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Origin of a large-scale fold nappe in the Montagne Noire, Variscan belt, France

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Abstract

Detailed structural analysis of a large recumbent fold in low-grade Palaeozoic sediments of the Montagne Noire, and the previously established tectonometamorphic history of its crystalline substratum, indicate a two-stage development history. First, relatively homogeneous crustal thickening produced folds with steep axial planes associated with a regional cleavage (S_1). Subsequently, these structures became rotated and amplified in a subhorizontal flow with pure shear and simple shear components related to low-angle thrusting. The development of an associated horizontal crenulation cleavage (S_2) with a component of vertical shortening of S_1, plus evidence for a synchronous decompression of autochthonous units allows this flow regime to be placed in the context of a thrust wedge undergoing gravitational spreading above a continuously contracting footwall. Decoupling of an extending thrust wedge from a contracting footwall by a basal thrust with low shear resistance, explains bulk shortening, uplift and exhumation of mid- to lower-crustal autochthonous basement during thrusting and recumbent folding at higher levels. Structural relationships in the southern Montagne Noire demonstrate that traditional tectonic units recognized in this area, the so called 'nappes', are in fact unrelated to the recumbent folding as inferred previously. These 'nappes' postdate not only the recumbent folding, but also a later phase of refolding (D_3) associated with the formation of a gneiss dome. The traditional nappe division can be simplified to a hanging wall and footwall domain of a major décollement that formed during a second syn-collisional collapse (D_4) associated with the formation of intermontane Stephanian basins. The late timing of the 'nappes' and simplified tectonic structure of the southern Montagne Noire imply a thinner D_2 recumbent fold structure with only one major anticline–syncline pair, and is in better agreement with the low metamorphic grade of the area. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The origin of large-scale recumbent folds, such as occur in the Variscan Montagne Noire (Arthaud, 1970), Variscan NW-Iberia (Martínez Catalán et al., 1990), or the European Alps (Ramsay, 1981) is a long standing question in structural geology. An added problem in the Montagne Noire is the very low-grade metamorphism, and hence superficial origin of an approximately 10 km long fold nappe with axial plane slaty cleavage. Crystalline basement of this structure is exposed to the north (Axial Zone; Fig. 1) and presents a regional schistosity in amphibolite-grade gneisses and schists associated with large-scale tight to isoclinal folds. These structures have been widely regarded as purely compressional ones, related to low-angle thrusting and the development of a medium- to high-pressure (M–HP) metamorphism (Bard and Loueyit, 1978; Thompson and Bard, 1982; Demange, 1994), but a different interpretation was proposed recently by Aerden (1998) after showing that thrusting was: (1) partially synchronous with decompression of pre-existing M–HP metamorphic assemblages, and (2) associated with the development of a subhorizontal crenulation cleavage involving components of vertical flattening, and suggesting an active role of gravity.

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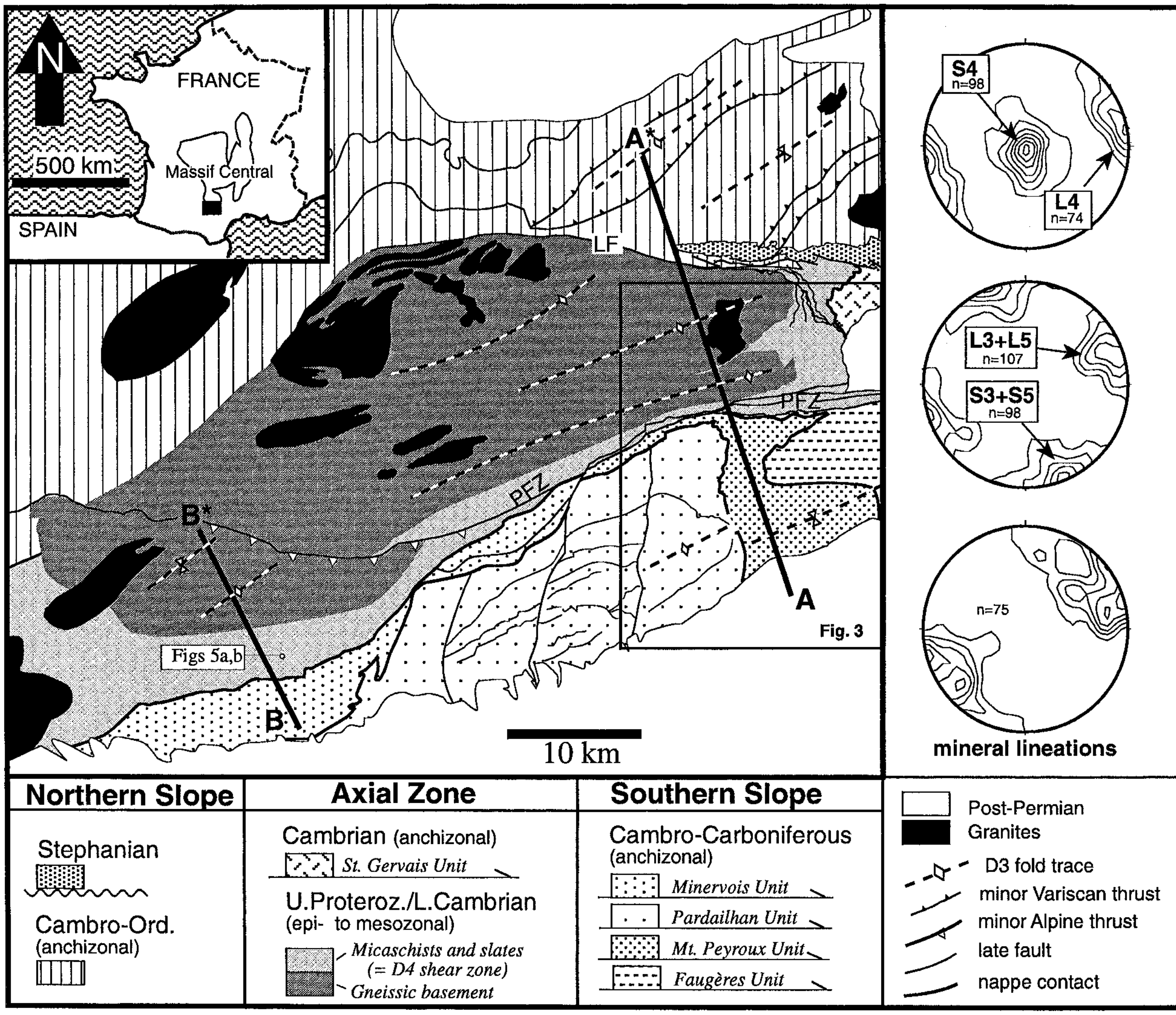

Fig. 1. Simplified geology of the Montagne Noire and main tectonic units recognized by previous workers. Note that the basal contact of the Pardailhan nappe is continuous with the northern limit of the Minervois nappe and that the contact between these units could be a late wrench fault (see Fig. 6). Cross-section lines correspond to Fig. 2, but the shading patterns are different from the ones used in Figs. 2 and 3. LF = Lacaune Fault. PFZ = Pujol Fault Zone.

Based on these results a conceptual model was proposed for the Variscan orogen, in which subhorizontal thrusts decouple an upper crustal wedge from a continuously converging autochthonous footwall to accommodate horizontal spreading and thinning of the wedge under the action of gravitational body forces. Thus, instead of building up the orogenic pile, thrusts were proposed to have transported upper crustal material away from the orogen centre and in this way to have contributed to unroofing (decompression) of autochthonous basement. In the present work, we investigate the implications of this model for the creation of a huge recumbent fold nappe in the low-grade southern Montagne Noire by presenting new data for the structural sequence in the area, and reviewing a large set of existing data from previous workers. A correlation is proposed between the structural-metamorphic development of cover and basement units and a kinematic model is built that illustrates how a gravitational spreading mechanism not only is consistent with the structural-metamorphic evolution of the schists and gneisses, but also provides an interesting solution for the origin of the low-metamorphic large-scale recumbent fold nappe of the Southern Montagne Noire, and perhaps elsewhere. We also reinterpret the traditional tectonic units or 'nappes' of the Southern Slope as being mostly unrelated and later than the recumbent folds, with important implications for the original macroscopic geometry of these structures.

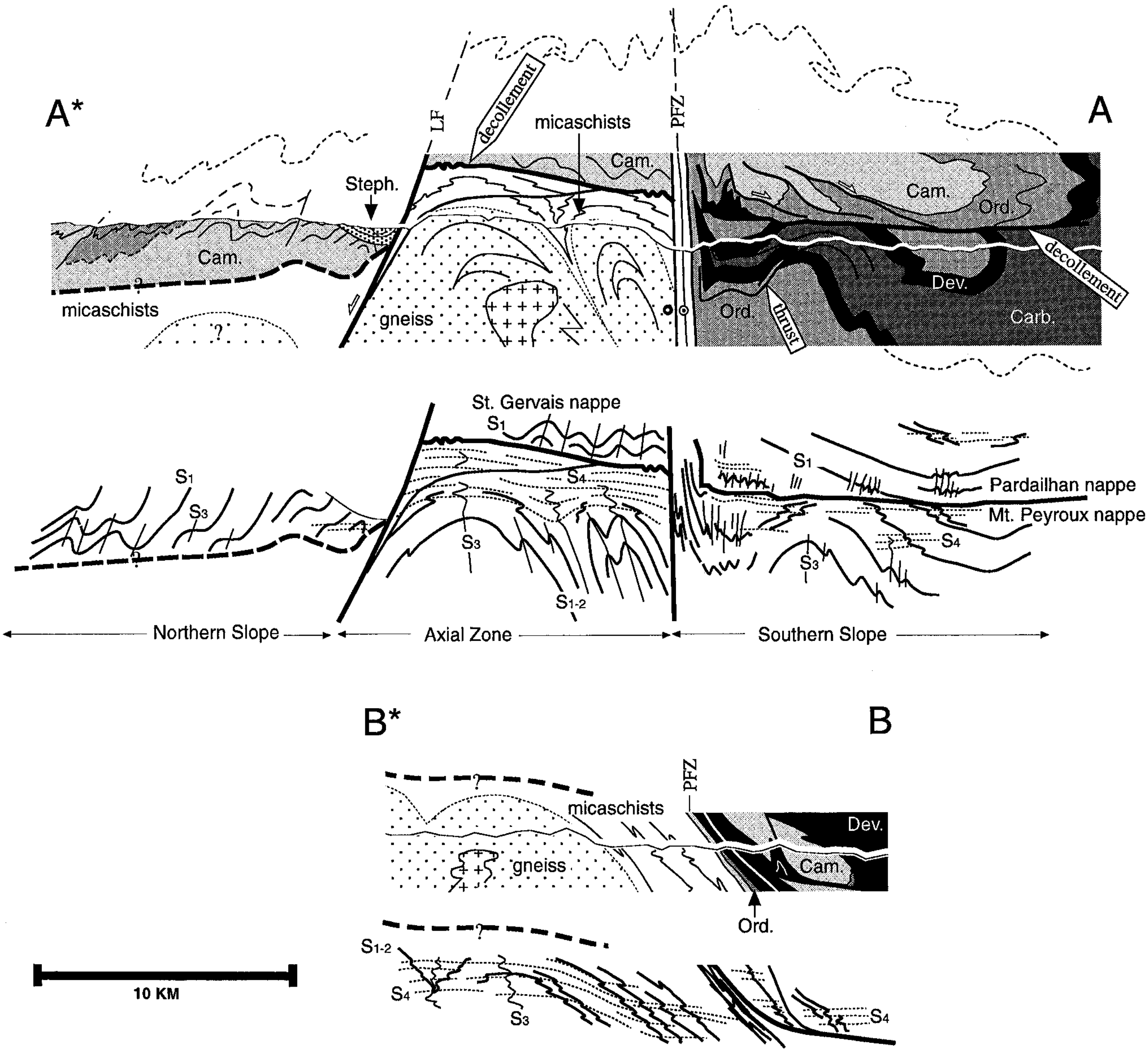

Fig. 2. Synthetic cross-sections along profile lines A–A* and B–B* of Fig. 1. Foliation relationships are shown separately below each cross-section. Shading patterns correspond to those of Fig. 3. A major D_4 subhorizontal décollement crosscuts a D_3-refolded, D_2-recumbent fold, but is itself deformed in the D_5 Pujol Fault Zone (PFZ). Ductile D_4 strain is concentrated in micaschists immediately overlying the gneisses.

2. Geological setting

The Variscan orogen developed during the Gondwana–Laurasia collision with progressive migration of crustal thickening to external parts of the belt from Devonian to middle-Carboniferous times accompanied by a Barrovian-type metamorphism (Matte, 1991; Martínez Catalán et al., 1997). Late-orogenic extension associated with a low-pressure high-temperature metamorphic overprint (Van den Driessche and Brun, 1989; Malavieille et al., 1990; Malavieille, 1993; Faure, 1995), and Alpine deformations caused fragmentation of the orogen into isolated segments, one of which is the French Massif Central. The Montagne Noire forms the southern extremity of the Massif Central comprising a core of gneisses, migmatites and micaschists of Proterozoic to Cambrian age, flanked and overlain by low-grade Palaeozoic cover series (Figs. 1 and 2). The area has traditionally been subdivided into the Axial Zone (higher grade units), a Southern Slope (Versant Sud) and a Northern Slope (Versant Nord), based on Late-Variscan faults separating these domains (Gèze, 1949). Molasse-type sediments of Stephanian-B (U. Carboniferous) age are exposed in a narrow strip following the Axial Zone–Northern Slope boundary. The deposition of these rocks in intermontane basin has been related to late-orogenic extension (Echtler and Malavieille, 1990).

The outstanding structural feature of the Montagne Noire is a series of kilometric upright folds deforming the regional main cleavage, and lying at the origin of the anticlinal structure of the Axial Zone. Superimposed on this fold pattern is a subhorizontal regional-scale shear zone of about 2 km thickness localized in micaschists and slates overlying the Axial-Zone gneisses (Van den Driessche and Brun, 1992; Aerden, 1996; Laumonier and Marignac, 1996; Brunel and Lansigu, 1997). The base of this shear zone affects sillimanite-bearing schists and gneisses, whereas the top is delimited by a subhorizontal tectonic contact or 'décollement', which separates lower-greenschist grade slates in the immediate footwall from anchizonal Cambrian sediments (St Gervais unit) in the hanging wall (Figs. 1 and 2).

In the Southern Slope, four main tectonic units or 'nappes' are separated by low-angle faults (from west to east, the Minervois-, Pardailhan-, Mount Peyroux-, and Faugéres-nappes), the significance and timing of which will be investigated. Upright folds with similar trends to the ones of the Axial Zone deform the regional slaty cleavage of the Southern Slope and associated recumbent folds of different scale developed in Lower-Cambrian to Middle-Carboniferous shales, slates and carbonate rocks (Gèze, 1949).

3. Basement evolution

3.1. Deformation sequence

Amphibolite-facies micaschists in the Axial Zone contain relicts of an early crenulation cleavage (S_1, S_2), uniquely preserved in low-strain microlithons, and as inclusion trails in staurolite and garnet porphyroblasts (Aerden, 1998). In the bulk of these rocks, however, S_1 and S_2 are generally not distinguishable and form a composite main schistosity we label S_{1-2} for the time being. There is general agreement that this schistosity is equivalent to the first slaty cleavage (S_1) in the anchizonal cover sequences where no equivalent of S_2 has been recognized. Both low-grade and higher-grade fabrics have been related to progressive southward thrusting because of their average subhorizontal position on regional cross-sections (Gèze, 1949), and close association with consistently south-verging recumbent folds of different scales. The youngest rocks affected by S_1 in the cover are synorogenic sediments of Upper-Visean to early Namurian age (340 Ma), providing a lower age limit for thrusting in the Southern Slope (Engel et al., 1981). Major folds with steep axial planes in basement and cover series deform the regional main cleavage associated with a subvertical S_3 crenulation cleavage (XY plane) and subhorizontal stretching lineation (L_3). These fabrics indicate shortening perpendicular to S_3 (in NNW–SSE direction), and synchronous horizontal stretching parallel to L_3, with the parallelism between L_3 stretching lineations and D_3 fold axes logically implied by the pre-D_3 horizontal position of S_{1-2} (cf. Mattauer et al., 1996).

As already mentioned, an approximately 2 km thick shear zone is superimposed on the D_3 folding and mainly affects the micaschist envelope of the gneisses. It is characterized by shear bands, a younger crenulation cleavage (S_4 of Aerden, 1998), and macroscopic mylonite zones that anastomose around lenses of moderate D_4 strain. The latter exhibit evidence for a polyphase folding history, which was resolved through a detailed analysis of oriented inclusion trail patterns in garnet and staurolite porphyroblasts (Aerden, 1998). The parallelism of L_3 and L_4 stretching lineations, the orthogonality of S_3 and S_4, and a likely component of vertical pure-shear necessary to develop S_4 suggest that the transition from D_3 to D_4 merely involved an inversion in the balance between constantly oriented horizontal compressional forces (responsible for S_3) and gravity (responsible for S_4). Aerden (1998) inferred this inversion to have been caused by progressive heating and rheological weakening of the micaschists to the point that these rocks collapsed internally, consistent with (1) an anomalously close spacing of metamorphic isograds in the D_4 shear zone (attributable to ductile thinning), (2) a late syn-D_3 to early syn-D_4 timing of peak-metamorphism (Brunel and Lansigu, 1997; Aerden, 1998), and (3) evidence for coeval surface extension and Stephanian basin formation (Echtler and Malavieille, 1990).

Metamorphic isograds become further condensed as they steepen in a (D_5) wrench zone situated at the boundary between the Axial Zone and Southern Slope (Pujol Fault Zone), with a poorly constrained shear-sense history. Late crenulations and folds (D_5) with similar orientation to the D_3 structures, but post-S_4 and post the (syn-D_4) Stephanian basin are probably coeval with wrench tectonics during the final stages of plate convergence. Finally, stretched pebbles, normal faults, fault-related fibres and striae in Stephanian and Permian sediments record post-orogenic crustal extension in N–S direction (Van den Driessche and Brun, 1989; St. Martin, 1993), oblique to earlier synorogenic stretching lineations. This second phase of extension can be attributed to relaxation of compressive plate forces at the end of the Variscan cycle, and restoration of normal crustal thicknesses (e.g. Ménard and Molnar, 1988; Malavieille, 1993). The narrow strip of Stephanian sediments exposed north of the Axial Zone escaped erosion in the hanging wall of a fault related to this final extension. This fault cuts the Stephanian

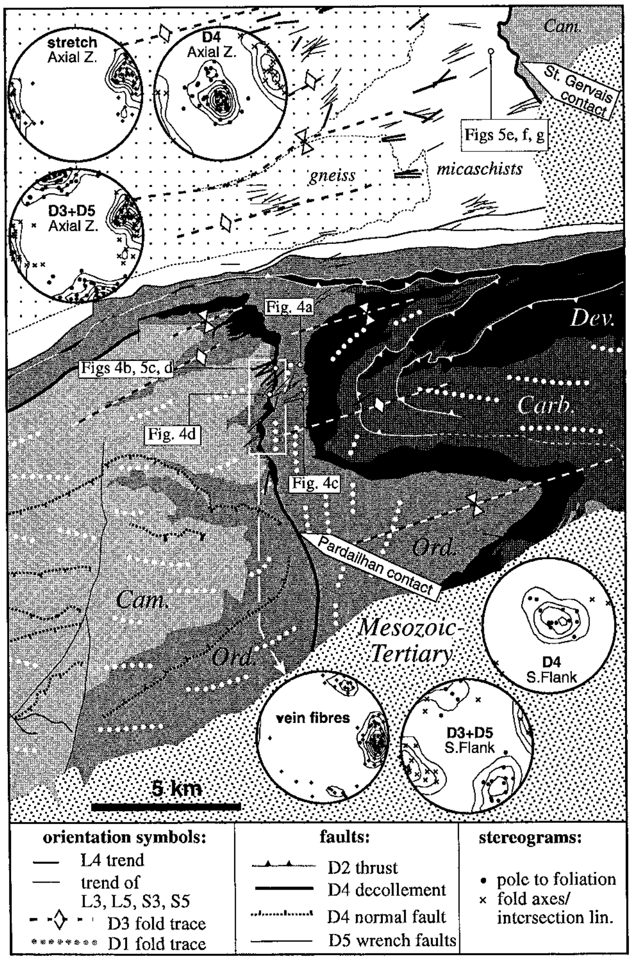

Fig. 3. Detailed structural map of the subarea indicated in Fig. 1, based on the 1:50.000 BRGM geological map of the area. The location for other figures is indicated. D_1 fold-axes orientations (after Arthaud, 1970; Harris et al., 1983) show variable trends consistent with southward or south-eastward thrusting. The orientations of D_3, D_4 and D_5 fold-axes in the Southern Slope (lower group of stereograms) and in the Axial Zone (upper group of stereograms) are subparallel. The trace of the basal Pardailhan contact (D_4 décollement), suggests truncation of D_3 folds in footwall and hanging wall units (see Fig. 2). However, an older thrust is outlined by narrow repetitions of Devonian and Carboniferous rocks in the footwall and folded by D_3. Fibre orientations in the Pardailhan Contact Zone (data mainly from Harris et al., 1983) are predominantly E–W, parallel ductile stretching lineations in the Axial Zone, and are inferred to record the main D_4 movement direction.

stratigraphy and the present basin geometry bears no direct relationship with the original (D_4) synorogenic extension that controlled sedimentation. A large part of the original basins was folded (D_5) and eroded before (discordant) deposition of Permian strata.

3.2. Metamorphism

Relic eclogitic assemblages and sporadic occurrences of kyanite grains aligning parallel to S_{1-2} in the deepest micaschist levels record an early Barrovian-type metamorphism, which in the micaschists progressively evolved towards HT–LP metamorphic conditions (575°C and 450 MPa or less) around 320 Ma, following a slightly prograde but decompressive P–T–t segment (Hamet and Allègre, 1976; Thompson and Bard, 1982; Demange, 1985; Demange and Jamet, 1985; Maluski et al., 1991). The decompression led to widespread migmatization of the Axial Zone gneisses and high geothermal gradients were maintained until at least Stephanian times (Becq-Guiraudon, 1973). Porphyroblast–matrix relationships in the micaschists indicate a syn-D_3 to syn-D_4 timing of peak metamorphic conditions in the micaschists (Aerden, 1998), and paradoxically implies that the preceding decompression took place during D_{1-2} thrusting. Anchizonal sediments in the Southern Slope yielded Rb–Sr ages and $^{40}Ar^{39}Ar$ ages between 346 and 332 Ma (Gebauer and Grünenfelder, 1974; Maluski et al., 1991), and were interpreted by these authors as the age of the Barrovian metamorphism. Close to the Axial Zone greenschist facies conditions are reached in the Palaeozoic sediments, but probably corresponding to the late HT–LP metamorphic overprint recorded in the deeper micaschists.

4. Structural analysis of the cover

4.1. General structure

The regional slaty cleavage in the cover series is axial-planar to up to kilometre-scale folds with variable inclinations. A large part of the Southern Slope has an inverted stratigraphy representing an overturned fold limb of approximately 10 km long (Fig. 2). The curvilinear map pattern of D_1 fold hinges in this area suggest differential tectonic transport to the south or south east during the development of these folds (Arthaud, 1970; Fig. 3). Curiously enough, the cover sequences of the Northern Slope and Axial Zone lack large-scale recumbent folds. In the Southern Slope, four main tectonic units or 'nappes' are traditionally distinguished, separated by low-angle tectonic contacts that locally produce stratigraphic repetitions. It is not surprising that these contacts have been widely inferred to be thrusts closely related to the recumbent folding (D_1). However, it is shown further that the nappes, in fact, post-date the recumbent folds, and even their later refolding.

Nappe contacts are disturbed by late-Variscan normal faults, wrench faults and some Alpine thrusts with limited northward displacement, but the basal contact of the Pardailhan Nappe is still well outlined by a train of hectometric fragments (megaboudins) of Devonian limestone sheared between Ordovician slates

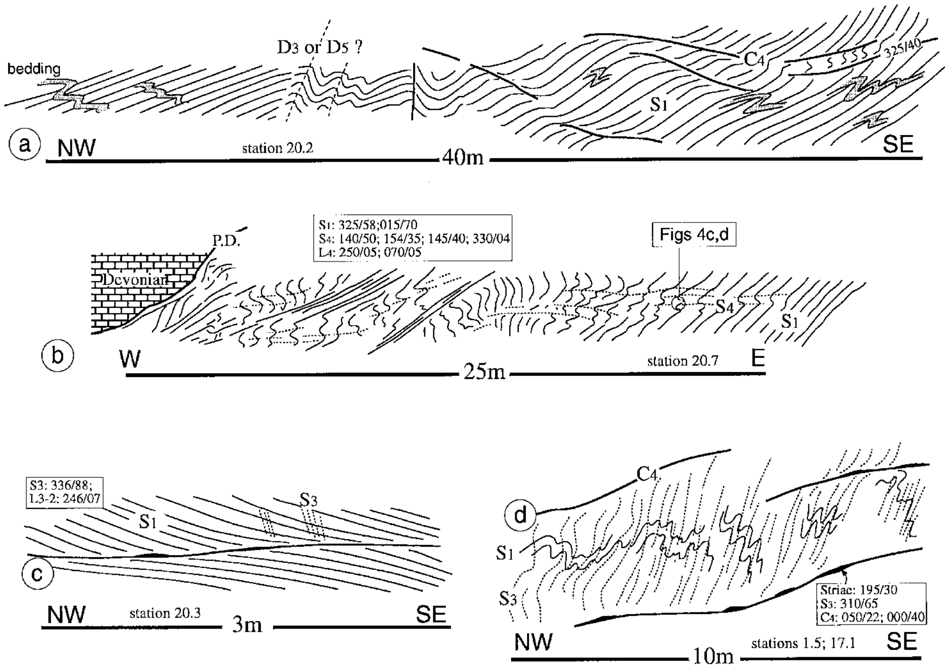

Fig. 4. Field observations in the Southern Slope demonstrating the late character of décollement-related mesoscopic and microscopic structures. (a) Metric D_4 shearbands deform the slaty cleavage (S_1) in Ordovician slates. (b) Subhorizontal crenulation cleavage (S_4) and small-scale recumbent folds immediately below the Pardailhan Detachment. In thin section, S_4 is seen to post-date S_3 crenulation cleavage (Figs. 5c, d). The Pardailhan décollement is marked by a train of hectometric boudins of Devonian limestone enveloped by Ordovician slates. The basal part of one of these boudins appears on the left-hand side of the cross-section. (c) Metric D_4 shearbands developed in Ordovician slates. (d) Metric D_4 shearbands, deforming a finely-spaced steep crenulation cleavage and associated mesoscopic D_3 folds in Ordovician slates. Figure locations are given in Fig. 3.

(Figs. 2 and 3). Low-angle normal faults or 'extensional detachments' in the hanging wall of this contact (in the Pardailhan nappe) have been attributed to late-orogenic extensional collapse of the Variscan orogen (Echtler, 1990). Nevertheless, Echtler (1990) maintained the classic interpretation of the basal contact as an early thrust, which he assumed to have been reactivated as an extensional detachment.

4.2. Fabric development history

The slaty cleavage of the Southern Slope is overprinted by two generations of crenulation cleavage and associated folds. Overprinting relationships in oriented thin sections combined with field observations allowed identification of a steep, closely spaced differentiated crenulation cleavage as the older one, and a more widely spaced subhorizontal crenulation cleavage as the younger. The steep crenulation cleavage is associated with mesoscopic and macroscopic upright folds (Figs. 3 and 4d), heterogeneously developed in E–W-trending corridors but becoming penetrative within approximately 1 km distance of the Axial Zone gneisses and difficult to distinguish from the slaty cleavage. The macroscopic folds tighten towards the Axial Zone and correlate well in orientation and relative timing with the D_3 folds of the Axial Zone (Mattauer et al., 1996). No traces of an S_2 were recognized, which suggests that this fabric was confined to the crystalline basement rocks.

The younger subhorizontal crenulation cleavage (S_4) is associated with shear bands of different scale and asymmetric folds with strongly sheared long limbs superimposed on the D_3 structures (Figs. 4 and 5). They are particularly abundant in a zone, several tens of metres thick, immediately below the basal Pardailhan unit contact called the 'Pardailhan Contact Zone' (PCZ). A detailed cross-section in the uppermost part of this zone (Fig. 4b) shows conspicuous D_4 structures until at approximately 1–2 m distance of the Devonian limestone boudin, the Ordovician shales become strongly disturbed, probably because of multiple reactivation of this contact (see below). The Devonian limestone itself shows few signs of internal deformation, and the overlying rocks of the Pardailhan unit only exhibit a slaty cleavage but no D_4 fabrics. Thus, D_4 strain was localized in the footwall.

The above described observations for the PCZ are strikingly similar to the ones we made immediately below the basal contact of the St Gervais unit in the Axial Zone. Here too, a similar subhorizontal crenulation cleavage (S_4) associated with shear bands overprints an earlier steep crenulation cleavage (S_3) (Figs. 2, 5e, f and g), and this relationship can be consistently

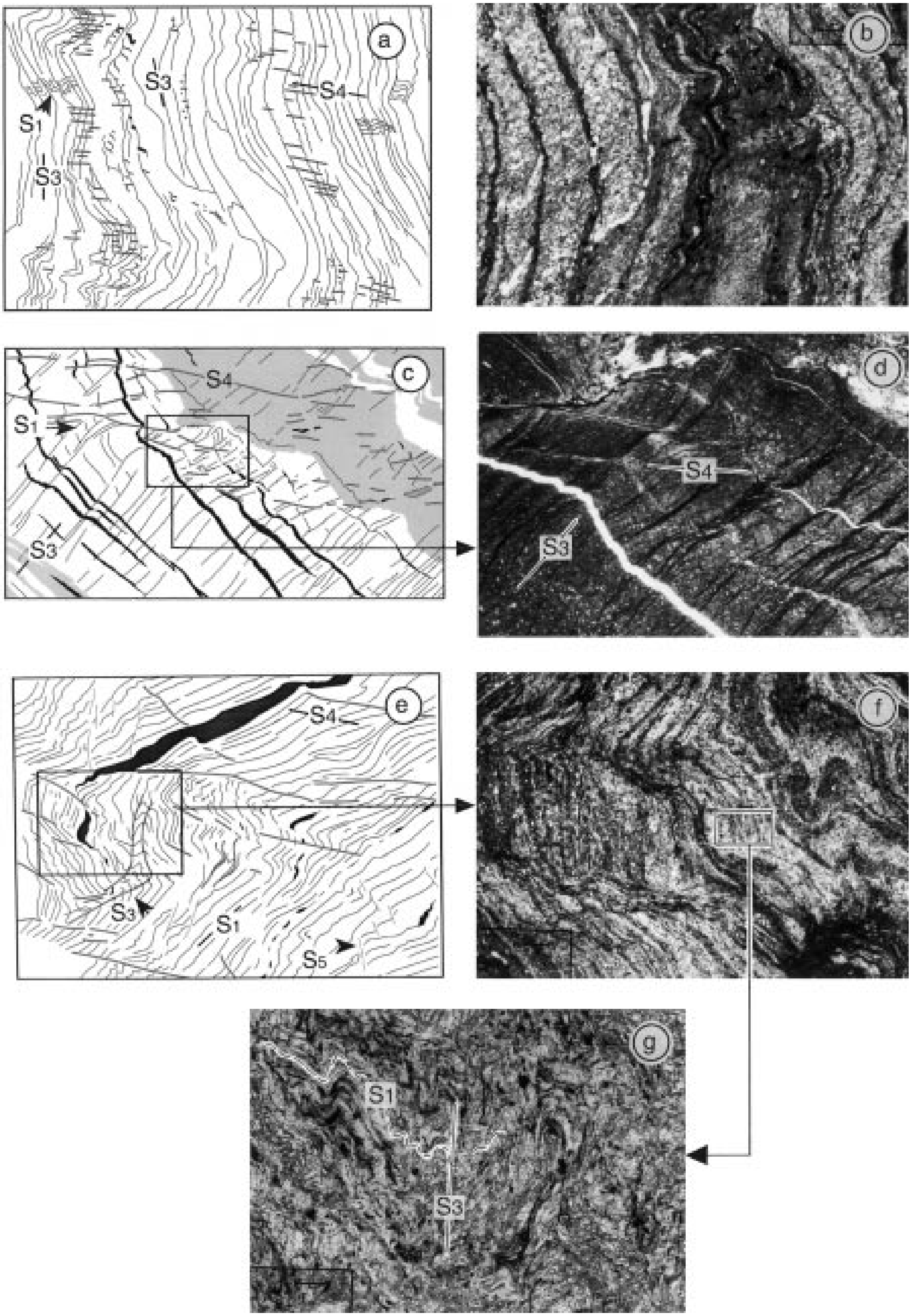

Fig. 5. Microscopic S_1, S_3, S_4 relationships. (a and b) Greenschist facies slate from the western Montagne Noire (location in Fig. 1). (c and d) Low-grade slate approximately 10 m below the Pardailhan Detachment (locations in Fig. 3). (e, f and g) Low grade slate approximately 200 m below the St Gervais Detachment (location in Fig. 3).

followed downward into upper-amphibolite facies micaschists (Aerden, 1998).

4.3. Timing of nappe contacts

The geometric similarities between the basal Pardailhan and St Gervais contacts, as well as their close association with D_4 structures indicates a late-orogenic timing (D_4), rather than an early origin as recumbent fold related thrusts. A late-orogenic timing is also suggested by macroscopic maps and cross-sections for the area showing these contacts truncating upright (D_3) folds in the slaty cleavage, as explicitly described by Latouche (1968), Demange et al. (1986), and Demange and Herrera Urbina (1989) for the basal contacts of the St Gervais and Minervois units, but equally indicated on the cross-sections of Guiraud (1965), Arthaud (1970) or Echtler (1990) for the Minervois, Pardailhan, and Mt Peyroux units. All their cross-sections show open to tight upright folds in the regional cleavage but flat subhorizontal nappe contacts until they steepen in the late Pujol Fault Zone (Figs. 2 and 3). A notable exception is the contact separating the Mt Peyroux and Faugères units. In contrast to the other nappe contacts, it is clearly folded with the slaty cleavage (Fig. 3), and associated with conspicuous stratigraphic repetitions indicating an early thrust origin.

4.4. Movement direction of the nappes

Mineral lineations and strain fringes (associated with pyrite) contained in slaty cleavage planes of the Pardailhan unit are mainly oriented N–S to NE–SW (Echtler, 1990), consistent with the direction of early Variscan thrusting suggested by the regional pattern of D_1 fold axes (Fig. 3). However, finite strain analysis on deformed fossils, and texture goniometry (Harris et al., 1983) paradoxically indicated that maximum elongation directions in the Pardailhan unit are systematically parallel to the D_1 fold-axes, and hence perpendicular to the inferred direction of thrusting. These data have never been satisfactorily explained, and we come back to them in a later section.

Folding and reactivation of the slaty-cleavage planes during the later crenulation-cleavage producing events produced abundant fibrous quartz and calcite veins. In the PCZ, a syn-D_4 timing of most of these veins is indicated by (1) vein geometries controlled by the intersection of slaty cleavage planes and S_4, (2) an abundance of veins proportional to the abundance of D_4 structures, and (3) the truncation of mesoscopic D_3 folds by some veins. Vein fibres in the PCZ and overlying Pardailhan unit were shown to be oriented mainly E–W, but a second (subordinate) set of N–S oriented fibres exists in the PCZ (Harris et al., 1983; Fig. 3). The relative age of the two fibre directions in the PCZ could not be determined, but as the E–W fibres parallel ductile L_3 and L_4 stretching lineations in the Axial Zone they support interpretation of the PCZ as a D_4 structure and that the main movements of the nappes occurred in E–W direction, instead of N–S as inferred previously. The N–S fibres in the PCZ match the direction of post-orogenic extension (D_6) recorded in Stephano-Permian sediments of the Northern Slope and are reasonably attributed to a later N–S reactivation of the PCZ.

S–C fabric-resembling geometries or 'extensional crenulations' in the PCZ generally result from a low-angle intersection between slaty cleavage planes and widely spaced S_3 or S_4 crenulation cleavage septae or shearbands. Their association with D_3 and D_4 folds in which S_3 and S_4 crenulate the slaty cleavage at a higher angle ('compressional crenulations'), indicate a common origin of both crenulation types during deformation of a pre-existing slaty cleavage (cf. Carreras et al., 1980; Bell, 1981; Aerden, 1994). The asymmetry of both compressional and extensional crenulations varies as a function of the position of these fabrics in macroscopic D_3 and D_4 folds and intersection lines are subparallel. Interpretation of these extensional crenulation geometries in terms of progressive shear-zone fabrics is inadequate and would provide false and conflicting shear senses.

4.5. Tectonic significance of the nappe units

A late-orogenic timing (D_4) of nappe units in the southern Montagne Noire has important implications for reconstructions of the original D_1 fold structure of this area. Previous reconstruction (e.g. Arthaud, 1970) parted from the assumption that the nappes developed synchronously with the recumbent folding, and consequently, that large-scale recumbent folds observed in adjacent nappes were originally stacked in a thick cross-section containing multiple synclinal and anticlinal hinges. However, nappe formation after D_3 implies that cross-sectional geometries in different nappe units may be representing lateral segments of the same recumbent fold structure possessing only one major anticline–syncline pair (Fig. 2). The much thinner rock pile implied is certainly in better agreement with the low-grade metamorphism.

Furthermore, inspection of the geological map (Fig. 1) permits the simplification of the traditional nappe division in terms of a main hanging wall and footwall domain of a principal D_4 contact. The basal Pardailhan contact is seen to be continuous with the Minervois–Axial Zone tectonic contact, whereas the Minervois–Pardailhan contact has limited displacement and could be regarded as a late wrench and/or normal fault (Fig. 1). The basal tectonic contact of both

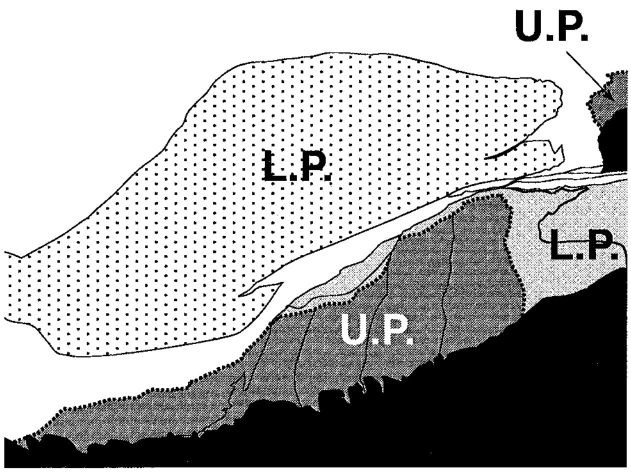

Fig. 6. Interpretation of the D_4 structure of the Montagne Noire characterized by a subhorizontal décollement with the hanging wall or Upper Plate constituted by the Minervois, Pardailhan and St Gervais units.

nappes therefore seems to be the same, and as this contact cuts laterally into the Axial Zone micaschists, it is also likely to be the same as the basal St Gervais tectonic contact in the eastern Montagne Noire. The distinctive similar stratigraphic column reported for the St Gervais, Pardailhan, and Minervois units (Demange and Herrera Urbina, 1989) supports limited displacements between them and their interpretation as a single hanging wall block (upper plate) of a principal D_4 contact (Fig. 6).

5. Model and discussion

5.1. Recumbent folding model

In the previous section, we interpreted the original D_1 structure of the Southern Slope as a single syncline–anticline pair, exclusively developed in the Southern Slope. This can be explained in terms of the thrusting model of Aerden (1998): Following bulk crustal shortening, upright folding, cleavage development (D_1), and a Barrovian metamorphism, the orogenic pile is inferred to have undergone gravitational collapse, possibly induced by thermal reequilibration and weakening of a rapidly thickened crust (cf. Willett, 1992). An upper-crustal thrust wedge developed that was spreading transversal to the orogen trend, and decoupled from a footwall undergoing continuous compression (Figs. 7 and 8). The strain geometry in the collapsing wedge was characterized by relatively coaxial flattening towards internal orogenic zones, changing to strongly non-coaxial regimes in more external zones (Figs. 7 and 8). This heterogeneous strain distribution explains the development of S_2 in internal, deep rocks where S_1 was shortened and crenulated, but not in external zones where S_1 was passively rotated and stretched (Fig. 8b). The slaty cleavage in the cover is therefore best correlated with S_1 of the crystalline basement, whereas thrusting in the Southern Slope and the development of a large fold nappe was coeval with the development of S_2 in the crystalline rocks. This model provides a possible explanation for Harris et al.'s (1983) evidence for finite strain ellipsoids in the Southern Slope being parallel to D_1 fold axes and perpendicular to the inferred thrusting direction: the greater part of this strain could have accumulated during D_1 crustal shortening and longitudinal stretching, while the later thrusting (D_2) locally created new stretching lineations in cleavage parallel zones being reactivated in transversal direction.

The development of a single fold nappe in the Southern Slope, but not in the Northern Slope, is consistent with a foreland inclined enveloping surface of D_1 folds and a downward increasing strain gradient of D_2 towards a horizontal or slightly backsloping basal thrust (Figs. 7 and 8b). A remaining problem is the timing of macroscopic folds in the Northern Slope, as their reported association with a subvertical crenulation cleavage and small-scale fold-overprinting relationships suggests an origin after the recumbent folding (D_2 of Brunel, 1974; D_3 here). During a preliminary field trip to the Northern Slope, we noted however, that the axial-plane fabric of these folds is commonly a first slaty cleavage and that overprinting relationships are concentrated in the SE part of the area where deeper levels are exposed, including some crystalline basement. We therefore suggest as a possibility to be verified in the future, that the macroscopic folds of the Northern Slope are D_1 structures but formed with axial plane orientations subparallel to those of future D_3 folds. Only at deeper levels was D_2 strain high enough to sufficiently rotate the D_1 structures to low-angle positions in order for them to be later refolded and crenulated by D_3. In the remainder of the Northern Slope, the D_1 structures are inferred to have maintained high dip angle and were merely tightened during D_3.

5.2. Post-recumbent folding history

D_3 refolding of S_1 and S_{1-2} indicates renewed compression in the wedge during the development of fold-axes parallel (L_3) stretching lineations (Fig. 8). The earlier extension associated with D_2, and consequent rise/exhumation of deep rocks explain an increased geothermal gradient consistent with evidence for a Barrovian metamorphism evolving towards LP–HT conditions (Fig. 7b). Progressive heating in the micaschists continued during D_3 and culminated around the onset of D_4, when the micaschists are inferred to

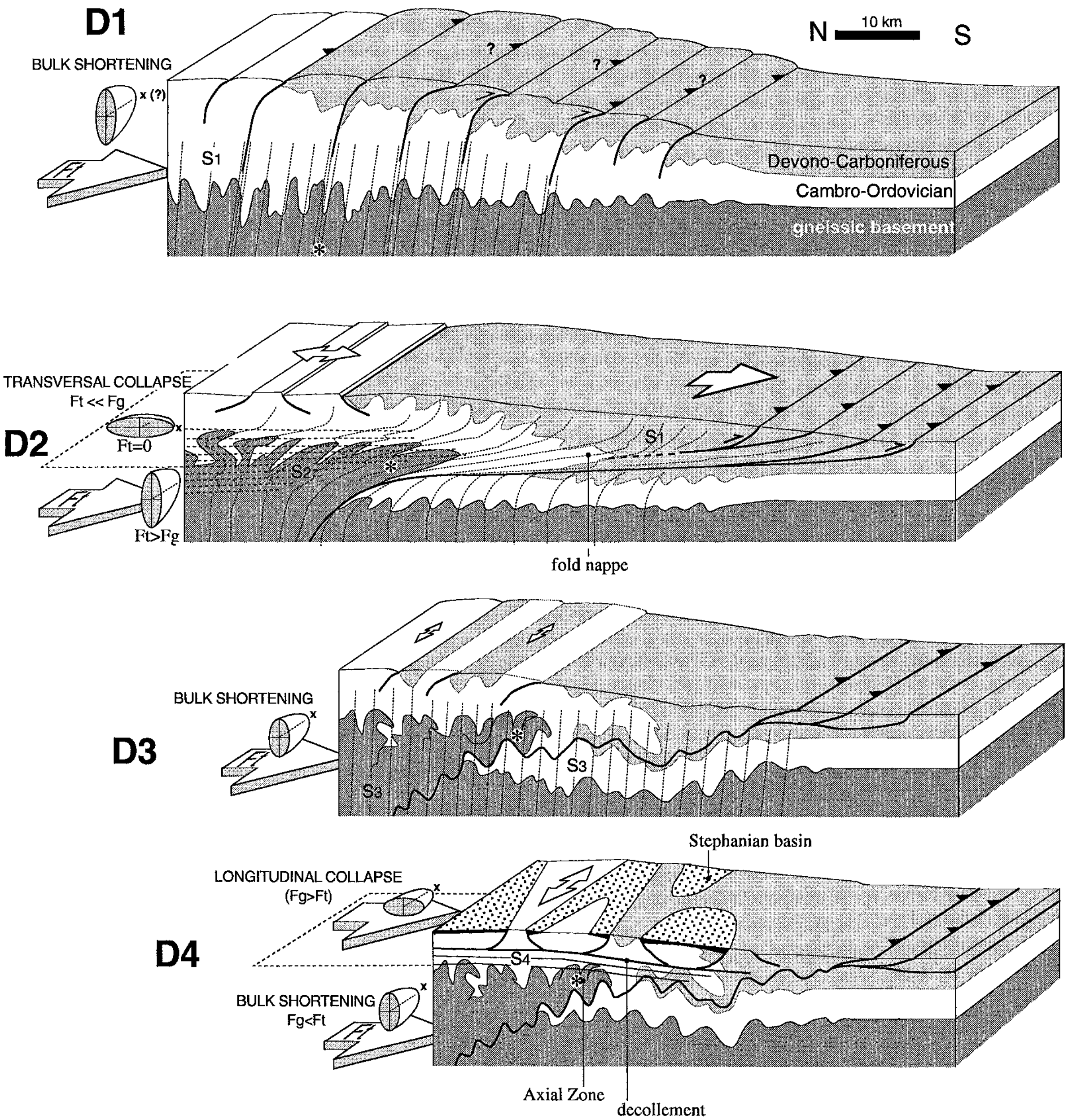

Fig. 7. Synthetic tectonic history of the Montagne Noire (not exactly to scale). D_1: crustal shortening by folding and generation of a regional cleavage. The maximum elongation direction is horizontal as suggested by strain data of Harris et al. (1983). D_2: gravitational collapse transversal to the orogen trend produces thrusts and a large-scale recumbent fold structure. A subhorizontal crenulation cleavage (S_2) develops in internal zones of the orogen where strain is more coaxial. D_3: renewed bulk shortening in the thrust wedge causing refolding of S_{1-2} and thrusts with fold-axes parallel stretching. D_4: a second gravitational collapse localizes in incompetent hot micaschists with the stretching direction of D_3 maintained. At higher levels, deformation is accommodated by normal faulting and a major décollement fault, that control Stephanian sedimentation. D_5 and D_6 are not represented but caused further uplift of the Axial Zone as a fault-bound block. Ft = horizontal tectonic force; Fg = gravitational force. The asterisk symbols indicate the structural paths of the rocks of the Axial Zone.

have become gravitationally unstable a second time. The underlying gneisses were not affected by D_4, presumably because of a coarser grained, more feldspar-rich and more competent lithology. The overlying cover sediments became detached from the regional D_4 shear zone by a major subhorizontal décollement to accommodate the different deformation styles in hanging wall (brittle) and footwall (ductile). The parallelism of L_3 and L_4 stretching lineations in the micaschists suggests that plate convergence continued, that the collapsing zone was not decoupled from horizontal plate forces (contrary to the D_2 collapse), and that D_3 kinematics (compression) probably continued in the footwall of the D_4 shear zone.

The above can be explained in analogy with a hypothetical experiment, in which a viscous layer with

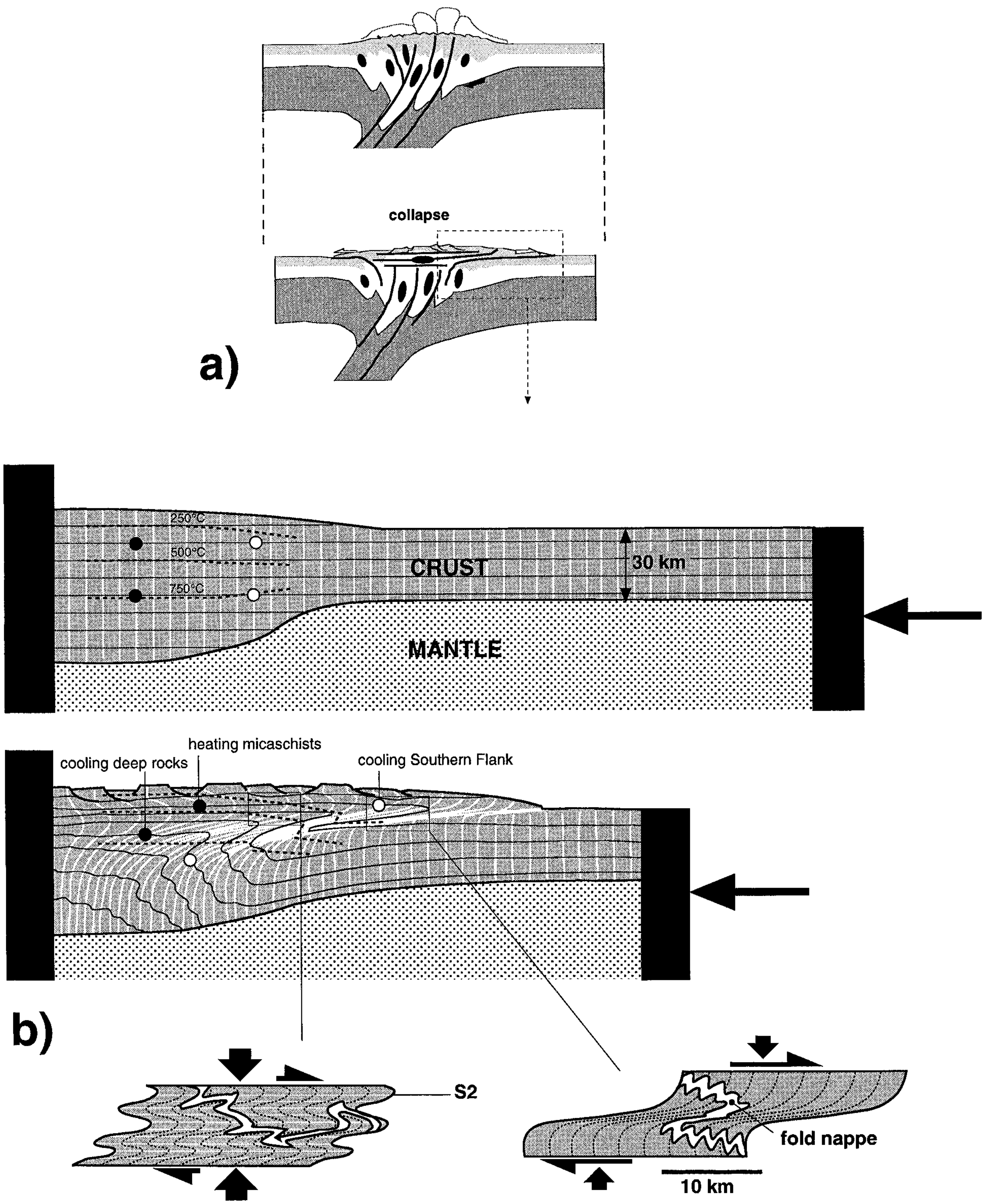

Fig. 8. (a) Conceptual orogenic model proposed by Aerden (1998) to explain the D_1 and D_2 events in the Montagne Noire. Gravitational thrusting and fold nappe development follows previous bulk shortening of a relatively deformable weak crust. The collapse of an upper-crustal double wedge facilitates the unroofing and uplift of deep autochthonous rocks undergoing continuous shortening. (b) Strain distribution in the boxed area indicated in (a) as illustrated with a deformed mesh. Two enlargements at the bottom illustrate the kinematics of recumbent folding in external parts of the orogen and the development of a crenulation cleavage (S_2) in internal zones only. Extension in the collapsing thrust wedge coeval with compression below it increases the heat flux from a cooling basement to a heating cover, as can be read from the changed positions of reference points and isotherms. Pre-D_1 deformations not recorded in the Montagne Noire, but likely in other zones of the Variscan orogen and post-D_2 deformations in the Montagne Noire, are not considered in this figure and predict a far more complicated structure with multiple generations of folds, refolded compressional and extensional shear zones.

heat-activated rheology (e.g. Camembert cheese) is placed on a rigid base and squeezed between two vertical walls. The layer, representing the micaschist cover of the Axial Zone, would first start to shorten and stretch in longitudinal direction between the walls (D_3). However, progressive heating during continuous wall convergence could eventually induce a 'syncollisional' gravitational collapse (D_4) resulting in thinning of the layer but with a longitudinal stretching direction maintained. A second more competent layer (gneissic basement) situated below the weak one could undergo continuous shortening while the upper layer was undergoing collapse with the same stretching direction in both layers (overlap of D_3 and D_4). Anchizonal cover rocks could be represented by a third top layer of sand, which would deform by listric normal faulting (Stephanian basins) and detach from its ductile basement.

Renewed shortening and wrenching during (D_5) with similar regional kinematic axes as D_3 corresponds to late stages of plate convergence when the micaschists had cooled down and recovered gravitational stability. Finally, post-orogenic extension (D_6) oriented at a high angle to synorogenic stretching lineations, and presumably at a high angle to the orogen trend, can be attributed to a relaxation of far-field plate forces provoking a generalized gravitational collapse aimed at restoring normal crustal thicknesses in the Variscan orogen (Ménard and Molnar, 1988; Malavieille, 1993).

6. Conclusion

The kinematic and metamorphic evolution of the Southern Slope and its metamorphic basement (Axial Zone) indicate an origin of recumbent folds and thrusts related to gravitational collapse of an upper-crustal double wedge, extending itself over autochthonous basement. Gravitational spreading created a subhorizontal non-coaxial flow at high crustal levels (D_2), in which preexisting steep D_1 folds corresponding to the preceding crustal thickening stage, became progressively rotated, amplified and translated to external zones of an orogen. At internal orogenic zones a progressively more important component of vertical pure shear explains the presence of thrust-related S_2 crenulation cleavage in the crystalline basement, not found in the cover series. The traditional 'nappe' units of the southern Montagne Noire postdate the large-scale recumbent folding and even the refolding of these structures. They originated late during the Variscan cycle (D_4) when a second synorogenic collapse affected mainly the metasedimentary cover of the gneissic basement. The different 'nappes' can be reduced to a hanging wall and footwall domain of a major D_4 décollement that separated zones of relatively brittle and ductile deformation, respectively.

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