacement of the overlying brittle crust blocks results in a horizontal décollement at the onset of extension. Of structural interest to us is that one limb of the dome-like structure is bounded by the detachment fault zone whereas the other limb results from block rotation forming a roll-under of the footwall (fig. 4d, e, f). As a result of this rotation, the transition zone between brittle and ductile layers is brought to the surface, giving a geometric marker to estimate the minimum relative displacement required to exhume the ductile crust (fig. 4).

For these estimates we have to assume that the detachment cuts across the brittle crust. A first calculation step consists in reaching the point where exhumation of the ductile crust begins, which depends on the thickness of the brittle layer. To it, must we add the width of the domal culmination of deep crust that has suffered a history from high temperature, ductile deformation to cooler, brittle deformation.

Application: the Montagne Noire Crystalline Axis

Van Den Driessche and Brun (1991-1992) have argued that strain and metamorphic patterns of the eastern "zone axiale" result from Late-Carboniferous to Permian extension. Gneisses and migmatites forming the crystalline axis raised by roll-under folding of the footwall

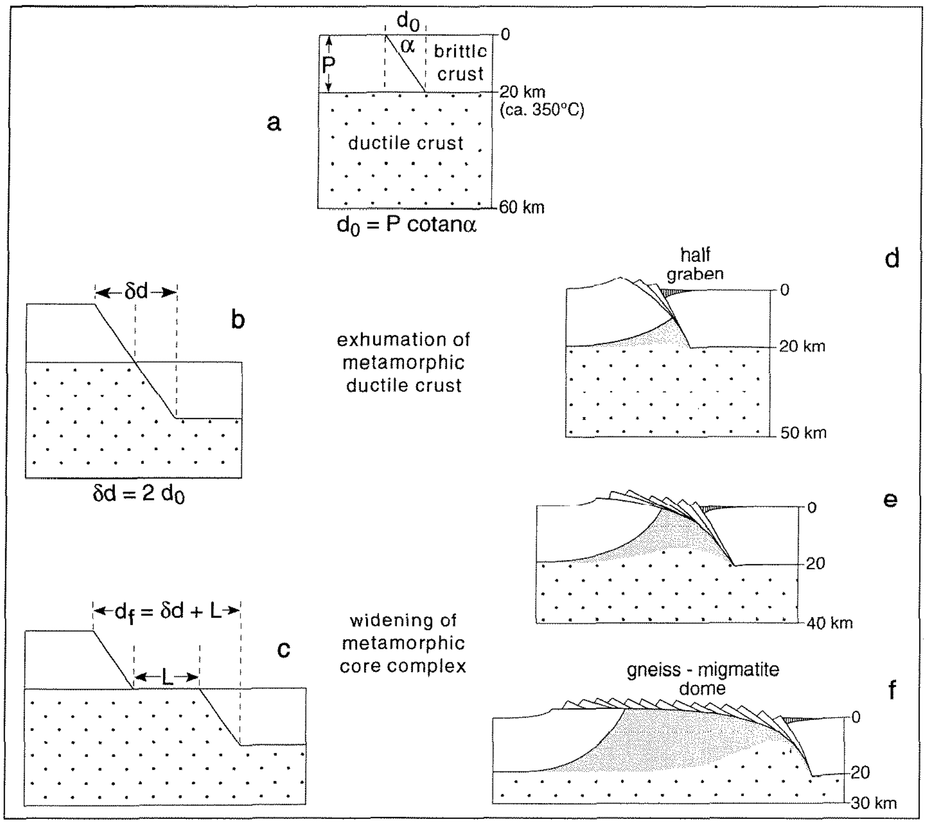

Fig. 4. – Right = sketch of a detachment system and core complex evolution as suggested by the experiment of figure 3. Left = geometrical calculation of the related amount of extension.

Fig. 4. – A droite = schéma d'évolution d'un système en détachement associé à un dôme telle qu'elle est suggérée par l'expérience de la figure 3. A gauche = calcul géométrique de l'extension impliquée.

of a north-dipping detachment inducing tectonic denudation of the ductile lower crust. This interpretation is consistent with early Carboniferous metamorphism and deformation being responsible for recrystallisation of the crystalline axis rock units (eventually Precambrian in age) before they were rolled-under (Demange, 1994). The Stephanian Graissessac basin deposited on the detachment zone, north of the rising gneiss and migmatites. We tentatively take the regional biotite isograde known on the southern limb of the dome as the initial brittle/ductile transition temperature at a depth of 10 to 15 km (4 to 5 kbars, Thompson and Bard, 1982), permitting "Caledonian" ages (415-445 Ma) to be preserved (Gebauer and Grünenfelder, 1976) at shallower depths. The average width of denuded ductile crust parallel to the extension direction is ca. 20 km (fig. 5). Applying the geometric calculation mentioned, 40 to 50 km of horizontal movement are to be inferred on the major detachment fault with an initial dip of 45°.

Early crestal grabens in the hanging wall of a décollement; roll-over structure

Experimental result and extension calculation

Experiments simulating a listric normal fault (fig. 6) show that early crestal grabens form in the hanging-wall brittle layer almost directly above the connection line between the ramp and flat segments of the fault (Ballard, 1989; McClay *et al.*, 1991; Roure *et al.*, 1992). Further extension is responsible for a roll-over geometry with a large, hanging-wall, half-graben basin that commonly overlaps the early crestal graben (fig. 6 and 7a). A simple geometric relationship (fig. 7c) shows that if one can identify early, relatively narrow grabens on one side of an asymmetric, roll-over

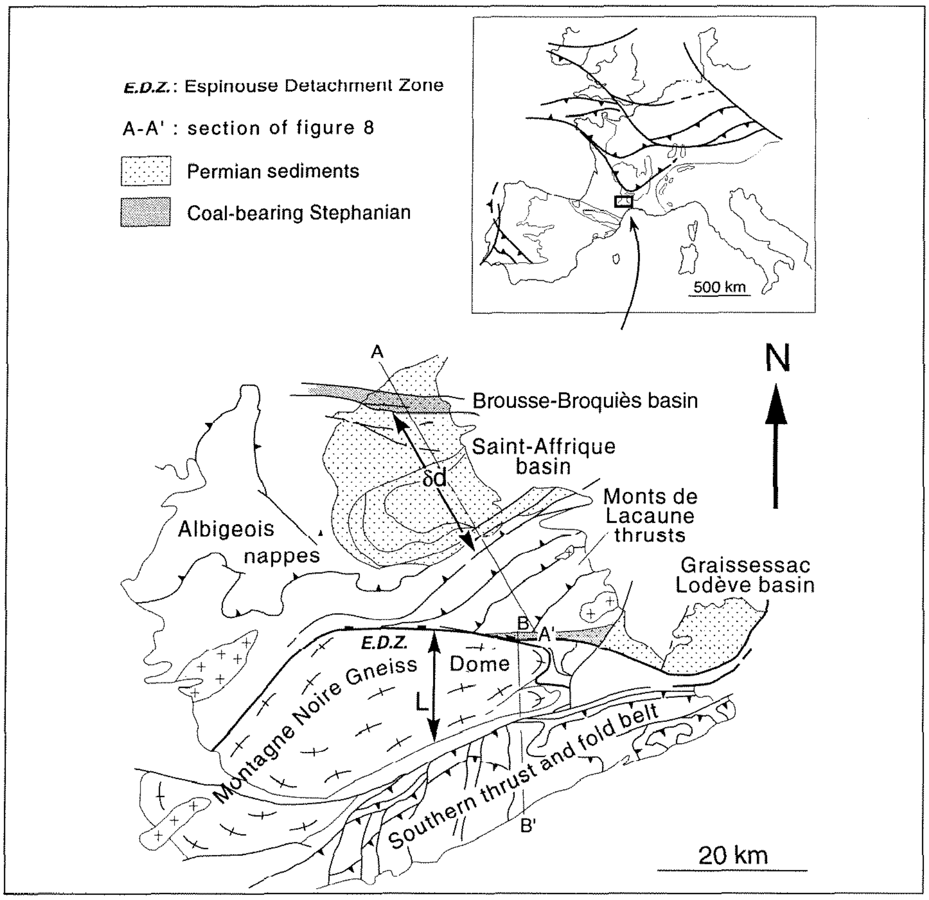

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Fig. 5. – Structural sketch map of the extension system in the southern Massif central. L and δd refer to values defined in figure 4.

Fig. 5. – Schéma structural du système extensif du sud du Massif central. L et δd sont définis dans la figure 4.

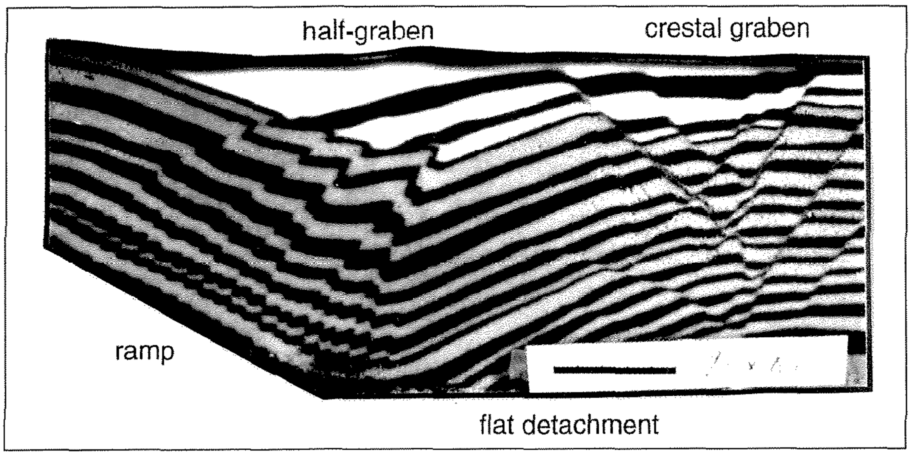

Fig. 6. – Experimental sand model of hanging wall deformation and basin pattern above a flat and ramp, extensional decollement (Faugère *et al.*, 1986). A crestal graben was initially developing above the flat and ramp connection, and progressively moved outward with regard to the ramp. The mobile side (to the right) was connected with a basal plate ending in the centre of the model. Displacement induces a basal velocity discontinuity which results in the development of an asymmetric graben bounded by a single normal fault on the mobile side. Note the asymmetry of the basin and compare with experiment E44 of Mcclay *et al.* (1991).

Fig. 6. – Modèle analogique de sable avec remplissage de bassin déformé au-dessus d'un système en plat et rampe (Faugère et al., *1986). Un graben précoce apparaît au-dessus de la jonction entre le plat et la rampe, puis s'éloigne progressivement de la rampe. Le côté mobile (à droite) est relié à une plaque basale qui s'arrête au milieu du modèle. Le déplacement induit une discontinuité de vitesse qui créée un graben dissymétrique limité par une faille normale. Remarquer la dissymétrie du bassin et comparer avec l'expérience E44 de McClay et al. (1991).*

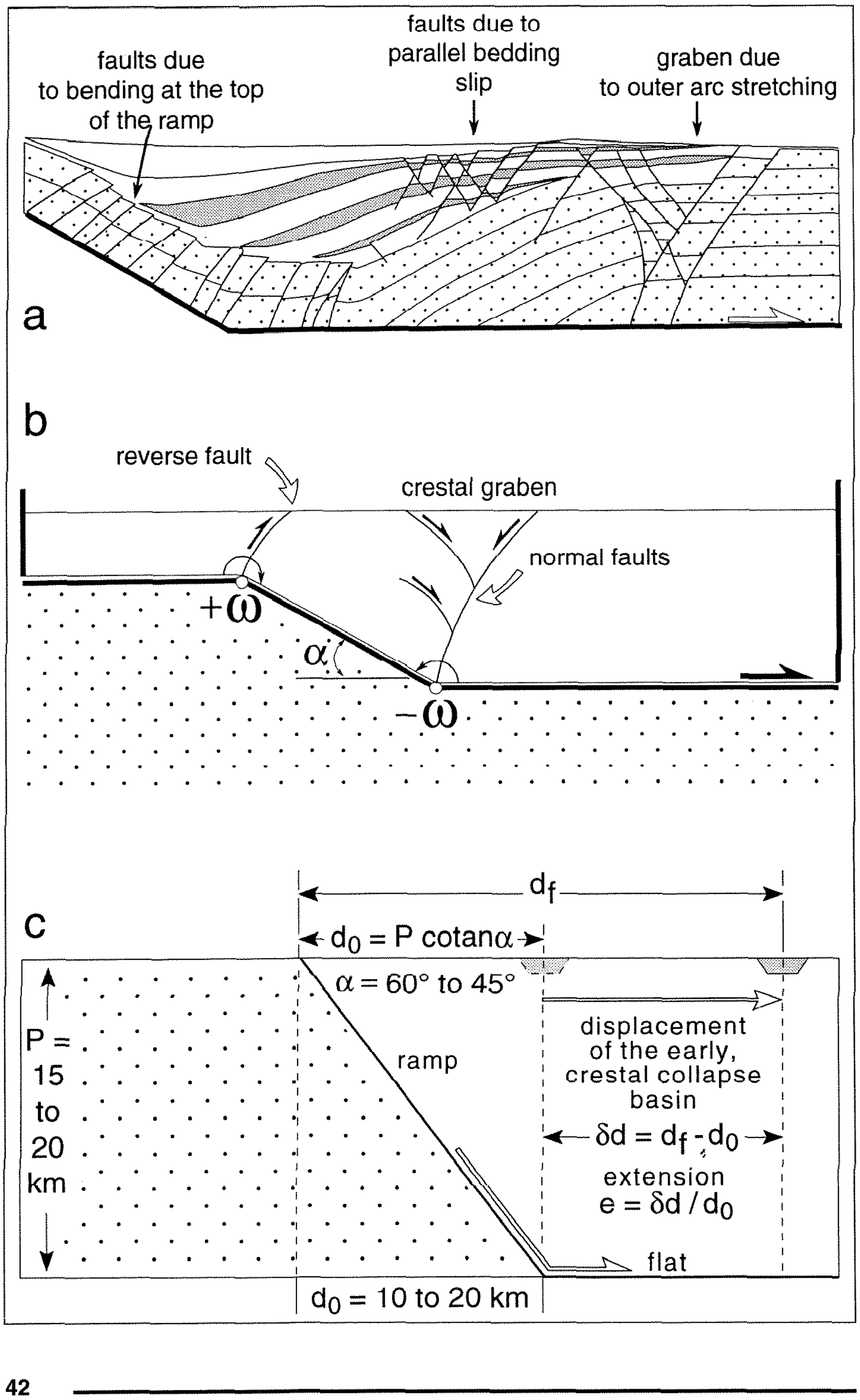

Fig. 7a. – Explanations of the main features in a sand experiment of flat and ramp detachment as in figure 6. b: Interpretation of fault pattern initiated at the onset of extension. + ω and - ω are bending moments at the top and base extremities of a blind ramp inclined at and angle α. Normal faults define a crestal graben above the ramp and flat connection (after Ballard, 1989), see also (Roure *et al.*, 1992). c: Sketch to illustrate the geometrical calculation of extension with a crestal rift/asymmetric basin system. Light grey and black: basin infilling; dark grey: basement.

Fig. 7a. – Explication des caractères principaux de l'expérience de la figure 6. b : Interprétation des failles formées en début d'extension. + ω et - ω sont des moments aux extrémités supérieures et inférieures d'une rampe inclinée d'un angle α. Les failles normales définissent un graben d'extrados au-dessus du point de jonction entre la rampe et le plat (d'après Ballard, 1989, voir aussi Roure et al., *1992). c : Schéma illustrant le calcul géométrique de l'extension à partir d'un graben précoce d'extrados et d'un bassin dissymétrique. Grisé et noir : remplissage du bassin ; gris sombre : socle.*

basin, the relative displacement δd of the graben can be measured, hence permitting a good approximation of crustal extension. Major inaccuracies stem i) in the estimate of the thickness P of the brittle part of the crust assuming that the major flat (décollement) follows the brittle/ductile rheological transition zone and ii) the dip of the ramp α which, according to the Mohr-Coulomb behaviour of brittle rocks, is 60 to 45°.

Application: Saint-Affrique-Broquiès Basins

Sedimentological and structural investigations of the Saint-Affrique basin (fig. 5) have shown that the asymmetry of the basin filling and southward tilt of layers were controlled by a roll-over semi-anticline in the hangingwall of an extensional detachment system during Late-Stephanian to Permian times (Legrand *et al.*, 1994). 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 mapped in the underlying "schistes de l'Albigeois" (Guérangé-Lozes, 1987). The northern part of the Saint-Affrique basin is occupied by the nearly E-W, narrow Brousse-Broquiès graben filled by Upper-Stephanian sediments and lavas (Arbey *et al.*, 1982). We suggest that it is a crestal graben developed at the onset of regional extension. Geometric relationships of figure 7 applied to this example suggest that the Brousse-Broquiès basin may have moved 10 to 20 km northward (fig. 8). We assume a large part of this hanging wall displacement to be related to the Espinouse Detachment System (fig. 5 and 8) thus accommodating essentially the exhumation of the Montagne Noire Crystalline Axis in Stephanian to Early Permian times.

A bulk amount of 50 km horizontal extension, representing a minimum 50 % extension for the whole area, including the Montagne Noire and the Albigeois, seems reasonable. Although there are rare estimates proposed by other authors, other Stephanian-Permian basins commonly account for more than 30 % extension (e.g. Henk, 1993).

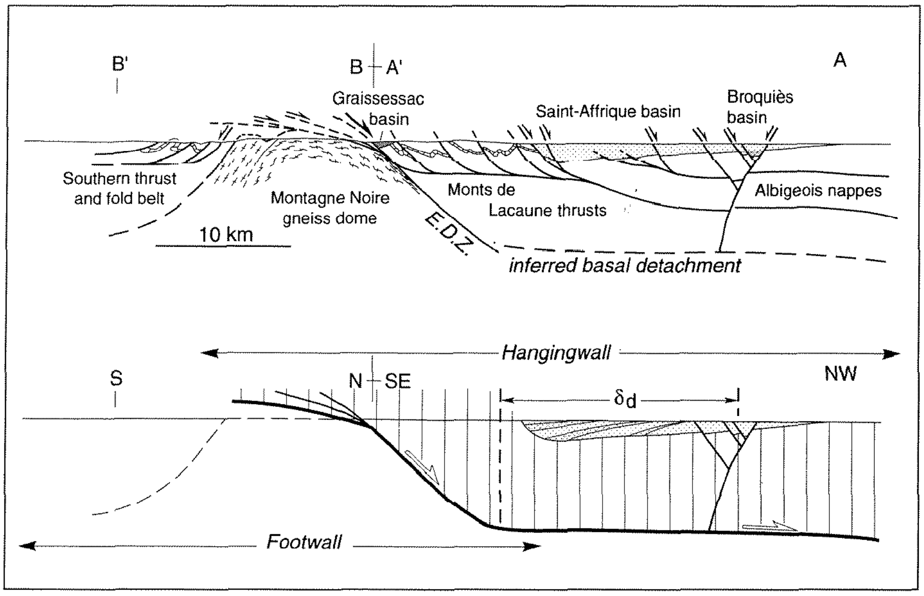

Fig. 8. – Top: Cross section of the Upper Stephanian-Lower Permian extensional system of figure 5. Bottom: Interpretation of the Saint-Affrique and Brousse-Broquiès basins development δd: inferred northward displacement of the Stephanian Broquiès basin during extension (compare with fig. 3 and 7a).

Fig. 8. – Coupe du système extensif Stéphanien supérieur-Permien supérieur de la figure 5 avec l'interprétation (dessous) des bassins de Saint-Affrique et Brousse-Broquiès. δd : est déduit du déplacement vers le nord du bassin stéphanian de Broquiès pendant l'extension (comparer avec fig. 3 et 7a).

Consequences on the collision structures

We now investigate the consequences of extensions on the finite structure of the Variscan Belt. The nearly orogen-parallel, Visean-Westphalian extension event that developed essentially symmetrical plutonic domes (Faure and Pons, 1991) has little effect on the transverse sections. On the contrary, large horizontal movements are involved in the Stephanian-Early Permian, at a high angle to the belt. Related structures are identified, and we removed from the present day sections the extension related surficial width appreciated according to half-grabens, granites or core complexes, and applying the rule that extension sites to be removed separate nearly untouched domains. The remaining, nearly untouched segments are adjusted to restore a preliminary, pre-extension section. The successive steps are shown on figure 9, 10 and 11 on the well known and representative sections of the Variscides by Matte (1986) across the Iberian Peninsula, the French Massif central and the Bohemian Massif, respectively. In this work, we consider only the inner part of the Ibero-Armorican arc, that is the southern belt of the Variscides. The inferred extension amount is given in the figures.

In the eastern part of the Iberian Peninsula, Stephanian to Permian basins are scarce. However, crustal E-W extension is indicated by pervasive subhorizontal kinking and crenulation (Matte, 1969) and by detachment fault/dome complexes such as the Vivero normal fault/Mondoñedo dome and the Allende fault/Narcea dome complexes (Pérez-Estaún *et al.*, 1991). These structures imply amounts of extension at least equal to the culmination width. Granite related stretching is important in Western Galicia, developing in places grabens as the Malpica-Tuy uni (Pérez-Estaún *et al.*, 1991), and possibly the flat bottom of the Ordenes klippe, although its shape may be related to very early, Devonian extension (Martínez Catalán and Arenas, 1992). In any case, the width of the culminations can be removed from the present day section, making an overall 120 km of late, horizontal extension across the nearly 400 km wide Variscides in Northern Iberia.

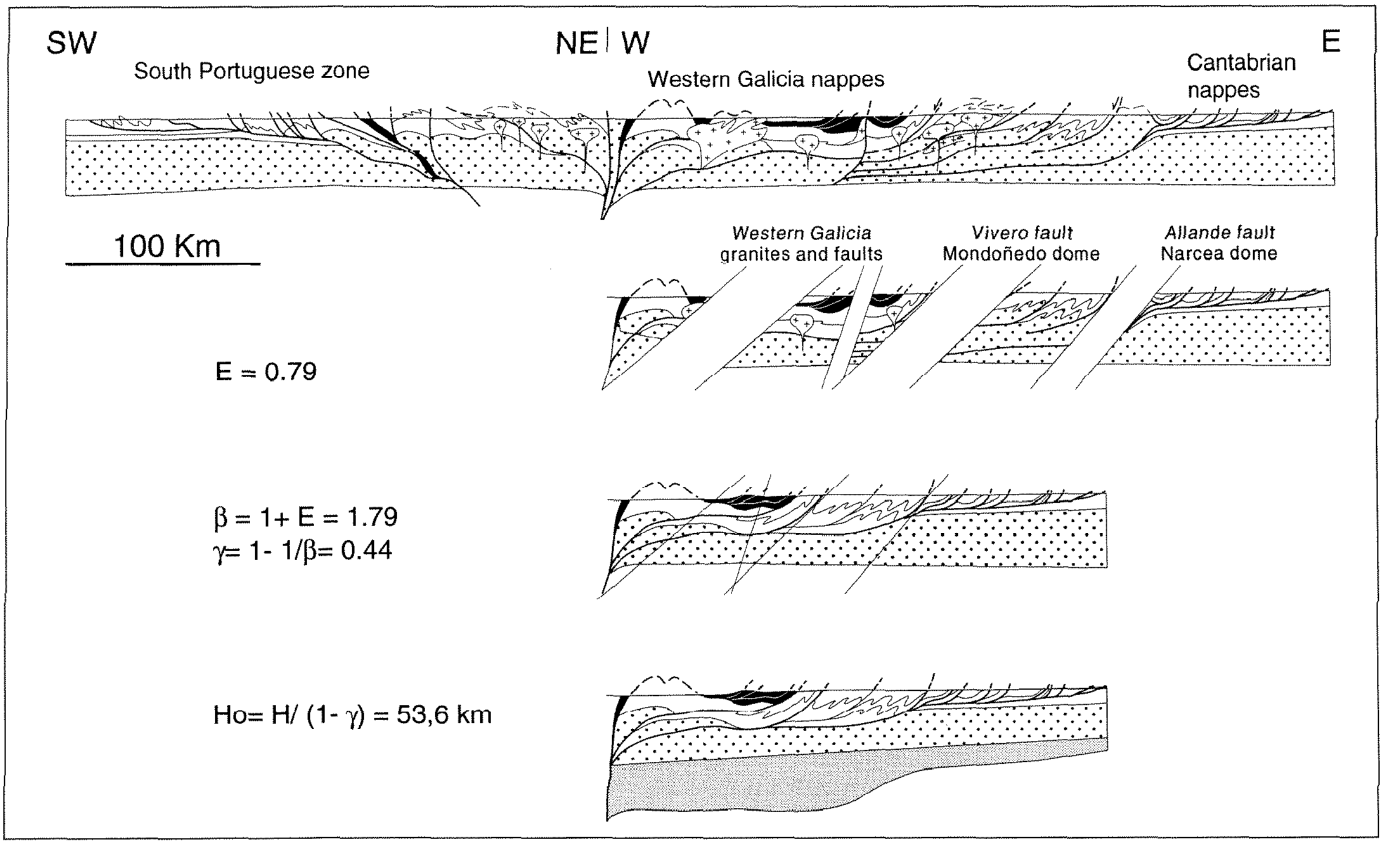

Fig. 9. – Restored section of the northern Iberian Peninsula ornaments and top section modified after Matte (1991). The extensional sites have a dip consistent with the asymmetry of related extensional structures, there length is calculated using geometrical derivations of figures 4 and 6. The dip angle is approximate and is of no consequence on the restoration.

Fig. 9. – Coupe restaurée du nord de la Péninsule Ibérique ; en haut, coupe modifiée d'après Matte (1991). Les sites extensifs ont un pendage cohérent avec la dissymétrie des structures, leur longueur est calculée par dérivation géométrique des figures 4 et 6. Le pendage est approximatif, ce qui est sans conséquence sur la restauration finale valable à 20 % près.

In the French Massif central, several Stephano-Permian basins are to be taken into account. Besides those of Graissessac and Saint-Affrique, the Rodez basin developed on the northern, mylonitized side of the Palanges dome (Burg *et al.*, 1986) in which northward senses of shear can be observed (unpublished data). This dome/basin system yields nearly 30 km horizontal extension. Farther north, in the Haut-Allier, several basins (namely Langeac, Brioude and especially Brassac) seem to accommodate laterally ca. 45 km of the unquantified horizontal extension involved in the Velay dome (Malavieille *et al.*, 1990), to the west of the presented section. The question comes as to whether the Haut-Allier area is a klippe belonging to the thrust nappe known in the Sioule (Grolier, 1971). We prefer to root the Haut-Allier thrust system not far to the north, in the continuation of the Monts du Lyonnais (Demay, 1948; Burg and Matte, 1978). In effect, above this major thrust, the so-called Morvano-Roannais domain is characterised by early erosion and unconformable Late-Devonian to Visean sedimentary and volcanic series (Vennat, 1985). We take this different timing and mode of deformation as a fundamental criteria to define a separate domain whose extension is tentatively approximated as the width of the huge pluton recognised in the region (fig. 10).

Due to lack of pertinent data, appreciating extension of the Bohemian massif is more intricate. A bulk amount of extension equal to the width of the elongated South-Bohemian pluton is tentatively inferred over the Moldanubian area, taking into account that it is a large domal structure dominated by low-pressure matamorphism and intruded at about 330 Ma (Van Breemen *et al.*, 1982). Conversely, we may have to widen the Barrandian domain to unfold late Carboniferous folding along the boundary with the Moldanubian. Extension related to the uplift history of the dome-shaped "granulit-Gebirge", to the north, is likely Late Devonian in age (Franke, 1989). Yet, a Late-Variscan event is pervasively shown by the 320-285 Ma old granitic plutons that occur in the area (e.g. Lenz, 1986).

These restoration are a preliminary exercise that calls for several observations.

– The original, pre-extension throw of the large eclogites-granulites nappes is reduced from nearly 200 km to ca. 100 km, a value which emphasises the importance of extensional processes on the apparently large thrust systems.

– As a corollary, the original width of the belt was significantly narrower than the present day situation. In particular, the eastern Massif central has been substantially more widened by

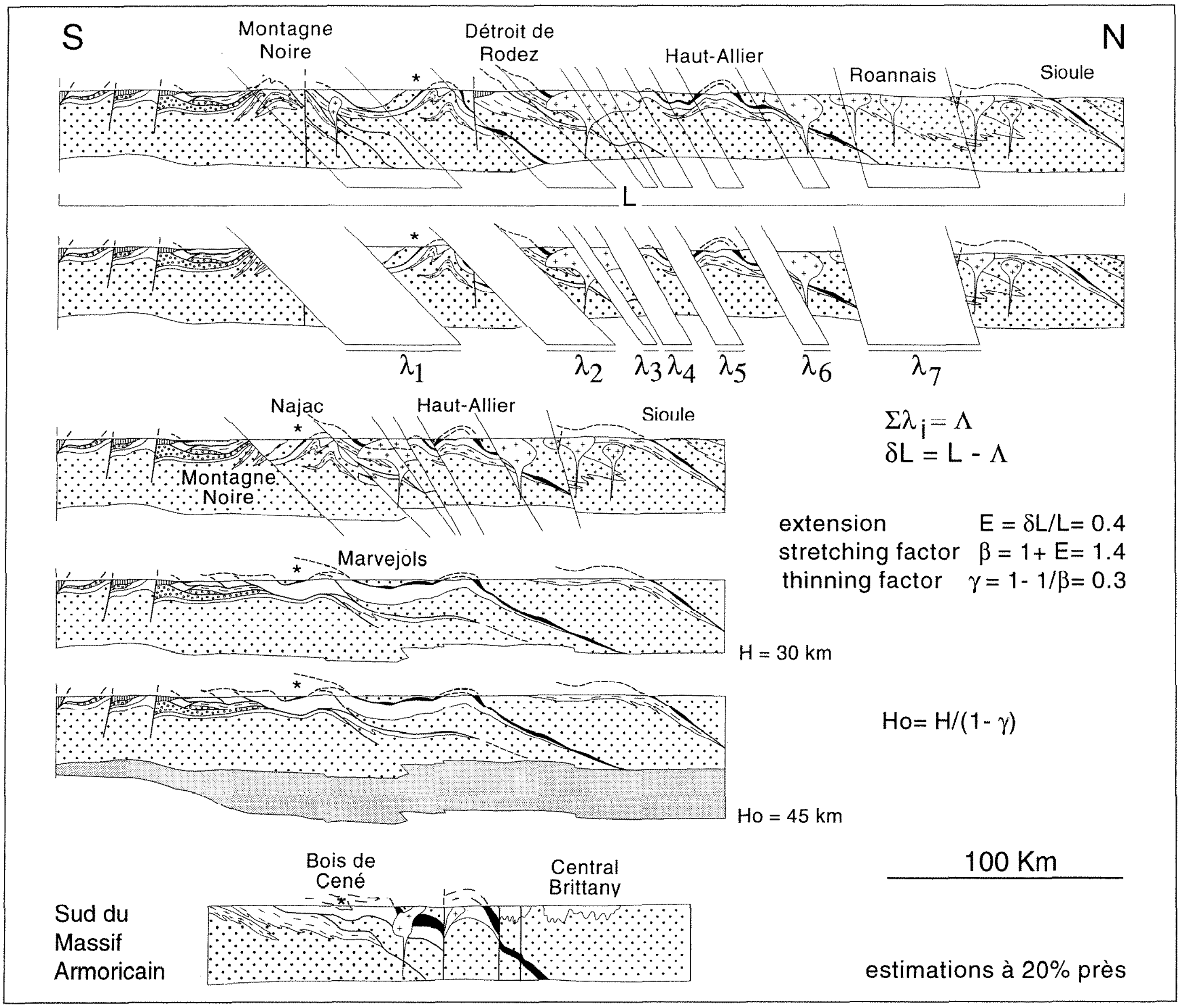

Fig. 10. – Restoration of the Eastern French Massif central section modified after Matte (1986). λi are amounts of shortening on sites discussed in the text, the restoration technique as in figure 9. The Armorican Massif (ibid.) which has suffered little transverse extension is shown for comparison.

Fig. 10. – Coupe restaurée du Massif central oriental modifié d'après Matte (1986). Les λi correspondent au quantité d'extension sur les sites discutés dans le texte, la technique de restauration est la même que pour la figure 9. Le Massif armoricain (ibid.) qui n'a subi que peu d'extension transverse est montré pour comparaison.

post-orogenic extension than the western Massif central and neighbouring Brittany (fig. 10). This means that the so-called Variscan V (Suess, 1888) is a consequence of late orogenic extension, with transfer faults playing a capital role.

– The European lithosphere has inherited from this extension event the major faults that will be active through the Mesozoic and Cenozoic eras.

– A further restoration consists in adding the area removed by extension to the lower part of the reconstructed section. This gives a figure for the minimum depth of the paleo-Moho, emphasising the amount of crustal material redistributed by tectonic processes from the root zones to the higher crust as magmatic rocks and basin infillings during the post-thickening extension (figs. 9-11). For some reason that may reflect our insufficient knowledge on extension in the area, the Bohemian Massif appears noticeably different from the Iberian Peninsula and the French Massif central, questioning whether the collision tectonics there were really comparable to those in western Europe. However, lateral flow of the lower crust, not taken into consideration in this attempt, may account for these differences.

– Finally, movement on extensional crustal-scale faults has an inevitable consequence: block tilting about a horizontal axis (e.g. Jackson, 1987). In particular, it is not clear whether large wavelength undulations remaining on the restored sections are large scale folds related to convergence or a not-eliminated feature of extension related tilts and dome and basin structures as seen on figure 3.

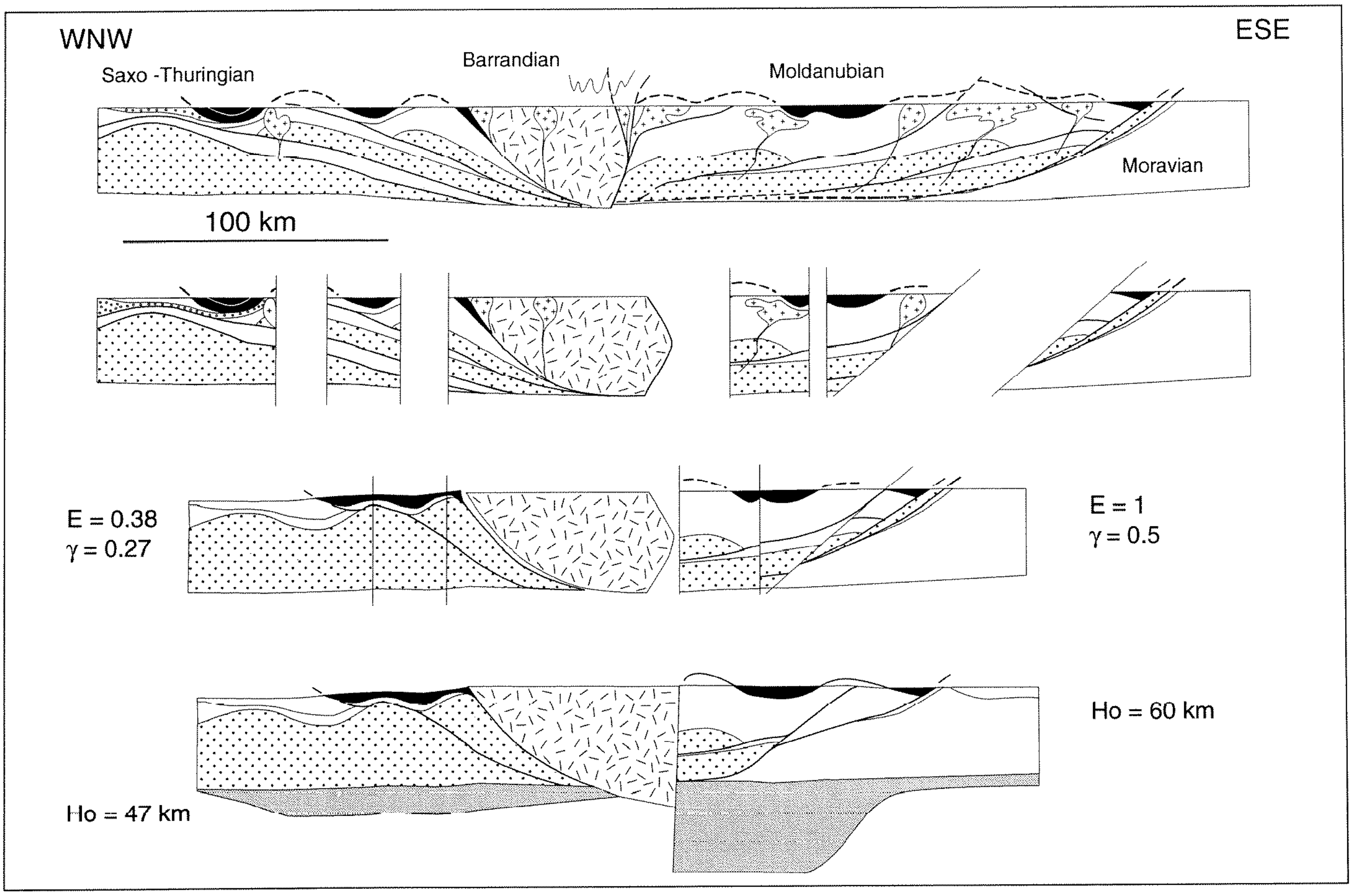

Fig. 11. – Restored sections of the Bohemian Massif as after Matte (1991). Restoration technique as in figure 9. Asymmetric extension in the central Moldanubian area is inferred. Vertical gap are drawn over the other supected, extended domains where asymmetry cannot be guessed.

Fig. 11. – Coupe restaurée du Massif Bohémien d'après Matte (1991). Technique de restauration comme pour les figures 9 et 10. La dissymétrie de l'extension dans le domaine Moldanubien central est deviné. La verticalité des coupes sur les autres sites traduit le manque d'information sur les structures de ces régions. Cette restauration peut être considérée à 50 % près.

Conclusions

Post-compressional extension is a common mechanical evolution that terminates the deformation and thermal histories of the Variscan Belt of Western Europe. Two general points stand out from the present survey of its structural characteristics: 1) Collapse of an orogen varies from one segment to the other in age and in direction. It is not necessarily sub-perpendicular to the mountain chain as implied in most models referring to the North-Western America Province. It begins during the waning convergence, associated with escape tectonics in arcuate belts. 2) Major strike-slip faults can be created during orogenic extensional direction and intensity. They are crustal, and may be lithospheric, discontinuities between areas of different extensional direction.

On a geodynamic point of view, the late Hercynian extension directions are consistent with the relative dextral transcurrent movement envisioned by (Arthaud and Matte, 1977), with no necessity to imply and unknon plate south of the system. We suggest that extensional collapse played a role more important than that played by the transpressive system implied by the Andersonian analysis of the conjugate fault sets (Blès *et al.*, 1989). The W-E zonation of granites (Pupin, 1985) and the voluminous ignimbritic and rhyolitic Permian volcanism known in the Eastern Alps (Falke, 1976) suggest that there was a free boundary on the south-eastern border of the continental mass formed by the Variscan collision, tentatively interpreted as the initiation of Tethys. This might explain why extensional systems essentially symmetrical in Visean times became fundamentally asymmetrical in the Stephano-Permian times.

The non-identification of the late and post-orogenic extensions is probably one of the main reasons that has precluded or seriously hindered direct comparison of correlation of work published by many students of orogenic systems. Many papers have been devoted to the geometric and kinematic analysis of compressional or extensional tectonic regimes. This work shows that this is a dubious procedure because such extrapolations from a described area to prediction about other areas should take into account the syn- to post-orogenic extension.

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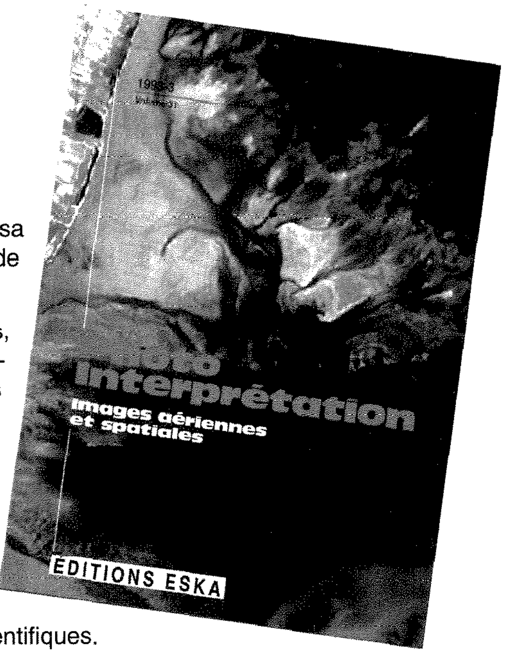

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