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Tectonic levels in the Palaeozoic basement of the Pyrenees: a review and a new interpretation

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Abstract—Two different structural domains, developed during the main Hercynian deformation events, were recognized by de Sitter & Zwart in the Hercynian basement of the Central Pyrenees. A deep-seated level (infrastructure) made of medium to high-grade metasediments and orthogneisses with dome-shaped gently dipping foliations, contrasts with a shallow level (suprastructure) of low to very-low grade metasediments with rather steep foliations. Since the recognition of this structural zonation, different interpretations have been proposed. Disagreements concern timing of deformation and tectonic regime considered to be prevalent of the structural development of each tectonic level.

The proposed interpretation regards the progressive development and differentiation of both structural domains and considers the following factors to be significant for the structural arrangement of the Pyrenean segment of the Hercynian belt: an increase with depth of the horizontal shear component of deformation related to tangential and transcurrent tectonics, a marked inhomogeneity of deformation and penetrability of related foliations, and the gradual evolution from an earlier compressive crustal shortening event to a late transpressive event responsible for crustal shortening and trend-parallel stretching.

INTRODUCTION

AMONG settings where Wegmann's (1935) concepts of *Oberbau* and *Unterbau* have been used to describe changes in structural style with depth, the tectonic levels distinguished by Haller (1955) in south Greenland and by de Sitter & Zwart (1960) in the Hercynian of the Pyrenees, have become two of the most classical examples. The distinction between an infrastructure and a suprastructure in the Hercynian basement of the Axial Zone of the Pyrenees (Fig. 1), emphasizes the difference of attitude of the main Hercynian foliation and related folds. In deep seated metamorphic domains, the main fold axial planes and related foliations are flat-lying or gently inclined while in lower-grade shallower domains, the main folds and associated axial plane foliation exhibit steeply inclined attitudes. An analogous structural distinction was later used by Fyson (1971) in a more broad setting, emphasizing that this arrangement is quite common in many orogenic belts and arises as the result of a tectonic style which evolved in space and time. Similar vertical structural zoning in orogenic belts has been distinguished in other areas: e.g. Sanderson (1979) in the Hercynian of Southwest Great Britain, Murphy (1987) in the British Columbia Cariboo Mountains and Matte & Xhu Zi (1988) in the Hercynian of Iberia and the Rheno-Ardennes massif and in the Quin Ling belt of China.

The Pyrenean example described here shows vertical structural zonation in the central Axial Zone (Fig. 1), where Palaeozoic rocks exhibit recognizable Hercynian structures, metamorphism and magmatism, while the effect of Alpine structural overprinting is generally local and restorable. Hence, the suprastructure/infrastructure differentiation applies to a particular segment of the Hercynian orogenic belt, regardless of its present Alpine setting. On the other hand, it must be emphasized that the Hercynian of the Pyrenees does not form a singular unit with a peculiar setting, but instead is only a small part of a much broader unit, the Hercynian belt. In consequence, any interpretation and conclusion reached must take into account comparisons and correlation with other segments of the belt. Furthermore, this suprastructure/infrastructure arrangement is not unique in the Hercynian belt and analogous structural settings exist in other segments of the belt, as stated above.

According to the original definition by de Sitter & Zwart (1960), the infrastructure is characterized by the development of a main foliation (a schistosity) which formed originally with a gently dipping or flat-lying attitude. In contrast the suprastructure exhibits predominantly rather upright folds and steep related foliations (slaty or very penetrative crenulation cleavages). Additionally, the metamorphic degree varies from very low- or low-grade in the suprastructure to medium- or high-grade in the infrastructure. The boundary between both structural levels is either gradual or sharp depending on lithology and metamorphic degree. A sharp

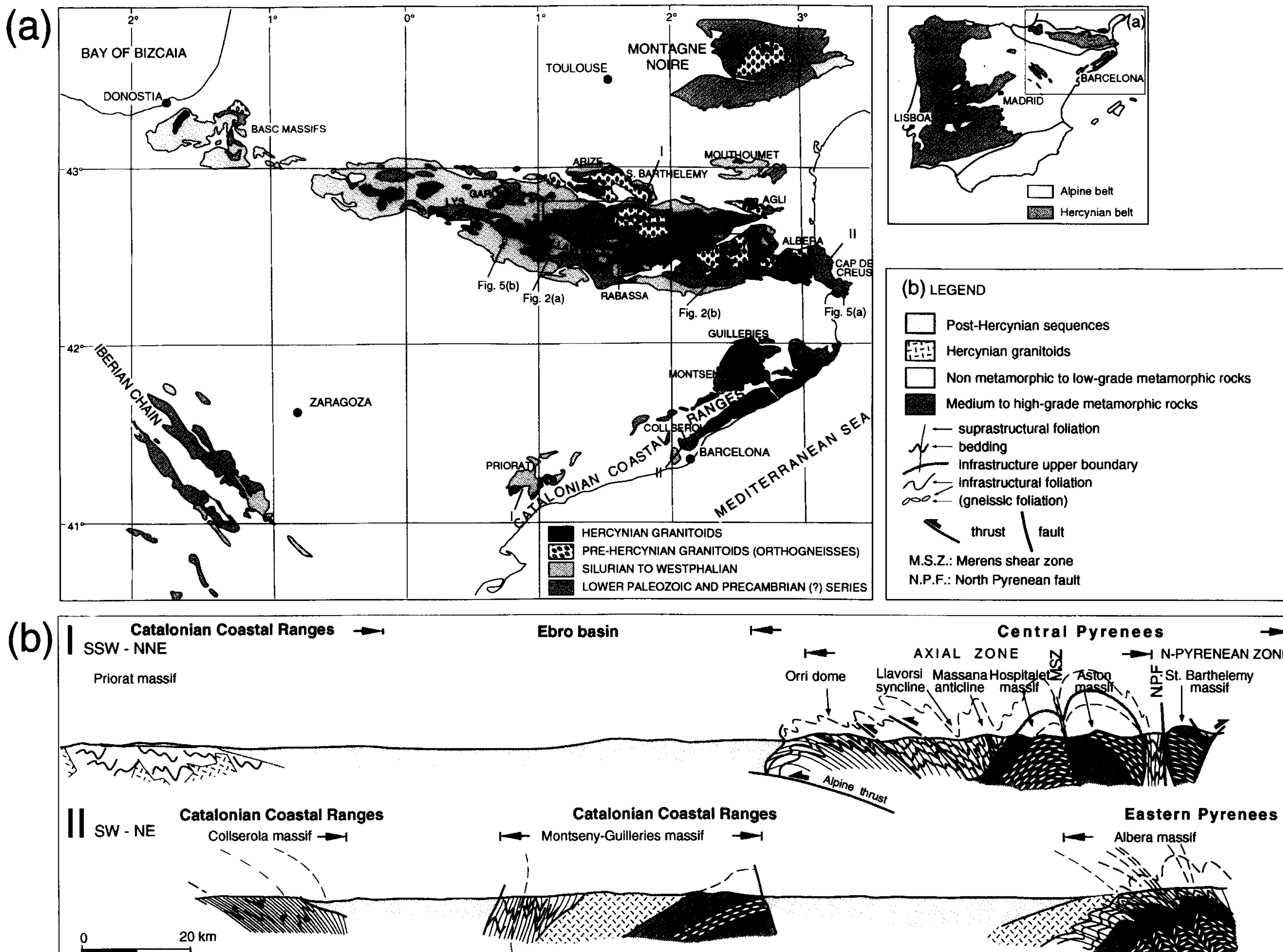

Fig. 1. Main lithological units in the Hercynian massifs of northeast of Iberia (a) and schematic section across the Hercynian belt showing the arrangement of domains with steep and flat-lying foliations (b). (I and II indicate the locations of sections.)

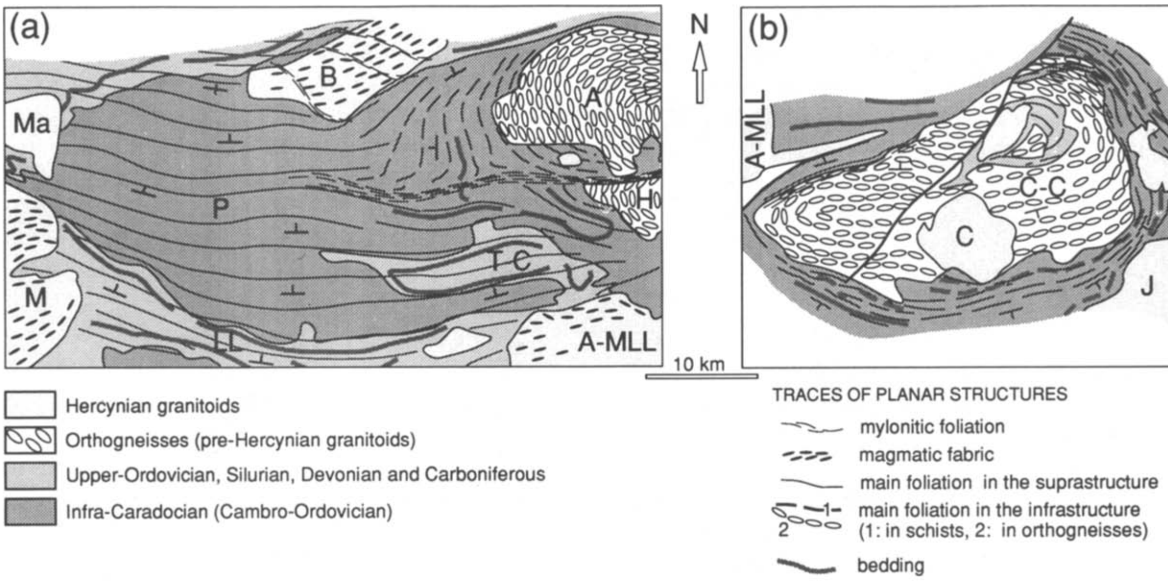

Fig. 2. Dome and antiform structures. (a) Pallaresa anticlinorium and western Aston massif. (b) Canigó massif. In the Pallaresa anticlinorium the antiform geometry is defined by the stratigraphic layout, but in the Aston and Canigó massifs, the dome shape is shown by foliation traces. Key: (a) A—Aston massif; H—Hospitalet massif; P—Pallaresa anticlinorium; LL—Llavorsí syncline; T-C—Tor-Casamanya syncline; Maladeta granite; Ma—Marimanya granite; A-MLL—Andorra-Montlluís granite; B—Bassiés granite. (b) C-C—Canigó-Carançà massif; C—Costabona granite; J—La Jonquera granite.

boundary forms where black Silurian slates act as a detachment horizon (Kleinsmiede 1960). A gradual boundary exists when the structural style change takes place along a complex transition zone, located in the Cambro-Ordovician, where the foliation steepens gradually upwards (Oele 1966).

The initial interpretation of de Sitter & Zwart (1960) considered that the flat and steep arrangements were primary tectonic features, and this view has been held by Zwart (1963, 1968, 1979) and co-workers (Kleinsmiede 1960, Boschma 1963, Oele 1966, Hartevelt 1970) until the end of the 1970s. Folds and related foliations in the infrastructure and suprastructure were assumed to form simultaneously, although a satisfactory mechanical and kinematical interpretation could not be given.

Nowadays, the existence of the structural zoning is still accepted by most authors and the infrastructure/suprastructure terminology is still used. Nevertheless, the original model considering synchronism of development of both structural levels has been questioned by new data, and alternative deformation histories have been proposed. The new interpretations have introduced controversial points which concern: (i) the contemporaneity or relative timing of tectonic events at each structural level, and (ii) the kinematic and tectonic regime assumed to be responsible for the development of each structural level, as well as their space and time variations. The main disagreements concern the deformation event giving rise to the flat-lying infrastructural foliations. Present day interpretations of the tectonic evolution are difficult to reconcile and in some cases are even completely contradictory.

It is the aim of this paper to review and discuss briefly existing hypotheses regarding the development of these structural levels, and to propose a model based mainly on the published data. For this purpose a general geological setting of the Hercynian basement of the Axial Zone of the Pyrenees will be first presented. This will be followed by a concise summary of the most relevant alternatives. In a later section the most significant facts which, according to the present authors, are relevant to the problem will be presented. Finally, a model to explain the structural differentiation of tectonic levels in space and time, will be presented.

Main structural features of the Hercynian of the Pyrenees

The Hercynian structure of Palaeozoic rocks in the Axial Zone of the Central Pyrenees is the consequence of polyphase tectonics that resulted in a predominant WNW–ESE structural trend of major units. On a large scale, a main structural feature consists of the presence of domes and broad antiforms or anticlinoria bounded by tight fold domains with steeply to moderately inclined axial surfaces. Domes have a WNW–ESE axial trend and frequently have orthogneissic cores bounded by infra-Caradocian metasediments (the so-called Cambro-Ordovician series). The dome shape in the gneissic cores is defined by the attitude of the dominant foliation (e.g. the Canigó and Aston domes, Fig. 2). These gneissic domes are located in the infrastructure. The dome structure in the overlying metasediments is rather complex. The metasediments bounding the orthogneisses exhibit a similar geometry as the gneisses, with a dome shaped disposition of the dominant schistosity. In shallower structural levels the dome structure is shown by the bedding and stratigraphic arrangement of mappable younger series (Upper Ordovician, Silurian, Devonian and Carboniferous), which delineate a broad anticlinorium. The main cleavage in these shallower structural levels (suprastructure) has a rather monoclinal steep attitude and shows no dome-shaped folding (e.g. Pallaresa anticlinorium, Fig. 2). Some domes (e.g. the Orri or Rabassa domes) are entirely located in the suprastructure, their shape being entirely defined by the layout of the bedding, while the dominant foliation has a rather monoclinal attitude striking parallel to the long axis of the dome.

Another major macrostructural feature is represented by tight WNW–ESE suprastructural folds. The most recognizable are synclines or synclinoria with Upper Palaeozoic sequences, pinched between the antiformal structures made of rather monotonous infra-Caradocian sequences. Folds display steeply to moderately inclined axial surfaces and an associated N-dipping axial plane cleavage. Tight folds of bedding are also present in the infra-Caradocian sequences, although these are difficult to identify due to the monotonous character of these metasedimentary sequences.

A N–S cross-section across the Axial Zone in the Central Pyrenees shows that the main foliation in the suprastructure displays on a regional scale a fan-like disposition, being nearly vertical at the northern border of the Axial Zone and gentle dipping at the southern border (Zandvliet 1960). Major structures display a south vergence.

Superimposed on the former major structural elements, Hercynian syn- to post-tectonic batholiths were emplaced preferentially in low grade domains. On the map these batholiths exhibit elongated shapes broadly parallel to the dominant trend of the Hercynian structures. In some profiles, the batholiths are sheet-shaped with a rather flat base located in medium-grade metasedimentary domains (Autran *et al.* 1970). Internally the batholiths display a magmatic fabric broadly parallel to their elongated shape. In three-dimensions dome or funnel shapes have been reported (e.g. Marre 1973, Gleizes 1992).

A network of dominantly reverse and dextral N-dipping shear zones, trending parallel to the bulk Hercynian trend, overprint the earlier structures. Their Hercynian or Alpine age is a matter of debate (Carreras *et al.* 1980, Lamouroux *et al.* 1980, Saillant 1982, McCaig 1986, Soula *et al.* 1986c, Soliva *et al.* 1989).

DIFFERENT MODELS FOR THE SUPRASTRUCTURE/INFRASTRUCTURE DEVELOPMENT

The shallow-steep vs deep-flat structural arrangement of the dominant foliation is an unquestionable fact in the Axial Zone of the Central Pyrenees, and a brief review and discussion of proposed models for the origin of this tectonic arrangement will be first presented. Beforehand, it should be considered that the structural arrangement is far more complex. Recumbent folds and associated flat-lying foliations are also present in some low-grade suprastructural domains, while foliation in some infrastructural medium to high-grade domains presumably achieved steep disposition during the Hercynian main deformation event.

Relative timing

The first question arising from the suprastructural/infrastructural differentiation in the Hercynian basement of the Pyrenees concerns the relative timing of the main deformation in each tectonic level. Various possibilities require consideration. One alternative is synchronism of both infrastructure and suprastructure; another is diachronous development of the main structural features in each tectonic level. For the diachronous interpretation, a further two-fold alternative is possible: the main penetrative foliation and related folds in the infrastructure formed earlier or later than those of the suprastructure. The second question depends on the assumption that there is a unique and coeval dominant foliation through the whole tectonic event and that its different attitude in each structural level was a later superimposed feature, or alternatively, that different non-coeval prevalent foliations formed in each tectonic level.

De Sitter & Zwart (1960) considered that the flat and steep foliations were original and coeval (Fig. 3a). Synchronism of infrastructure and suprastructure introduces kinematic and strain coupling problems between the two structural levels, if we assume crustal stretching in deeper levels to be contemporaneous with crustal shortening in shallower levels. This interpretation problem was discussed by Oele (1966), although the idea of synchronism was maintained by Zwart until 1979, but

Fig. 3. Different interpretations of the development of the infra-and suprastructure. (a) Coeval development of flat and steep foliation during the main Hercynian orogenic event as proposed by de Sitter & Zwart (1960). (b) A coeval main foliation formed in a flat attitude throughout the tectonic building became later selectively upright in the suprastructure as proposed by Seguret & Proust (1968a,b) and Matte (1969). (c) Non-coeval main foliation and structural levels. A flat foliation formed in an early event restricted to deep seated structural levels. Steep structures formed in a later event with development of a crenulation cleavage in the infrastructure grading to a slaty cleavage above the first foliation front, as proposed by Carreras *et al.* (in press). (d) An early extension event was followed during the main Hercynian crustal shortening by steep folding associated with diapiric uprise of gneissic domes. Flat and steep foliation formed coevally around and in the gneissic domes, as proposed by Soula (1982) and Soula *et al.* (1986a, b). (e) Crustal shortening with development of steep foliation in deep structural levels and a fold and thrusts belt above the Silurian formed simultaneously during an early event. Later crustal extension coeval with the peak of metamorphism developed a flat-lying foliation transposing the earlier steep foliation in the infrastructure, as proposed by Verhoef *et al.* (1984), Eeckhout (1986), Eeckhout & Zwart (1988) and Vissers (1992). Note that in (a), (b) and (c) only bulk crustal shortening is considered, whereas in (d) crustal extension pre-dates bulk shortening, and in (e) extension post-dates bulk shortening.

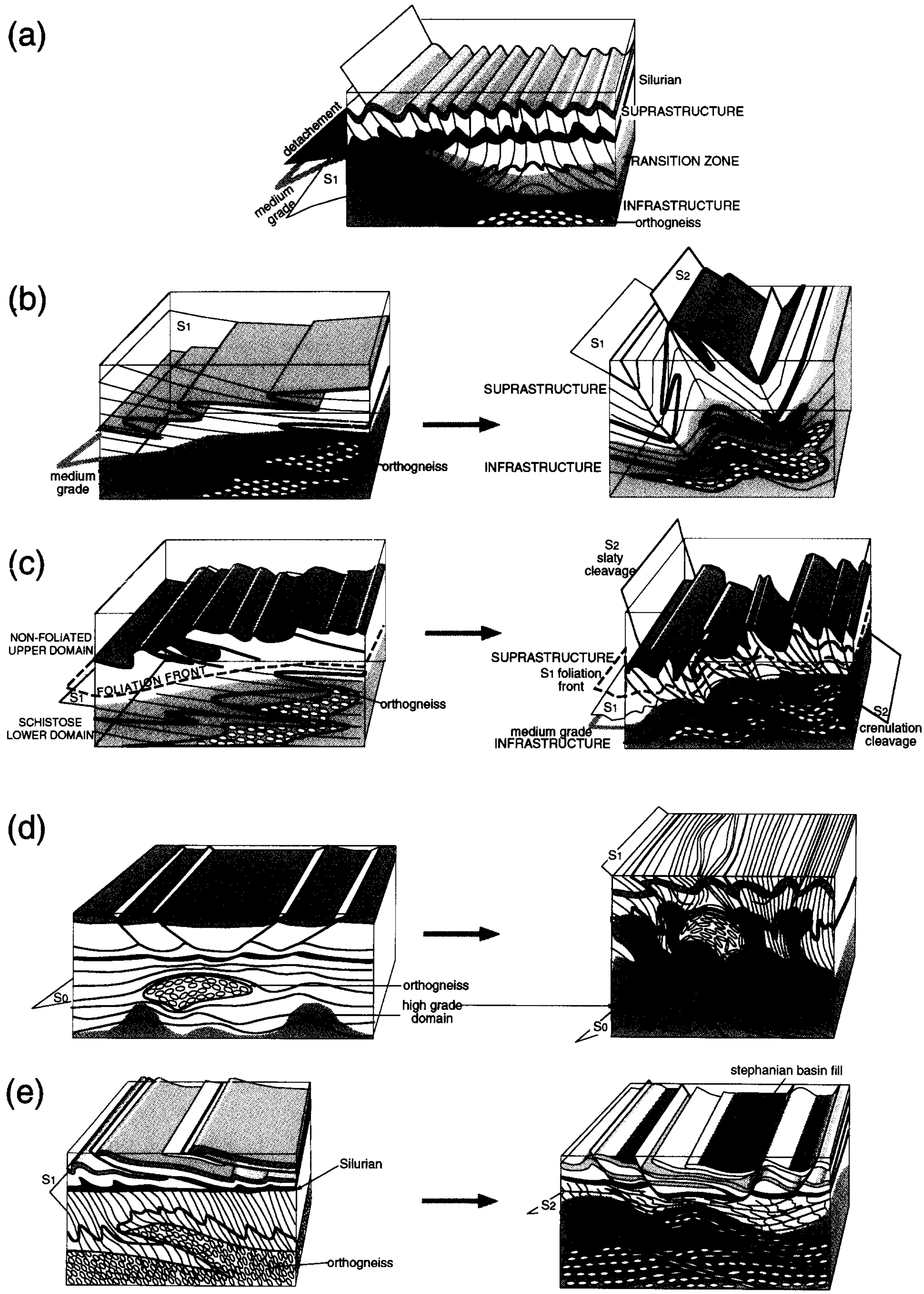
(a)
Silurian
SUPRASTRUCTURE
TRANSITION ZONE
INFRASTRUCTURE
orthogneiss
detachement
S1
medium grade
(b)
S1
medium grade
orthogneiss
S2
S1
SUPRASTRUCTURE
INFRASTRUCTURE
(c)
NON-FOLIATED UPPER DOMAIN
S1
FOLIATION FRONT
SCHISTOSE LOWER DOMAIN
orthogneiss
S2 slaty cleavage
SUPRASTRUCTURE
S1 foliation front
S1
medium grade
INFRASTRUCTURE
S2 crenulation cleavage
(d)
S0
orthogneiss
high grade domain
S1
S0
(e)
S1
Silurian
orthogneiss
stephanian basin fill
S2

Fig. 3

later questioned in more recent publications (Zwart 1981), where he suggested that the tectonic event responsible for the flat-lying foliation might post-date the event which gave rise to the steep foliation. A modification of the initial interpretation, considering also contemporaneity of steep and flat foliation was proposed by Soula (1982) and Soula *et al.* (1986a,b). In their model, gentle or steep attitudes depend on their position with respect to the gneissic domes, which are interpreted as diapiric structures. Thus, flat-lying attitudes were formed exclusively on top of the gneissic domes while steep attitudes formed at the margins. In such a model the foliation disposition neither depends on structural level nor on metamorphic grade.

Other alternatives consider that the attitudes of main foliations in each structural level were reached diachronously as the result of the polyphase tectonic. As stated before, diverse possibilities arise. A first option considers that there is a unique prevalent foliation formed during a main deformation event and the different attitude of foliation was achieved subsequently during later events. Foliation formed initially in a gentle dip or flat-lying attitude across the entire tectonic regime and was later selectively steepened in shallow levels during disharmonic late folding (Fig. 3b) (Seguret & Proust 1969a,b, Matte 1969).

Further options consider that dominant foliations on each of the tectonic levels are not coeval and thus related to different folding phases. A two-fold possibility regarding relative timing exists: the deep seated flat-lying foliations being older or younger than the steep shallower ones. Both alternatives require in addition the existence of foliation fronts in order to keep each foliation prevalent in each tectonic level.

Geotectonic significance

Until this point, regardless of the existence of different models, the tectonic regime is considered to have entirely been formed during the Hercynian crustal shortening. However, a new element of discussion, which concerns the tectonic regime which is responsible for each of the structural associations, must be introduced.

The development of steep foliations associated with tight upright folding does not introduce any significant problem concerning their kinematic and geotectonic significance, and can be well understood in the context of the Hercynian fold belt. A minimal vertical tectonic thickening by a factor of 1.15 is considered by Corstanje *et al.* (1989) as a result of upright folding in the Pallaresa anticlinorium. Similar or slightly greater values (1.10–1.25) were obtained from strain analyses performed by Capellà (1991) in the same area.

However, all alternatives must take into account an event responsible for the formation of horizontal foliations which implies horizontal stretching. The assignment of a tectonic regime to the deep flat-lying foliation domains opens even more the spectrum of possibilities. Among the models with non-contemporaneous infrastructure and suprastructure and associated foliations development, the following will be considered: (i) flat-lying foliations formed in a bulk crustal shortening process which pre-date steeper shallower structures, (ii) the same relative timing but developed under an extensional tectonic regime, or (iii) steep structures which pre-date a later flat-lying foliation formed in a crustal extension event, and causing the transposition in the infrastructure of the earlier steep structures.

Early interpretations consider flat-lying foliations formed either as the result of vertical flattening in deep levels without reference to the tectonic significance, or as the result of tangential tectonics with fold-nappes or recumbent folds. Flat-lying structures arising from tangential tectonics might form throughout the entire tectonic event or be restricted to a given depth with the existence of a foliation front (Fig. 3c). In such a tectonic setting, flat-lying foliations have been associated with recumbent folding with Penninic-type nappes (Guitard 1964, 1970, Autran & Guitard 1969, Lagarde 1978, Garcia-Sansegundo 1991) or thrusts (Soliva *et al.* 1989) involving medium- to high-grade metasediments and orthogneisses, and recumbent folding in shallower domains of low grade Palaeozoic rocks. This tectonic setting coincides with similar suggestions made to explain the widespread presence of flat-lying foliations in deep seated medium- to high-grade domains, and the prevalence of steep folding in later events in various orogenic belts. Several authors (Fyson 1971, Murphy, 1987, Matte & Xu Zhi 1988) conceive an evolution where sub-horizontal shearing in deep-seated domains may account for the formation of gently dipping foliations and associated stretching lineations, with an achievement of high strain values and in consequence tight isoclinal folding. Shallower levels assume deformation by bulk translation and lower strain values. In later stages continuous folding of the shallower sequences generates axial plane cleavages that might appear as crenulations when they reach the flat-lying foliation front, (Fig. 3c).

In the above hypothesis, horizontal stretching is not necessarily associated with an extensional tectonic regime, and can be achieved by deep horizontal shearing during a bulk shortening. However, horizontal stretching can also be achieved in other ways like extension-related deep shearing, vertical coaxial flattening or a combination of both shear and flattening (sub-simple shearing, De Paor 1983). Vertical bulk flattening (Fig. 4a) is incompatible with a crustal shortening event whereas simple shear (Figs. 4b & d) and sub-simple shear (Figs. 4d, e & f) are compatible with both crustal shortening or extension. The up or down dip of the movement direction in a low dipping plane is not a definite criterion to distinguish between crustal extension or shortening, as low angle normal shear geometry can form under a bulk crustal shortening event (Fig. 4f). Although it can be seen from Fig. 4 that not all settings require bulk crustal extension and thinning, most of the recent proposals are strongly influenced by the increasing role attributed to extensional tectonics in orogenic belts (Wernicke 1981, 1985, Wernicke & Burchfield

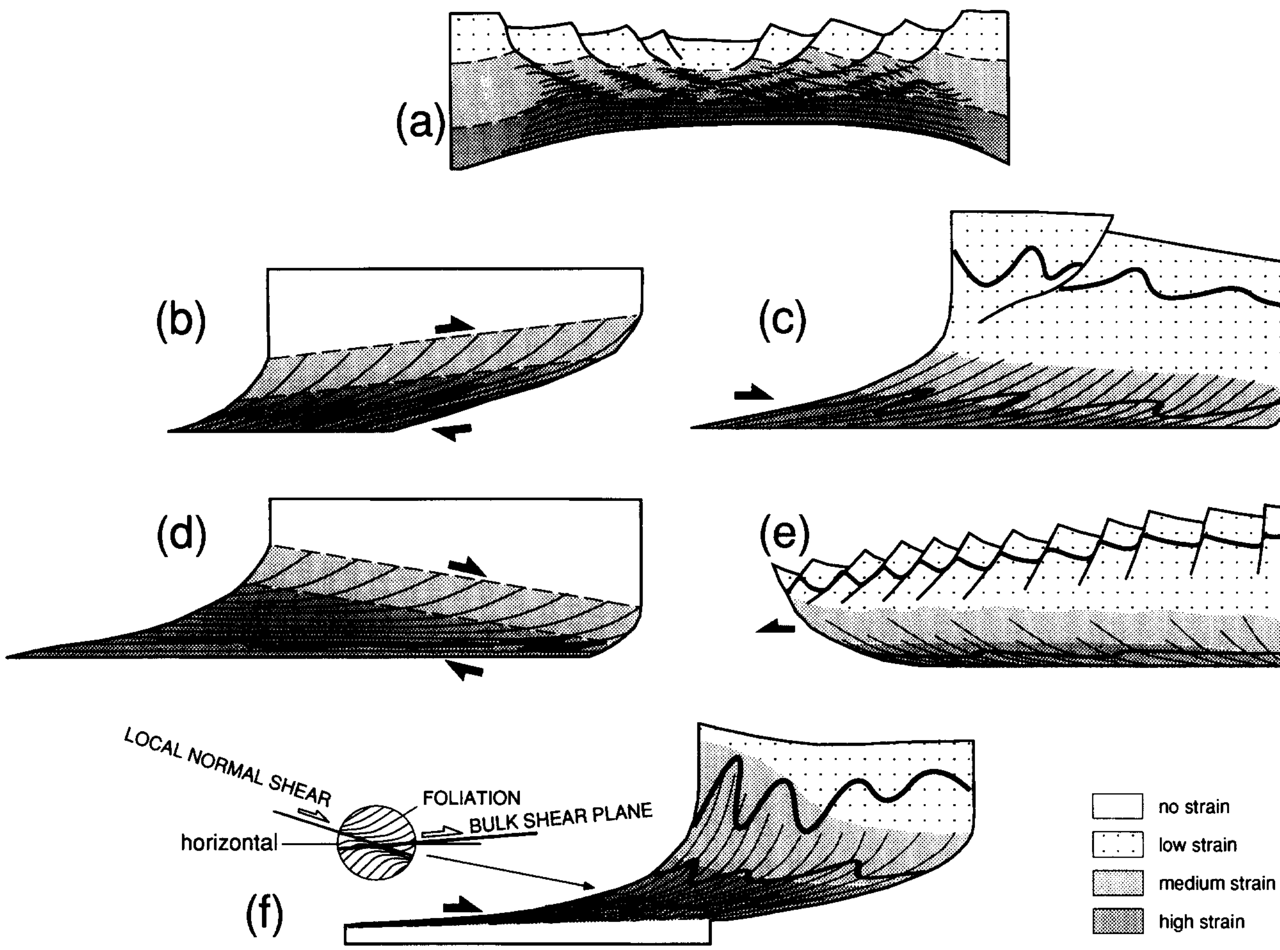

Fig. 4. Basic tectonic regimes leading to the formation of flat-lying foliations. (a) Bulk extension is accommodated by homogeneous pure shear extension in deep-seated structural levels, and inhomogeneous ductile and brittle extension in intermediate and shallow structural levels. (b) Ductile simple shear deformation in deep-seated structural levels with upward displacement of an undeformed suprastructure. (c) Ductile shearing causing shortening in the suprastructure. Bulk shortening of the suprastructure induces a shear gradient in the infrastructure which leads to sub-simple shear deformations. (d) Ductile simple shear with downward movement of a undeformed suprastructure. (e) The same with normal listric faulting in the suprastructure. (f) Sub-horizontal shearing in the infrastructure producing inhomogeneous horizontal shortening in the suprastructure. Lateral shear gradient induces sub-simple shear in the infrastructure. Inhomogeneity of horizontal shearing causes the development of crustal scale shear band structures with extensional geometry compatible with the bulk shortening event.

1982, Lister *et al.* 1986, Malavieille 1993). After the controversial models of Wickham & Oxburgh (1985, 1986, 1987) suggesting a rifting event as being responsible for the metamorphic and structural arrangement of an area of the North Pyrenean segment of the Hercynides (see Matte & Mattauer 1987, Carreras *et al.* in press, for discussion), other authors have introduced an extensional event in the evolution of this segment of Hercynides to explain the development of flat-lying dominant foliations in deep crustal levels. However, the correlation of flat-lying foliations to crustal extension and thinning events may be a possible source of misinterpretation regarding mountain building processes. The existence of sub-horizontal stretching lineations in flat-lying foliation planes of the infrastructure does not imply a bulk crustal extension as understood by Vissers (1992), and horizontal stretching parallel to the main trend of structures may be also a prevalent feature during compressional events, as documented in many orogenic belts (Arthaud 1970, Woodcock 1986, Vauchez & Nicolas 1991).

As the assumed crustal-thinning related extension is supposed to be coeval with the peak of metamorphism, authors' disagreements about the relative timing of this peak and the deformation events have led to divergent results.

If the low-P high-T metamorphic peak is considered a rather early event with regard to deformation history (Soula *et al.* 1986a,b), the syn-metamorphic extension should pre-date the crustal shortening associated with the late folds. In consequence, these authors considered the existence of an early orogenic extension event, although they do not consider this early event as responsible for the development of a main flat-lying foliation. However, it is clear that in such a model, flat-lying foliations pre-dating steep folds could form in deep seated levels affected by ductile crustal extension, while non-schistose extensional structures (i.e. listric faults) could form in shallow crustal levels (Fig. 3d). From a geotectonic point of view, this interpretation disagrees with models considering a late extension collapse and furthermore requires a change in course of the orogeny from a bulk extension to a bulk shortening.

In a contrary model which takes into account the microstructural relationships, the peak of metamorphism is interpreted as a late event with regard to the deformation phases (Verhoef *et al.* 1984, Zwart 1986, Eeckhout 1986, Eeckhout & Zwart 1988, Vissers 1992). Additionally, detailed structural analysis reveals that the flat-lying foliations post-date earlier steep axial plane cleavages. These observations led the above authors to postulate that flat-lying structures formed as a result of crustal extension and thinning superimposed on the earlier steep folds (Fig. 3e). In this inverse succession of events, earlier bulk crustal shortening gives rise to steep folds and cleavages through the whole tectonic regime, while a later crustal extension is responsible in deep seated levels for flat-lying foliations transposing the previous steep fabrics. In shallow levels late extension is partially accommodated by more brittle faulting with development of graben structures filled up with Upper Carboniferous sediments and/or bulk translations leaving a relatively undisturbed suprastructure. Although no detailed discussion will be presented, it should be emphasized that this late origin of flat-lying foliation does not explain the widespread presence of steep folds affecting the flat-lying infrastructural foliation observed in several areas in the Eastern and Central Pyrenees (Guitard 1970, Groen 1978, Santanach 1982, Casas 1984, Laumonier *et al.* 1984, Liesa 1988, Liesa & Carreras 1990, Garcia-Sansegundo 1991).

STRUCTURAL ASPECTS IN THE SPACE AND TIME: DEVELOPMENT OF THE STRUCTURAL ZONATION

Evidently, a great spectrum of alternative and contradictory explanations have arisen from the study of one of the geologically best known segments of the Hercynian belt. It should be emphasized that the role of Alpine reworking is in fact not a relevant cause of controversy as the main Hercynian structures are recognizable and healed by Hercynian granites and post-Hercynian unconformable sedimentary rocks. As formerly mentioned, a detailed discussion of each of the presented models will be avoided as there is a large amount of literature (e.g. Banda & Wickham 1986) with well-documented arguments. On the other hand, although the presented hypotheses are apparently contradictory, it seems reasonable that each of them contains arguments sustained on unquestionable facts, and that the disagreements arise from the primacy given to different observations.

In this section an attempt will be made to establish an account of data which according to the present authors are most relevant for the interpretation of the discussed structural zonation. A proposal, which tries to render compatible these observations, will be finally presented in the next section.

A review of the most relevant points is considered as follows.

(1) Alpine deformation is not a determinant factor for the present tectonic structural zoning. Although some of the doming could be accentuated by Alpine tectonics, the original dome-shaped structures are essentially Hercynian features. Some small domes are sealed by undisturbed Hercynian granodiorites. Dome structures are also present in other segments of the Hercynian belt outside the Pyrenean realm (e.g. Montagne Noire to the north, Guilleries Massif to the south, or Lugo dome to the west in the Iberian Massif).

To a certain degree, the fan-like geometry of the main foliation in suprastructural domains can be the result of Alpine tilting, especially along the southern border of the Axial Zone. However, this variability of the attitude of the main foliation is also present in areas outside the Pyrenean domain where the effects of Alpine tectonics are negligible.

The Alpine tectonics are not responsible for the main uplift of high-grade metamorphic rocks as suggested by Wickham & Oxburgh (1986). Along the Hercynian belt there is evidence of an important uplift and erosion taking place before the beginning of the Mesozoic, and even before the Stephanian.

(2) Setting the Hercynian basement of the Central Pyrenees in this much broader context reveals that the alternation of steep and flat domains is not only found in vertical sections like in the Central Pyrenees but is also present in most horizontal sections across the belt. A vertical zonation which is similar to that of the Hercynian of the central Pyrenees has been also described and interpreted in the Central Iberian Massif (Bard *et al.* 1970, Capote *et al.* 1982). There, upright folds form above a detachment level, while flat-lying foliations occur below it (Matte & Xu Zhi 1988). A section through the Western Astur-Leonese zone in the Iberian Massif reveals also a structural zonation with a gradual transition from steep folding above a décollement surface in the east to a fold nappe rooted domain with steep (e.g. Ollo de Sapo antiform) and recumbent folds in the west (e.g. Mondoñedo fold nappe; Matte 1968, Martinez-Catalan *et al.* 1977). In such settings upright and recumbent folds are related to a unique crustal shortening event, and do not necessarily represent a change in the bulk geotectonic regime. Flat-lying foliations are not an inherent feature of infrastructural domains, while foliations developed in an originally steep disposition are also present in medium to high-grade infrastructural domains.

(3) The above described vertical infrastructure/suprastructure arrangement does not apply for the whole Hercynides Pyrenean segment. The Orri Dome is a suprastructural megastructure consisting of a gently inclined anticlinorium in which the stratigraphic sequence displays a dome-shaped geometry, while the main cleavage has a gently inclined attitude. Low-grade suprastructural domains also with gently inclined main foliation can be followed towards the south in the northeast of the Catalonian Coastal ranges.

In the Eastern Axial Zone of the Pyrenees, infrastructural foliations are strongly folded by unquestionable Hercynian deformation events. Consequently, this ex-

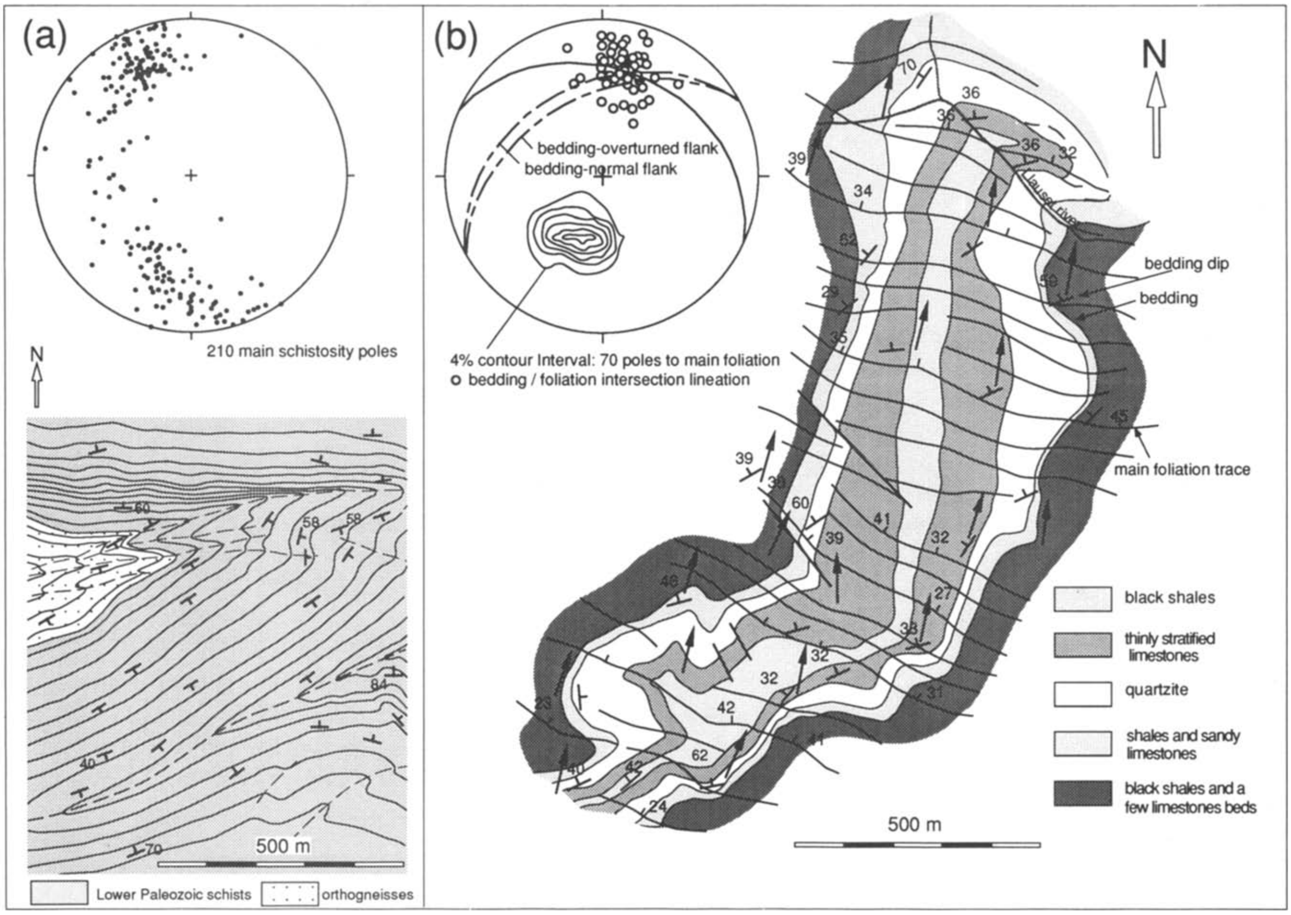

Fig. 5. Comparison of structures developed as a result of polyphase tectonics in different structural levels. (a) In shallow levels 'pre-cleavage' folds are frequent, while the main foliation displays a fairly constant dip. (Llauset area, Central Pyrenees.) (b) In deep-seated levels the main foliation is folded on all scales by 'late folds'. Foliation poles display cylindrical or conical distributions (la Birba, Cap de Creus; Eastern Pyrenees). For location see Fig. 1.

cludes their development during a late extensional episode. Foliations in medium to high-grade domains might have even formed in a rather upright attitude. Steep infrastructural foliations are cross-cut by Hercynian vertical pegmatite dykes, indicating that this main foliation was already in an upright position prior to or during the metamorphic climax (Carreras & Druguet 1994). Thus, in the Eastern Pyrenees the infrastructure and suprastructure distinction cannot be applied using foliation attitude criterion and fold attitudes range from recumbent to upright in low-grade domains. Otherwise, similar fold attitudes exist in domains with a marked different metamorphic degree.

(4) The identification and correlation of minor structures through space and time, including the correlation of minor and major structures remain one of the most puzzling problems of the Hercynian geology of the Pyrenees which hinders the interpretation of the evolution. Many attempts of correlation have been presented (for details see Santanach 1973, Bourke 1979, Poblet 1991). Most of the correlation problems arise from the assumption that a prevalent unique foliation was formed throughout the entire tectonic activity (Guitard 1960, Matte 1969, Guitard *et al.* 1984, Laumonier *et al.* 1984, Zwart 1979). The acceptance of an ubiquitous dominant foliation led some authors (Guitard 1964, 1970, Carreras & Santanach 1983) to establish a clear distinction between pre-schistose, syn-schistose and post-schistose events. When such separation is assumed, one realizes that in the infrastructure several post-schistose deformation phases, affecting the main foliation and giving rise to locally penetrative foliations, can be recognized (two phases by Oele 1966, Boschma 1963 and Zwart 1963, 1979, five phases by Laumonier *et al.* 1984). On the contrary, evidence of pre-schistose structures in the infrastructure is very restricted (Gibson 1989) and uncertain. In spite of local anomalies, it can be stated that the gently dipping foliation in deep seated levels is a relatively earlier structure and it is largely affected by later folding on all scales (Fig. 5a). This foliation appears as the first penetrative structure in the orthogneisses, or as a composite transposition foliation in the nearby metasediments (Seguret & Proust 1968a, b, Casas 1978). Stretching lineation associated with this foliation indicates sub-horizontal E–W to SW–NE stretching. Tight minor asymmetric and isoclinal folds of layering or veins are present in many areas (Seguret & Proust 1968a,b, Matte 1969, Guitard 1970, Santanach 1972, Zwart 1979).

In contrast at shallower levels the pre-schistose deformation structures are abundant, while the dominant foliation displays a rather regular attitude over regions hardly deformed, except for small scale folds mainly kinks or large scale bending and tilting. The early or so called pre-schistose folds are abundant in shallow low-grade domains, (Boschma 1963, Mey 1967, 1968, Hartevelt 1970, Déramond *et al.* 1969, 1971, Déramond 1971, Déramond & Soula 1971, Muller 1973, Valero 1974, Laumonier & Guitard 1978, Groen 1978, Zwart 1979, Bourke 1979, Eeckhout 1986, Poblet 1987, 1991, Speksnijder 1987, Capellà 1988, 1991, Bou 1988, Cirés *et al.* 1990, Garcia-Sansegundo 1991). In some instances large mappable folds can be recognized where different lithologics are involved (Fig. 5b), while in most cases these can only be detected by the wide scatter of intersection lineations originated during the main foliation development. Thrusts transected by the main foliation have also been recognized, (Mattauer *et al.* 1967, Donnot & Guerange 1974, Majesté-Menjoulas 1981, Muller 1973, Raymond 1980, 1986, Raymond & Weyant 1982, Moret & Weyant 1986, Bodin & Ledru 1986, Losantos *et al.* 1986). The widespread presence of these folds and thrusts suggests that a crustal shortening event started quite early during the Hercynian orogeny, while folds related to the main foliation remained almost undisturbed after their formation.

The correlation based on the existence of a unique coeval foliation across the entire tectonic event results in the remarkable conclusion that the earlier deformation story was exclusively recorded in the superstructure while the late deformation story was mainly registered in the infrastructure. Detailed cross-sections across the eastern Pallaresa anticlinorium (Capellà 1991, Capellà in press) and across the Eastern Pyrenees, reveal that no unique main cleavage exists across the entire region. The main cleavage in shallow seated levels corresponds, in deeper structural levels (the infrastructure and the transition zone of Oele, 1966), to crenulation cleavages with variable degree of penetrability. Such crenulations are associated with folds affecting a previous foliation, with similar style and attitude as the folds affecting bedding in shallower structural levels.

A comparison of foliation pole distributions in different tectonic levels clearly reveals a rather constant attitude of the dominant foliation in the suprastructure with a single maximum distribution, and a cylindrical or conical scattering in the infrastructure and the transition zone (Fig. 5).

(5) Comparative finite strain analysis in the infrastructure and the suprastructure provide further arguments against the existence of a unique prevalent foliation. Most remarkable is the changing attitude of the stretching direction in different tectonic levels. Steeply plunging X-axes of finite strain ellipsoids have been determined in several areas of the suprastructure (Pallaresa anticlinorium, Orri and Rabassa domes and Massana anticline) by means of strain analysis of deformed coarse detrital beds in the Cambro-Ordovician sequences (Capellà 1991). For two-dimensional strain analysis, the R_f/Φ technique in the version of Matthews *et al.* (1974) has been applied to the elliptical geometry of the markers. The procedure of Ramsay & Huber (1983) was used for compilation of the finite strain ellipsoid. Strain analysis together with direct measurement of stretching lineations from deformed sulphur aggregates and the associated quartz pressure shadows reveal the prevalence of a N–NW plunge of X-axes. However, a certain scatter of X-axes of strain ellipsoids with regard to the more clustered distribution of stretching lineations occurs. In spite of these slight orientation variations a majority of determinations indicate that the X-direction is steeply plunging and lies at a high angle to the axial-trend of the related folds. This orientation shows a close analogy to the stretching direction in late mylonite belts in the northeast part of the Pallaresa antiform but also in all mylonite belt outcropping along the Axial Zone. This coincidence would indicate, if the assumed Hercynian age of mylonites is correct (Carreras *et al.* 1980), a persistence of the orientation of the bulk stretching direction from the main until the late Hercynian events. A steeply plunging X-direction of finite strain ellipsoids was also reported by Corstanje *et al.* (1989) in the Pallaresa Anticlinorium, although these authors locate their maximum on a NE-plunging direction.

In contrast, strain analyses in the infrastructure, using the same method, with deformed quartz–feldspathic aggregates and K-feldspar megacrystals from the orthogneiss in domes, shows a predominant E–W to SW–NE extension direction, i.e. closely parallel to the Hercynian structural trend. This direction is coincident with direct field measurements of stretching lineations in the gneisses. These divergent X-direction orientations in different structural levels render unlikely from a kinematic point of view, the interpretation of a simultaneous development of the infrastructural and suprastructural main foliations.

(6) The inhomogeneity of deformation is another often neglected fact that should be taken into account. The degree of penetrability and attitude of all foliations vary in space. In the infrastructure and the transition zone, more than one penetrative dominant foliation exists, reflecting a rather heterogeneous deformation during early, main and late deformation events. Thus, a correlation based on assignment to the same event the most penetrative foliation throughout a crustal domain can be a source of misinterpretations. The frequently used orientation criteria, which assigns to a given phase a specific orientation of fold axes, and vice versa, should also be avoided. As it can be seen in different areas of the Hercynian of the Pyrenees (Carreras & Cirés 1986, Carreras & Casas 1987) coeval folds exhibit variable attitudes of axial planes and axes, and change their style as a result of inhomogeneous non-coaxial deformation. In addition previous orientation of the bedding or cleavage plane causes also the development of variably oriented fold axes (Mey 1967, 1968, Speksnijder 1987, Poblet 1987, Bou 1988, Capellà 1988, 1991). Thus, fold orientation and style are also poor correlation elements. In consequence, evolutionary models based either on the assumption of the existence of a first penetrative foliation across the whole orogenic belt which serves as a

structure correlation element for earlier (pre-schistose) and later (post-schistose) events, or on correlating structures on the basis of apparent similar orientation and timing, can be incorrect.

(7) Most models emphasize the controversial role of crustal shortening vs crustal extension, while they overlook the role of strike-parallel motions. Major and minor structural analyses reveal that the overall WNW–ESE trend of the Hercynian structures and the long axes of the domes are in fact the result of superposition of differently orientated structures arising from the Hercynian polyphase tectonics. Particularly in the Eastern Pyrenees, but also in the Central Pyrenees, it is evident that throughout the deformation history, WNW–ESE fold trends become superimposed on previous ENE–WSW or even NE–SW trending structures. A clockwise rotation of the regional trend is responsible for some of the dome-shaped structures (e.g. Roc de Fraussa Massif, Liesa & Carreras 1990) and the development of conical folds (e.g. Cap de Creus area, Carreras 1975) caused by interference of different trending structures. Such structural rotation is accompanied by an increase of deformation components induced by strike-parallel movements. Late folds in infrastructural domains in the Eastern Pyrenees display a persistent parallelism of fold axes and stretching lineation, a rather common feature in deformations bearing high shear components. Similar conclusions concerning rotation of structures have been reached from the study of granitoid fabrics in batholiths, where an igneous syntectonic WNW fabric is overprinted by later solid state mylonitic deformations induced by NW–SE dextral shearing (Simpson *et al.* 1982, Gleizes & Bouchez 1989, 1991, Gleizes 1992, Leblanc *et al.* 1994).

INTERPRETATION

Cross-sections in the Pyrenean region, but also in other areas of the Hercynian belt, show that different foliations prevail at different structural levels and domains, indicating that inhomogeneity of deformation prevailed through space and time during all the Hercynian orogenic building. How flat-lying structures formed preferentially in deep-seated domains and upright folds formed in relative shallow domains will be first interpreted. Secondly, the role of transcurrent tectonics will be introduced to explain some particularities of the zonation that transcends the infrastructure/suprastructure setting. The interpretation presented here is based on the assumption that the Pyrenean segment of the Hercynian chain, similar to other segments of the Hercynian belt, can be interpreted as a whole and essentially as a result of crustal shortening in a collisional belt (Matte 1986).

Relative timing and dominating tectonic regimes in each structural level are crucial points to any interpretation. The lack of an ubiquitous regional foliation through the whole tectonic phase reveals the inappropriateness of an absolute distinction between pre-schistose, main syn-schistose, and post-schistose events. Avoiding the initial assumption of the existence of this unique prevalent foliation, introduces a great simplification to most of the time-space correlation problems, because the so-called pre-schistose events in shallow domains can be correlated with syn-schistose or even post-schistose events of deep seated levels. The proposed correlation depicted in Fig. 6 shows how Hercynian deformation differently affected shallow and deeper domains from the beginning. The gently inclined folds and foliations found in deep-seated structural levels cannot be easily explained by purely coaxial vertical shortening with bulk extension if this deformation event is synchronous with folds and thrusts in shallow structural levels. On the other hand, the required component of non-coaxial shear strain is easily rendered compatible with a shearing event related to crustal shortening (Fig. 4c), rather than with a rifting related shearing (Fig. 4e). A tangential tectonic regime is the most likely regime as proposed by Autran & Guitard (1969), Guitard (1970), Lagarde (1978), Soliva *et al.* (1989), although major recumbent folding in deep seated levels is not easily recognizable and the Penninic-type nappes with gneissic cores (Guitard 1964, 1970) are more interpretative than actually well recognizable structures. Thrust sheets of gneisses have been also considered to be related to this tectonic event (Soliva *et al.* 1989), although the sheet shapes of gneissic bodies parallel to the main foliation are more likely a reworked primary sheet-shaped intrusive structure than the exclusive result of tectonics. In the model presented here, pre-schistose folds and thrusts in the suprastructure are interpreted as coeval with gently dipping foliations in the infrastructure, with a zigzag shaped foliation front in between. Progression of horizontal shearing in deeper structural levels synchronous with the development of a shallow fold and thrust belt in the less deformed overriding structural levels, is a compatible setting and furthermore a rather common situation in orogenic belts (Fyson 1971, Breddin 1973, Mattauer 1973, Sanderson 1982, Murphy 1987, Matte & Xu Zhi 1988). This possibility of generating gently dipping foliations in deep seated levels by a crustal shortening event related to shearing does not require a shift in the tectonic regime by replacing a crustal shortening event for an extension event, or vice versa. A shear strain up to $\gamma = 5$ in a 5 km thick deep-seated crustal levels can be achieved by only a 30 km displacement of an overlying crustal layer. In a 200 km wide belt this shearing can be accommodated by only 15% of shortening in upper levels. In this way, during the early deformation stages, shallow shortening induced by deep-seated shearing could be accommodated by non-schistose or locally schistose folds and thrusts (Fig. 7a). As a result of progression of deep-seated shearing, the suprastructural rocks achieve an amount of shortening enough to cause parallel folds to tighten with the development of steep or moderately dipping axial plane cleavages. Slaty cleavages form in previously non-cleaved rocks, while very penetrative crenulation cleavages occur in domains where rocks had

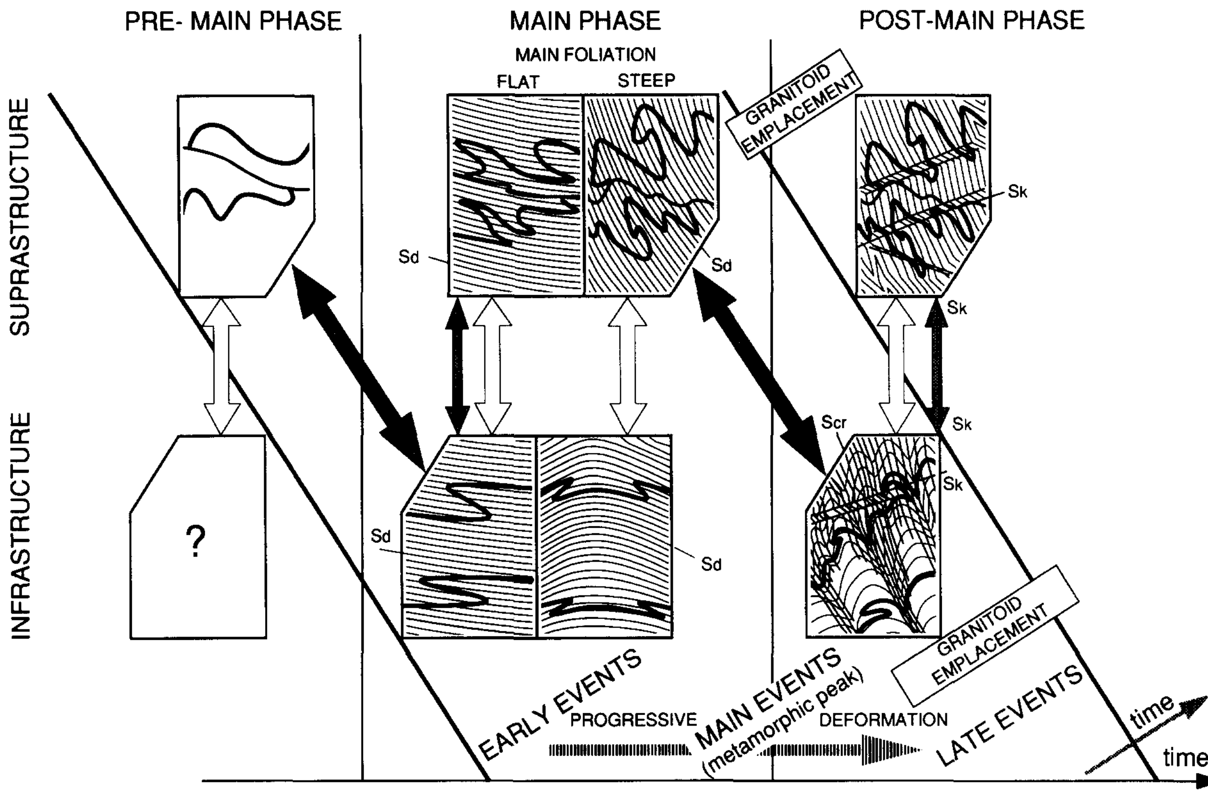

Fig. 6. Correlation of deformation phases in space and time. In a majority of models involving crustal shortening, a distinction between pre-main phase, main phase and post-main phase events is accepted. White arrows indicate proposed correlation between infra- and suprastructures. For the main phase in the suprastructure, two options are considered: dominant foliation (Sd) originally flat (Seguret & Proust 1968a,b, Matte 1969) or steep (de Sitter & Zwart 1960). An alternative correlation based on the non-existence of a ubiquitous main foliation and on progression of deformation without clear breaks is indicated by the dark arrows. (*Scr* is a crenulation cleavage and *Sk* refers to axial planes of late kinks.)

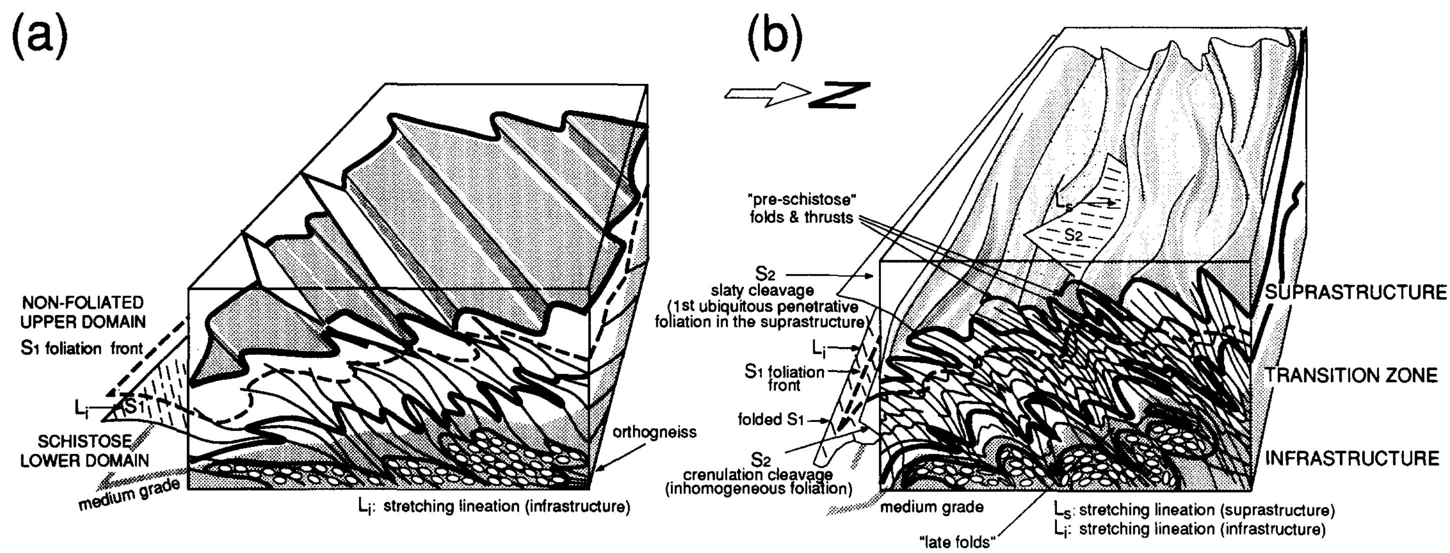

Fig. 7. Schematic representation of the development of structural zonation, achieved during Hercynian early compression evolving to late transpressional events. Early deformation (a) gave rise to a deep gently inclined foliation achieved by crustal inhomogeneous shearing (simple and sub-simple shear). Rocks in shallow structural levels assumed deformation by non-schistose or locally schistose folds and thrusts. Dominant trend of structures was SW–NE. Progression of deformation (b) under a transpressive tectonic regime led to development of rather steep folds across the entire tectonic zone. Associated foliations appear as a 'first' slaty cleavage in previously non-schistose shallow domains, but as a crenulation cleavage in previously schistose deep levels. Deformation becomes gradually inhomogeneous, downwards.

previously achieved a slaty cleavage. Coaxial refolding and folded thrusts might form in the suprastructure.

Steep folding might reach the infrastructure either by downward migration of the suprastructure foliation front, or by progressive refolding of foliation during shearing in a similar way that intramylonitic folds form in shear zones (Carreras *et al.* 1977). With progression of deformation, earlier gentle-dipping deep seated foliations start to fold and crenulate (Fig. 7b). These late locally penetrative crenulation cleavages in the infra-

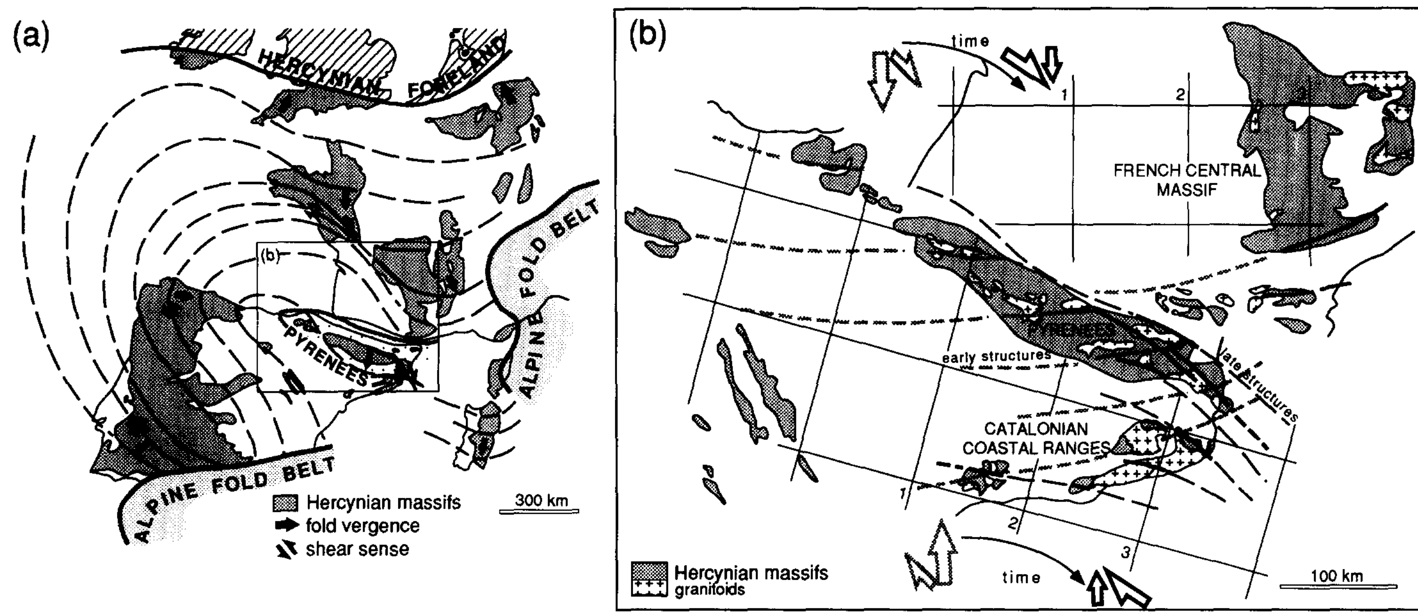

Fig. 8. Trend of the Hercynian dominant structures in Iberia and Western Europe. (a) In the Pyrenees early SW–NE trending structures formed under a compressional event were progressively overprinted by WNW–ESE to NW–SE structures developed under a transpressive event, forming the southern margin of an hypothetical extension of the South Armorican shear zone. (b) Gradual clockwise rotation of the trend of the dominant structures in the Pyrenean segment of the Hercynides, induced by the progressive prevalence of the transpression regime.

structure are thus correlated with slaty cleavages in rocks above the first event foliation front. In the final setting, while it is true that dominant foliation passes gradually from gently dipping attitudes to steeply dipping, both are related to different fronts of schistosity that intersect in a rather complex transition zone where two dominant foliations may exist.

Continuous transpression with uplift and unroofing of the tectonic zone causes the late development of retrograde shear zones in the crystalline rocks, while late folding continued in metasediments. This way, a further structural zonation superimposed on the previous one formed with folds forming in shallow levels, and shear zones occurring in the crystalline deeper seated levels of the infrastructure or transition zone (Carreras 1975, Carreras *et al.* 1980).

Another important point which requires an interpretation concerns the variability of structural trends through space and time. The E–W to SE–NW trend of the stretching lineation in deep seated levels, together with the SE–NW or even N–S trend of early folds, indicates that earlier structures were oblique to the final WNW–ESE trend of the Hercynian late structures. Fold orientations vary in time but depend also on the strain related to the non-coaxial regime. As suggested earlier, this setting can be interpreted as the result of a gradual clockwise rotation of regional crustal shortening direction, and an eastward increase of strike-parallel motions, causing an increase in the same direction of oblique refolding interference patterns. A gradual localization of transpressive tectonics towards the eastern Axial Zone, which represents also a more internal part of the Pyrenean segment of the Hercynides, caused the development of a complex domain with late folding forming in transpressive shear regime (Fig. 8a) where folds develop in a similar kinematic setting as proposed by Graham (1978), Berthé & Brun (1980) and Iglesias & Choukroune (1980). The structural history can be interpreted as the result of a changing tectonic regime from compressional to transpressive and finally transcurrent, leaving the bulk crustal shortening direction basically unchanged and implying a continuous horizontal crustal shortening, compatible with a strike parallel stretching, (Fig. 8b). Oblique stretching will be recorded mainly in W–E trending suprastructural folds.

Inhomogeneity of deformation throughout the Hercynian deformation history is considered as the determining factor for the development of structurally differentiated domains, with coeval flat and steep structures forming synchronously in the same structural level. It must be emphasized that deep-seated medium- to high-grade domains are not always related to a tangential tectonic regime, and heterogeneity of deformation in deep crustal levels was most likely active since the earlier stages of the Hercynian deformation, with local formation of steep foliations associated to a wrench tectonic regime. The development of flat and steep structures in the infrastructure would depend on the prevalence of flat or wrench shearing respectively.

The fan-like attitude of the suprastructural folds and main cleavage can also be attributed to regional inhomogeneity of deformation with occurrence of upright fold domains (i.e. Pallaresa anticlinorium), and recumbent fold domains (i.e. Orri Dome), developed under essentially the same compressional regime but with a variable horizontal shear component. Moderately inclined NW–SE trending folds in the Eastern Pyrenees with axis-parallel stretching developed under a wrench tectonic regime inducing a N–S rotation to NE–SW crustal shortening.

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