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

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In a recent paper in this Journal, Carreras & Capella (1994) present a concise and complete overview of current structural interpretations of the Hercynian segment of the Pyrenean mountain range. As they point out, the persistence of conflicting tectonic interpretations largely stems from correlation problems between what appears as the macroscopically-dominant cleavage and lineation in different massifs. They present a new tectonic model, in which different structural styles in adjacent zones and at different crustal levels result from heterogeneous deformation and important late-Hercynian strike-slip movements. While acknowledging most of their interpretation as an important contribution, I would like to discuss some microstructural aspects that appear to pose a critical problem.

Carreras & Capella (1994) interpret the presence of two separate foliations at different structural level (suprastructure and infrastructure): a steep main foliation in the suprastructure, which formed after a flat foliation in the infrastructure. They present this idea as a major step forward with respect to superseded interpretations by Séguret & Proust (1968), Matte (1969), de Sitter & Zwart (1960) and Zwart (1979), who originally assumed that the main foliation in the supra- and infrastructure is the same. The idea of a unique main-phase cleavage, however, was already disproved by Verhoef *et al.* (1984), van den Eeckhout (1986, 1990), Lister *et al.* (1986), van den Eeckhout & Zwart (1988), de Bresser *et al.* (1986), Pouget *et al.* (1988), Kriegsman *et al.* (1989), Kriegsman (1989a, 1989b), Gibson (1989, 1991), Vissers (1992) and Aerden (1993) who showed by combined detailed structural mapping and microstructural analysis that the low-dipping foliation in the infrastructure (S3) post-dates an earlier steep schistosity (S2). This is the opposite time relationship to that in Carreras & Capellas (1994) model. However, no effort has been made to clarify this conflicting observation.

The explanation is perhaps simple. The same authors who showed the flat-lying infrastructure foliation to be at least a second generation microstructure (S3 of Aerden, 1994), also showed that this foliation was locally overprinted and folded by a heterogeneously-developed steep cleavage (S4), which locally is the main schistosity due to transposition of S3 and/or S2. In fact, there is evidence for two, still later but weaker crenulation, cleavages (S5 and S6 of van den Eeckhout 1986, in the Hospitalet Massif). Carreras & Capella (1994) have emphasised the S3–S4 relationship, but ignored the S3–S2 relationship, even though S2 forms the dominant foliation in large infra- and suprastructural zones (van den Eeckhout 1986, Pouget *et al.* 1988, Kriegsman *et al.* 1989).

Irrespective of how one prefers to interpret the tectonic significance of the flat-lying foliation, the fact that it overprints an earlier schistosity must be taken into account. The authors who recognized that S3 crenulates S2 favour a crustal extension origin, either of local extent, related to diapirism, or on the orogen scale. Crustal extension during D3 has been recently confirmed by porphyroblast inclusion-trail data showing that S2 formed in a subvertical orientation (Aerden 1993, 1994, 1995); its subsequent rotation and crenulation in the infrastructure implies a vertical shortening component. Carreras & Capella (1994), nevertheless, prefer an origin for the flat foliation by progressive simple shearing during thrusting. Let us examine their arguments.

Firstly, the flat foliation is locally overprinted by steep late-Hercynian foliations (S4), which is difficult to fit into a 'late-orogenic extension' model (Kriegsman *et al.* 1989, Vissers 1992). However, this does not pose a problem for syn-orogenic extension (Aerden 1994, in press). Secondly, orogenic extension would require a switch in plate-tectonic setting for which little evidence exists. However, neither late- nor syn-orogenic extension requires a switch in plate motion, as an orogen may undergo internal extension (thinning) due to gravitational instability, while plate convergence continues (Royden *et al.* 1983, Dewey 1988, Molnar & Lyon-Caen 1988). In this light it is not difficult to explain a late phase of renewed orogen thickening and generation of a steep cleavage (S4) after gravitational equilibrium was restored, but plate convergence still continued. Their third argument is that (compressional) pre-cleavage folds and thrusts are common in upper levels (suprastructure), but would not be present in infrastructural domains. The flat foliation in the infrastructure would therefore be synchronous with these structures and hence, inconsistent with a crustal extension. This reasoning is no longer valid when one recognizes that the flat foliation postdates a steep penetrative cleavage (S2) in the infrastructure.

Apart from this, pre-cleavage deformation has been documented in the infrastructure as well, although more difficult to recognize due to higher metamorphic grades and deformation intensities (e.g. den Brok 1989). This deformation occurs below a discordant conglomerate unit in the Cambro–Ordovician sequence and therefore is pre-Hercynian. Is it possible that at least some of the pre-cleavage deformation in the suprastructure is also pre-Hercynian? Another factor requiring caution is that the main-cleavage in the suprastructure may not be everywhere S2, but locally an S4, or a syn-D4 reactivated S2.

For the sake of objectiveness I should point out that an extensional interpretation of the flat-lying main foliation in the infrastructure also encounters problems. For example, this foliation does not always appear as a crenulation cleavage (S3) but commonly as a first schistosity (S2) in the metasediments. In the gneissic basement, a foliation predating the flat-lying main foliation has never been convincingly demonstrated either, yet where traced into the sedimentary cover, it may appear as a spaced crenulation cleavage overprinting an early schistosity (van den Eeckhout 1986). A possible explanation for these paradoxical observations is that foliations can become obliterated during subsequent deformation by two processes: (i) isoclinal crenulation and disruption, which destroys the pre-existing fabric; and (ii) progressive decrenulation and stretching of a pre-existing fabric, which obliterates the (younger) crenulation cleavage. Crenulation cleavage formation and subsequent destruction by the latter process may occur within a single deformation event as a pre-existing fabric rotates out of the incremental shortening, into the incremental extension field (Bell 1986; Davis & Forde 1994, Aerden 1994). Both foliation-destroying processes can be responsible for the preservation of a single foliation despite a two-phase deformation history and whether such a foliation belongs to the first or second event can only be demonstrated from detailed analysis of relic microstructures in strain-protected zones (e.g. porphyroblasts). Coarse-grained gneisses unfortunately have shorter memory in this respect than more delicately-structured porphyroblastic metasediments.

In conclusion, the Carreras & Capella (1994) model only considers two phases of penetrative cleavage formation in the Pyrenean Hercynides, whereas previous microstructural analysis indicates that there are at least three phases; two steep cleavage generations separated by a flat-lying foliation related to syn-orogenic crustal extension. Still later deformation structures (e.g. van den Eeckhout 1986) and the existence of late-orogenic Stephano–Permian basins may suggest a second, possibly much weaker (post-orogenic) extension event (Vissers 1992). Thus, a single phase of plate collision is not inconsistent with a complex deformation history in an orogen, due to its dynamic response to changes in thermal and/or mechanical boundary conditions and the interplay between tectonic and gravitational forces.

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