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Variscan tectonometamorphic evolution of the eastern Lys-Caillaouas massif, Central Pyrenees – evidence for late orogenic extension prior to peak metamorphism

L.M. Kriegsman[1], D.G.A.M. Aerden[1, 2], R.J. Bakker[1], S.W.J. den Brok[1] & P.M.T.M. Schutjens[1]
[1] *Institute for Earth Sciences, Budapestlaan 4, P.O. Box 80.021, 3508 TA Utrecht, The Netherlands;*
[2] *Present address: Geology Department, James Cook University, Townsville, Q. 4811., Australia*

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Abstract

Four deformation phases have been distinguished in the Cambro-Ordovician metasediments of the eastern Lys-Caillaouas massif. D1 only affected rocks of a stratigraphic unit below and Ordovician metaconglomerate horizon and is of pre-Variscan age. During D2 tight folds with steep E–W trending axial plane foliations S2 have formed, indicating N–S shortening. D3 consists of :

(i) porphyroblast rotation,
(ii) formation of gently dipping crenulation cleavages S3 and
(iii) transposition of S2 to S3 in highest grade metamorphic rocks.

D3 is interpreted as vertical shortening and horizontal extention. Both D2 and D3 are of Variscan age. D4 includes various deformation phenomena of unknown age, postdating peak metamorphism.

Metamorphism started at the end of D2 and continued until after D3. Three phases have been distinguished: plurifacial regional metamorphism M1 and M3 and contact metamorphism M2 around the Lys-Caillaouas porphyritic biotite granite.

This study shows that Variscan N–S shortening in the eastern Lys-Caillaouas massif was followed by metamorphism and crustal extension. Flat-lying structures overprinted steep structures during the extensional phase. Peak metamorphism was reached afterwards.

Introduction

The Lys-Caillaouas massif forms part of the central Axial Zone of the Pyrenees. It comprises metasediments of Cambro-Ordovician age (e.g. Clin, 1959), deformed, metamorphosed and intruded in Variscan times (Zwart, 1979). The northern border of the massif is formed by a north dipping thrust of Alpine age (e.g. de Bresser et al., 1986), the southern border by the steep Esera-Gistain fault of unknown age.

Structures in the Axial Zone of the Pyrenees have been subdivided into suprastructure with steep foliations and relatively low grade metamorphism, and infrastructure, with gently dipping foliations and relatively high grade metamorphism (Zwart, 1979). Recent investigations have shown for the western Aston massif (Verhoef, Vissers & Zwart, 1984), the western Hospitalet massif (Van den Eeckhout, 1986) and the western Lys-Caillaouas massif (De Bresser et al., 1986) that infrastructure overprints the deeper parts of the suprastructure and its therefore younger.

In this paper we present new structural data which suggest that also in the eastern Lys-Caillaouas massif infrastructure is younger than suprastructure and we propose a mechanism for its formation. We also present new results concerning the relation between deformation and metamorphism.

Lithology

The metasediments encountered in the eastern Lys-Caillaouas massif have been assigned to the Cambro-Ordovician (Clin, 1959; Zwart, 1979). We have subdivided these sediments into a lower and an upper series (Fig. 1):

- The lower series mainly consists of low grade psammitic phyllites to medium and high grade schists with quartzites and various quartzite-marble alternations. In the eastern part of the area minor lenses of metaconglomerate have been observed within this series.
- The upper series has a metaconglomerate horizon at its base, which is attributed to the Upper Ordovician (Caradocian; Clin, 1959). It mainly consists of quartz- and quartzite grains and pebbles varying from 0.1 to 40 cm in diameter and is overlain by a sequence of microconglomerates, chloritoidschists and pelitic schists. A 40 m thick quartzite-marble alternation occurs in the upper part. This series is cut off by faults from overlying black slates, attributed to the Silurian (e.g. Wennekers, 1968).

These metasediments have been intruded by porphyritic biotite granite, quartz diorite, fine-grained two-mica granite and lamprophyric and aplitic dykes.

Metamorphism

Within the Cambro-Ordovician metasediments Variscan metamorphism (Zwart, 1979) has led to the growth of porphyroblasts, of which andalusite is the most conspicuous in the field.

We distinguished seven mineral zones (Fig. 2), six of which represent a low P/high T metamorphic zonation from low grade (zones 1 & 2) through medium grade (zones 3, 4 & 5) to high grade (zone 6).

Zones 5 and 6 closely follow the northern contact between porphyritic biotite granite and metasediments and are only about 10 and 2 m thick, respectively, at this contact. We interpret this as contact metamorphism.

Zone 4 follows the same contact, but in the Lys valley transformation, textures of staurolite to white mica in the absence of sillimanite, typical of zone 4 metamorphism, have been observed at more than two kilometres from this granite (Fig. 2), separated from zone 4 by zone 3.

In the southwestern part of the area, zones 5 and 6 are approximately 700 and 400 m thick, respectively. Here, the metamorphic grade increases with increasing distance from the overlying porphyric biotite granite (Fig. 4, cross-section AA') and grades into migmatite. Hence, zones 5 and 6 are not related to the porphyritic biotite granite.

In the eastern part of the area (Fig. 2, zone 7) a zone exists with stable andalusite + cordierite in the absence of staurolite. This zone is distinct from zone 4, where relics of staurolite have frequently been observed. Zone 7 may be characterized by a high Mg/(Fe + Mg) ratio, inhibiting staurolite growth (Winkler, 1979).

Deformation

Deformation has been studied at macro-, meso- and microscale. We distinguish four deformation phases:

D1. Concluded from an abrupt change in delta-lineations across the lower boundary of the Upper Ordovician metaconglomerate and a considerable spread of delta-lineations in metasediments of the lower sedimentary series; consequently of pre-Variscan age (Den Brok, 1989, this issue).

D2. Characterized by tight to isoclinal folds with axial plane cleavage S2; average strike of S2 is W–E to WNW–ESE, while its dip varies due to later deformation. D2 antiforms and synforms have

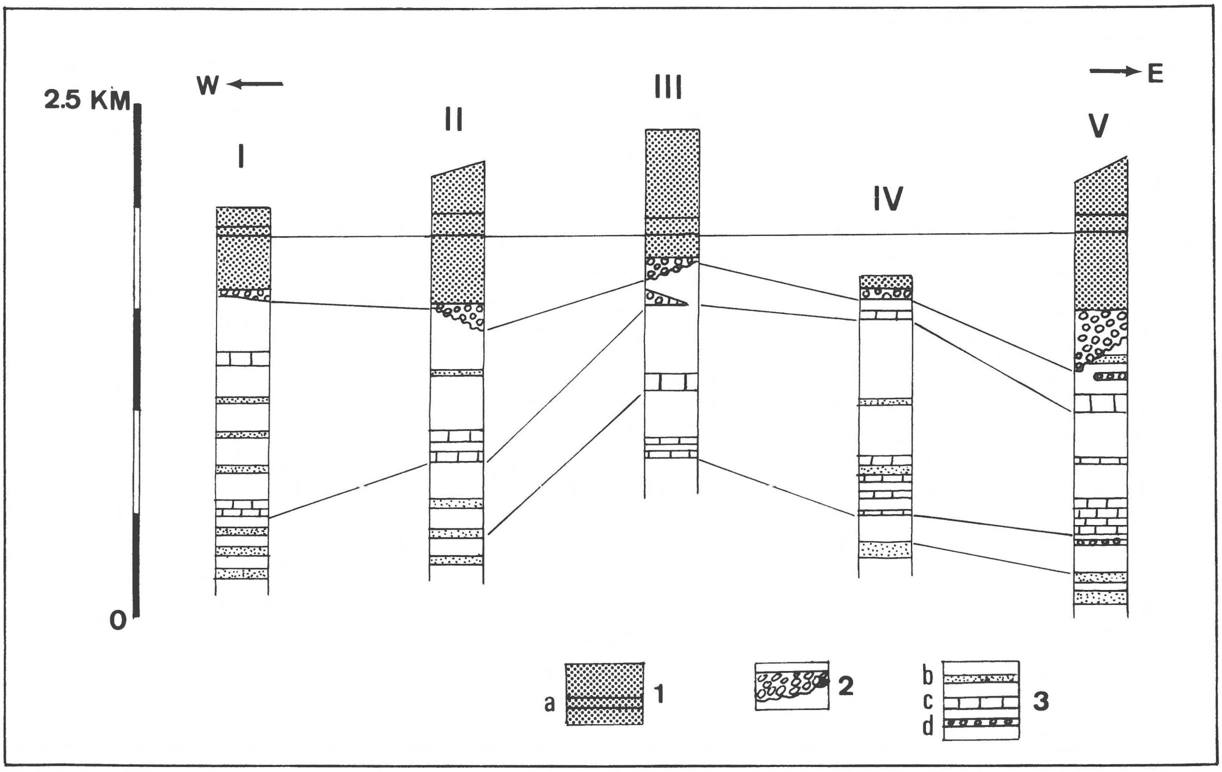

Fig. 1. Correlation of simplified stratigraphical columns of Cambro-Ordovician metasediments in the eastern Lys-Caillaouas massif. 1 = upper series, including quartzite-marble alternation (a); 2 = basal metaconglomerate of the upper series; 3 = lower series, including quartzites (b), quartzite-marble alternations (c) and conglomerate (d). Columns I, II, III, IV and V are from areas covered by sections AA', CC', EE', FF' and HH' of Fig. 3, respectively.

been observed at all scales (Figs. 3 and 4). E–W elongation of conglomerate pebbles in areas relatively unaffected by later deformation phases points to an E–W component of stretching during D2.

D3. This phase consists of several synmetamorphic deformation phenomena which clearly overprint D2 (the relative order is based on locally observed overprinting relations):

D3a: rotation of porphyroblasts relative to S2 around a subhorizontal E–W axis with sinistral movement looking west; rotation angle up to 90°.

D3b: crenulation of S2 by subhorizontal crenulation cleavage S3; the following observations were made concerning the relation between S2 and S3:

1. Where S2 has a subvertical attitude, S2 and S3 are near perpendicular (Fig. 4, cross-section HH').
2. In subareas with minor D4 overprint, S-vergent* S2–S3 relations correlate with S-dipping S2; sinistral rotation of porphyroblasts looking west (D3a) has mostly been observed in the same rocks. Locally observed north-vergent S3–S2 relations correlate with north-dipping S2 (cross-section HH'); in one of such outcrops dextral rotation of porphyroblasts, looking west, has been observed.

* Relations between foliations are her called south-vergent when the younger foliation becomes parallel to the older one after sinistral rotation of less than 90° looking west.

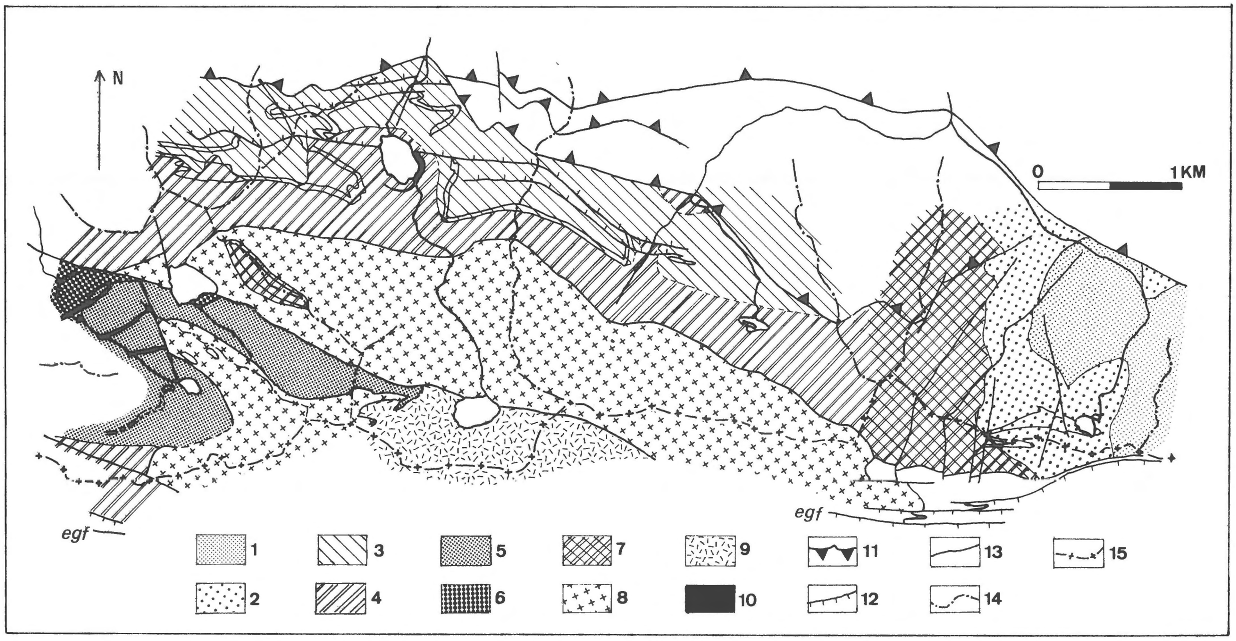

Fig. 2. Metamorphic map of eastern Lys-Caillaouas massif.
1 = chlorite-sericite schists (zone 1); 2 = biotite-schists (zone 2); 3 = andalusite-staurolite-cordierite schists (zone 3); 4 = andalusite-cordierite schists with relics of staurolite (zone 4); 5 = sillimanite-muscovite schists (zone 5); 6 = kalifeldspar-sillimanite schists with gneisses and migmatites (zone 6); 7 = andalusite-cordierite schists, staurolite absent; 8 = porphyritic biotite granite; 9 = quartz diorite; 10 = two-mica granite; 11 = thrust; 12 = normal fault; 13 = valley; 14 = mountain ridge; 15 = Spanish-French border; EGF = Esera-Gistain fault.

D3c: rotation of S2 to a moderately south-dipping attitude (Lys valley, cross-section FF') or a subhorizontal attitude (southwestern part of area, cross-section AA') and rotation of S3 relative to S2; main observations:

1: In subareas not affected by D4, a correlation exists between southward dip of S2 and the angle between S2 and S3: this angle varies from ± 45° where S2 dips ± 70° south to ± 15 ° where S2 dips 10–20° south (cross-sections AA' and FF'), with south-vergence) in all cases; in these subareas sinistral rotation of porphyroblasts, looking west, (D3a) has also been observed.

2. In the eastern part of the area, some andalusite and cordierite porphyroblasts enclose D3 crenulations with axial planes at high angles to S2; outside these porphyroblasts the angle between S2 and S3 is smaller, in most cases ± 30°, with south-vergence; S2 dips south at 50° to 70° here.

3. In areas with flat-lying structures and highest grade of metamorphism (zones 5 and 6), complete transposition from S2 to S3 has occurred; intrafolial folds with approximately N–S fold axes have only been observed in these infrastructural rocks.

During D3, boundage structures of andalusite and strain shadows around porphyroblasts, giving rise to an E–W subhorizontal stretching lineation, developed parallel to the intersection lineation of S2 and S3. Locally andalusites enclosing D3 crenulations have been boundinaged. Hence, the stretching lineation at least partly developed after formation of S3.

D4. Deformation phenomena occurring after the peak of metamorphism (the relative order is based on local overprinting relations):

D4a: steep E–W trending dip-slip normal faults with an average offset of ± 100 m; these faults

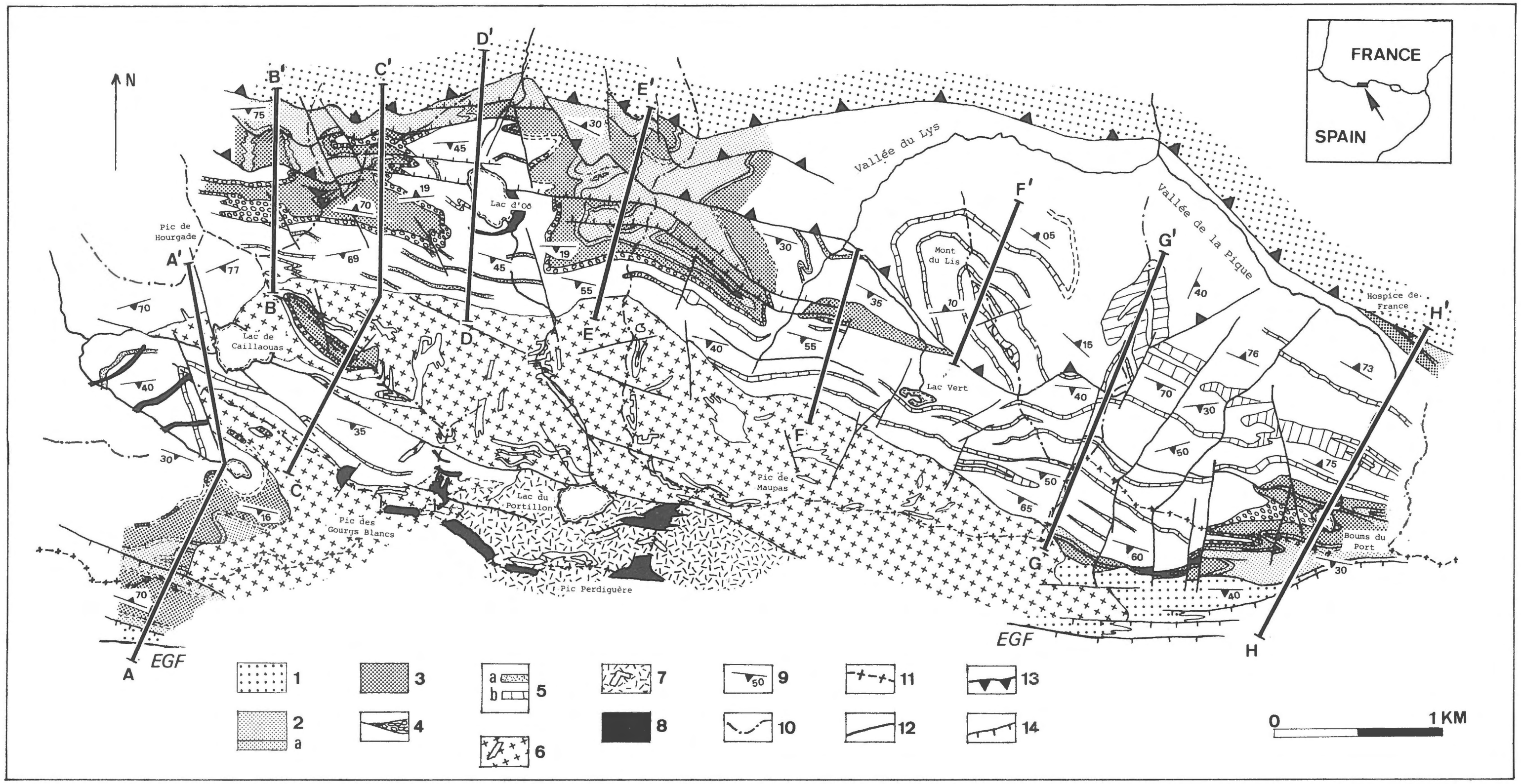

Fig. 3. Geological sketch map of eastern Lys-Caillaouas massif.

1 = Silurian metasediments; 2/3/4 = Cambro-Ordovician metasediments of upper series, including: quartzite-marble alternation (2a) and overlying micaschists (2), metasediments overlying metaconglomerate (3) and metaconglomerate (4); 5 = Cambro-Ordovician metasediments of lower series, including quartzites (a) and quartzite-marble alternations (b); 6 = porphyritic biotite granite; 7 = quartz diorite; 8 = two-mica granite; 9 = dip direction and angle of main foliation; 10 = mountain ridge; 11 = Spanish-French border; 12 = valley; 13 = thrust; 14 = normal fault; EGF = Esera-Gistain fault.

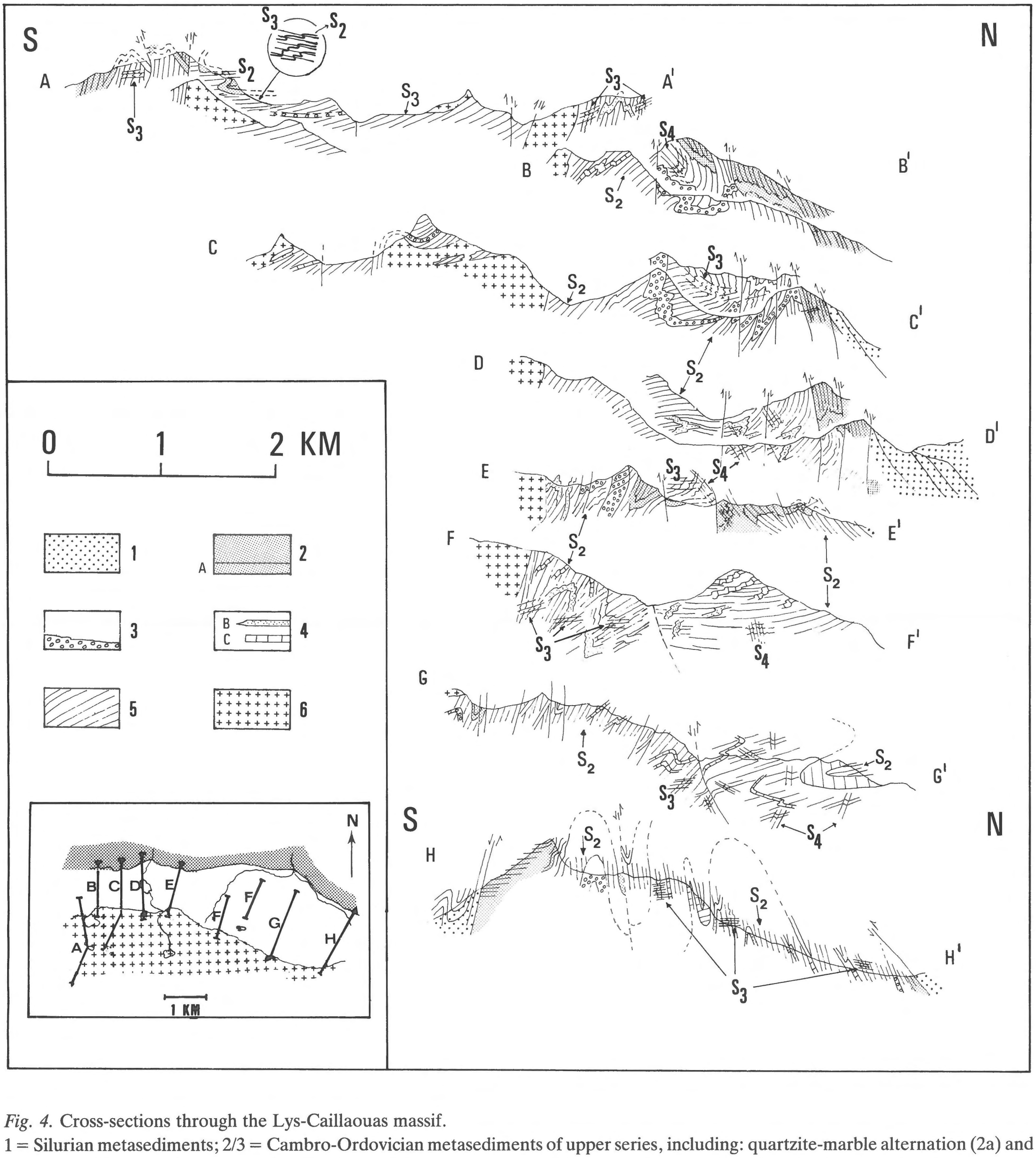

Fig. 4. Cross-sections through the Lys-Caillaouas massif.
1 = Silurian metasediments; 2/3 = Cambro-Ordovician metasediments of upper series, including: quartzite-marble alternation (2a) and overlying micaschists (2), metaconglomerate and overlying metasediments (3); 4 = Cambro-Ordovician metasediments of lower series, including quartzites (b) and quartzite-marble alternations (c); 6 = porphyritic biotite granite. For location, see Fig. 3.

have downthrown north blocks in the northwestern part of the area (cross-sections BB', CC', DD', EE') and downthrown south blocks in the eastern part of the area (cross-section GG', HH').

D4b: vertical kink bands

D4c: a steep north dipping crenulation cleavage S4 and southward directed thrusts, both restricted to the northern border of the area; micas in hinges of D4 crenulations have not recrystallized.

Several large WNW–ESE trending faults, possibly having considerable offsets, transsect the massif and have also been classified as D4.

A special phenomenon is the Lac d'Oô structure along the northern border of the studied area (cross-sections BB', CC' and DD'). This structure is a large scale Z-fold, looking west, deforming the main foliation S2. The constant angle between S2 and S3 across this structure, irrespective of the dip angle of S2, suggests it is younger than S3. It is cut by southward directed thrusts (D4c) and is therefore older than these thrusts; its timing with respect to metamorphism is unclear.

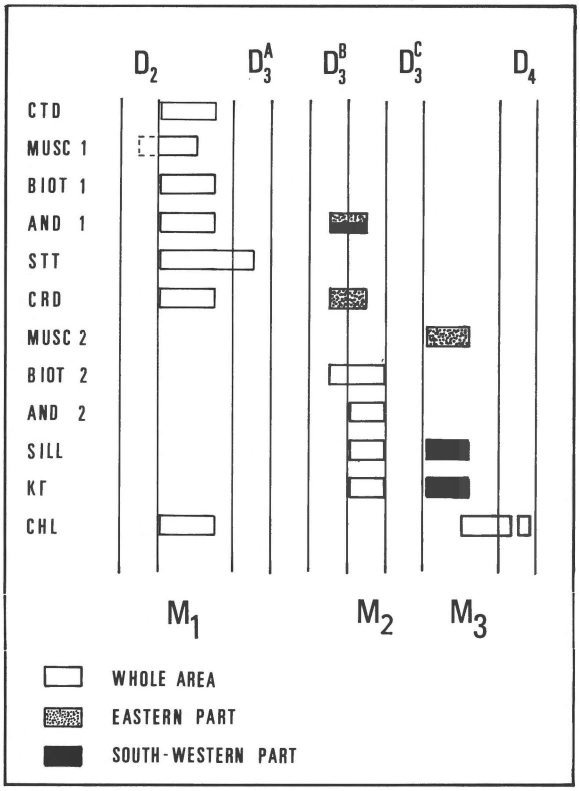

Fig. 5. Relation between deformation phases and mineral growth, as deduced from microstructural observations.

Relation between deformation and metamorphism

Relative timing of deformation and mineral growth was studied in detail. The following microstructural observations have been compiled in Fig. 5:

1. Chlorite and small flaky muscovites (MUSC 1) and biotites (BIOT 2) have their basal trace parallel to S2.
2. Most porphyroblasts (staurolite, cordierite, biotite 1 and andalusite 1) in zone 3 and 4 throughout the studied area have straight inclusion trails at an angle with S2, which we interpret as growth after D2 and before the rotational D3a phase. Curved internal foliation in the rim of some staurolites indicates final growth at the onset of D3a.
3. Chloritoid (zones 1 & 2) has straight inclusion trails at an angle with S2, interpreted as post-D2/pre-D3a growth. Locally observed flattening perpendicular to S2 after its growth may point to growth at a late stage of D2.
4. In the eastern and southwestern parts of the area andalusite and cordierite (CRD) porphyroblasts enclosing D3 crenulations have also been observed; in most cases the amplitude of these crenulations is smaller than of those in the matrix, indicating syn-D3b growth. Growth of small flaky biotite (BIOT 2) parallel to S3 suggests the same timing. In the southwestern part of the area, syn-D3b grown andalusites have been boudinaged during later D3c deformation.
5. Near the porphyritic biotite granite small andalusite (AND 2), nucleated on older andalusite (AND 1), overgrows S3 (Fig. 6a).
6. Prograde breakdown of staurolite to andalusite + biotite or an aggregate rich in white mica (MUSC 2) in zone 4 and 5, described in detail by De Bresser et al. (1986), took place after D3. This is shown by the undeformed state of these aggregates (Fig. 6b).

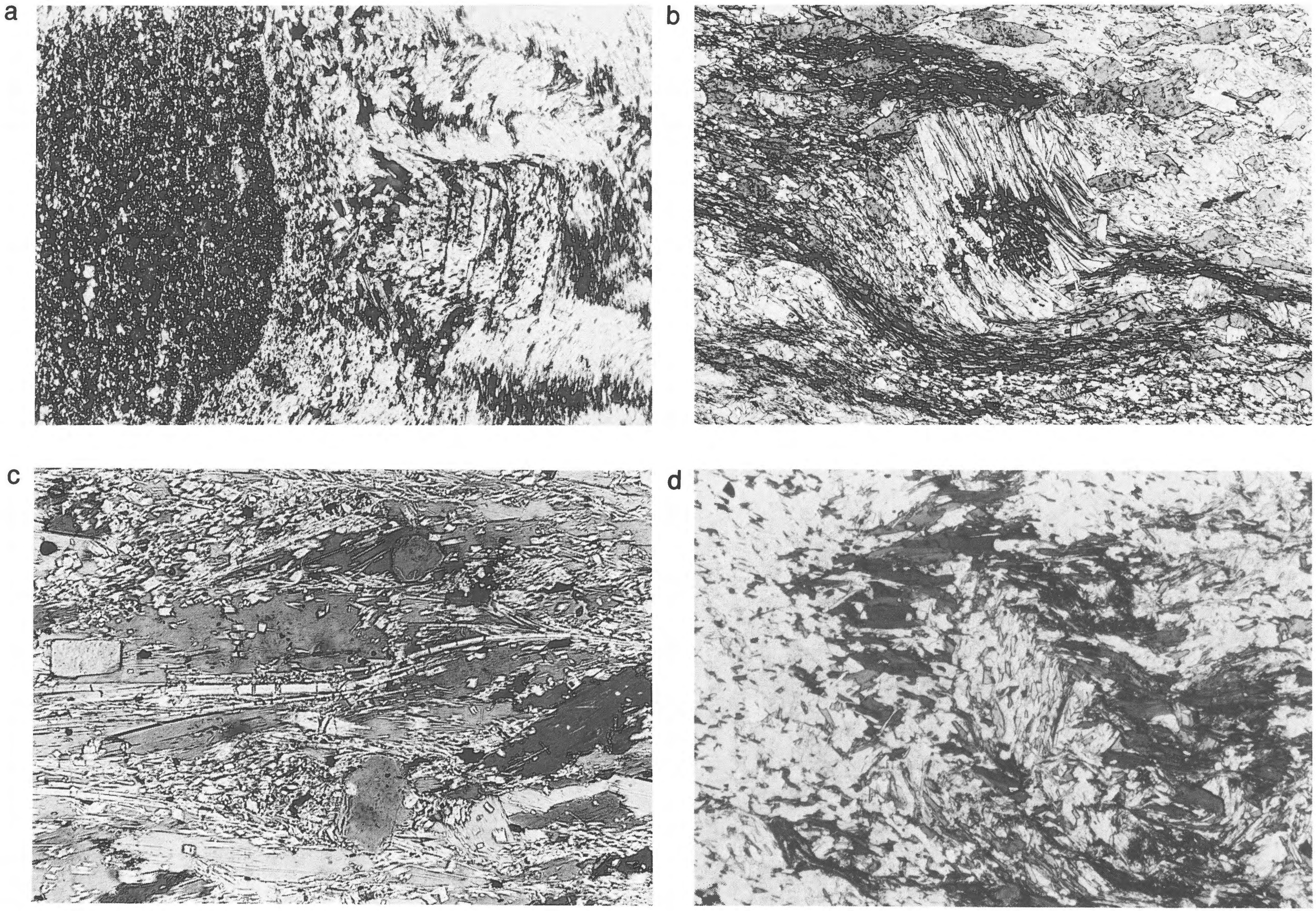

Fig. 6. Photographs of thin sections. (a) andalusite containing straight inclusion trails (right) and smaller andalusite overgrowing S3 (left), zone 4; (b) rotated staurolite transformed into an undeformed aggregate rich in white mica, zone 4; (c) broken and boudinaged sillimanite, zone 5, near the porphyritic biotite granite, zone 5; (d) rotated potassium feldspar porphyroblast and newly grown biotite parallel to S3, zone 6, near the porphyritic biotite granite.

7. Large undeformed muscovites (MUSC 2) overgrow the matrix and replace andalusite in zones 5 and 6.
8. Sillimanite and potassium feldspar (KF) are mostly undeformed, indicating post-D3 growth. In the southwestern part of the area, close to the contact with the porphyritic biotite granite, they show signs of internal deformation (Fig. 6c) or rotation (Fig. 6d).

Timing of intrusives

Porphyritic biotite granite

Crenulation cleavage S3 has been found in inclusions in the porphyritic biotite granite, while pegmatite dykes at the contact have locally intruded parallel to S3. This shows that intrusion of the porphyritic biotite granite occurred after S3 (D3b). Cross-section AA' shows that the porphyritic biotite granite participates in the large scale D3c deformation causing a more gentle dip of the main foliation. It is therefore concluded that this granite intruded during D3, more specifically between D3b and D3c.

Two-mica granite

Large dykes of two-mica granite cut the gently dipping foliation in the southwestern part of the area and are undeformed. Hence, these dykes intruded after D3. Like the dykes of two-mica granite near Lac d'Oô they typically occur within the highest grade metamorphic zones (4, 5 and 6). Similar dykes cut and overly porphyritic biotite granite and quartz diorite (Fig. 3).

Interpretation of D3 as a phase of vertical shortening and horizontal extension

Porphyroblast rotation (D3a) followed by asymmetric crenulation (D3b, observation 2) is interpreted to result from shear along S2, in agreement with the model of Lister & Williams (1983). Rotation of S3 with respect to S2 (D3c, observation 2) is interpreted as being due to continued shear during D3c. Heterogeneous southward shear causing rotation of previously E–W oriented fold axes may also explain the presence of N–S fold axes in the infrastructure (D3c, observation 3).

We interpret D3a and D3b as two expressions of the same deformation phase, being vertical shortening of originally steep foliations S2. This caused layer parallel shortening where S2 was vertical (D3b, observation 1); it caused rotation of S2 and concomitant shear along S2 where it had an original dip to the south or north (D3b, observation 2).

During D3c, rotation of S2 accompanied by rotation of S3 with respect to S2 (D3c, observations 3 & 4) continued. Therefore we conclude that D3c is another aspect of the same phase of vertical shortening.

D3 can therefore be summarized as vertical shortening leading to overprinting of infrastructure on the deepest parts of the older suprastructure by a combination of rotation (Fig. 7a), crenulation (Fig. 7b) and transposition (Fig. 7c). Transposition was enhanced by recrystallization during peak metamorphism.

Assuming constant volume deformation, vertical shortening implies horizontal extension. Hence, D3 may be interpreted as a phase of horizontal extension. Intrusion of the large body of porphyritic biotite granite during D3 points to an increase of bulk volume, making this interpretation even more likely.

Directions of extension

It has been argued that southward shear along the main foliation plane S2 during D3 caused porphyroblast rotation up to 90°. Shear strains for similar porphyroblast rotation (D3a of De Bresser et al., 1986) in the western Lys-Caillaouas massif have been estimated at 0.7–1.0 for 20–30° porphyroblast rotation and 2.5–2.8 for 70–80° rotation (Lister et al., 1985). These estimated shear strains imply considerable N–S extension. In some thin sections N–S oriented strain shadows around biotite were observed, crenulated by S3, also pointing to N–S stretching during D3a. Southward shear continued during D3b and D3c, implying a large component of N–S extension during D3.

Stretching lineations defined by boudinaged andalusites and by strain shadows around most bio-

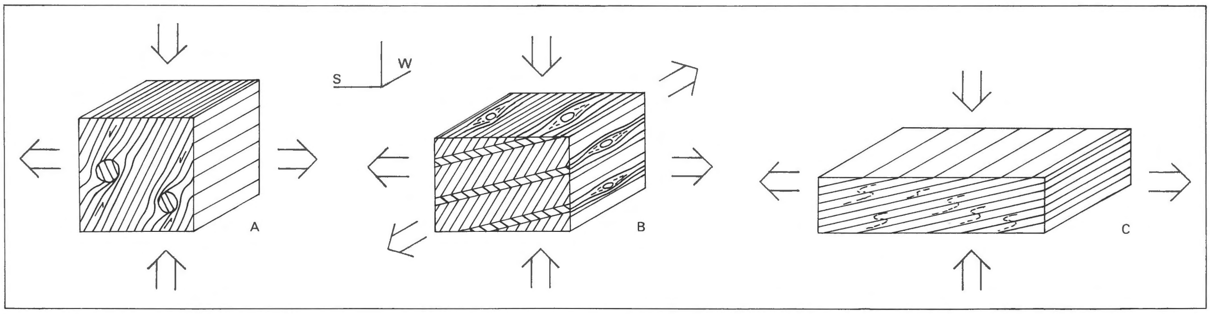

Fig. 7. Model for the formation of infrastructure during D3. Vertical shortening of steeply S-dipping foliations S2 (suprastructure) leads to rotation of this foliation to a more gentle attitude and southward shear along the foliation plane; shear causes (a) rotation of porphyroblasts, (b) formation of asymmetric crenulation cleavages S3 and (c) transposition of S2 to S3 in highest grade metamorphic rocks. An E–W stretching lineation has developed during D3.

tites, however, are E–W and horizontal. As mentioned in a previous section, these E–W stretching lineations at least partly developed after formation of S3. This implies that E–W extension is either younger than N–S extension or that it was contemporaneous during the final part of D3, indicating a flattening type of strain during formation of the infrastructure.

Interpretation of relations between deformation and metamorphism

From Fig. 5 we deduce that metamorphism can be subdivided into three metamorphic phases M1, M2 and M3.

In the whole area muscovite, biotite, andalusite, staurolite and cordierite were present before the onset of D3 and before intrusion of the porphyric biotite granite. We interpret this as regional metamorphism M1, between D2 and D3a, causing formation of zones 1, 2 and 3.

Observations attributed to M2 all come from zones 4, 5 and 6 near the contact between metasediments and porphyritic biotite granite. This fact, together with the timing of intrusion of this granite between D3b and D3c, shows that M2 is a phase of contact metamorphism around the porphyritic biotite granite, causing formation of zones 4, 5 and 6 near the granite contact.

At the contact of the porphyritic biotite granite in the southwestern part of the area, sillimanite and potassium feldspar are deformed (Fig. 6a, b). In the underlying metamorphic rocks (zones 5 and 6), however, they are not deformed. This fact, together with the observation that metamorphic grade increases away from the granite contact (i.e. downwards) indicates that zones 5 and 6 in that area are related to a younger metamorphic phase M3, occurring after D3. The prograde breakdown of staurolite in the lower Lys valley (zone 4) is also attributed to M3. The large dykes of two-mica granite, intruded post-D3 in zones 4, 5 and 6 only, may be related to M3.

We interpret these metamorphic phases as plurifacial regional metamorphism M1 + M3 and contact metamorphism M2 around the porphyritic biotite granite. Peak metamorphic conditions during M3 (anatexis in zone 6) are estimated at 650–680° C, 2.0–3.0 kb. Peak metamorphism (M3) occurred after the D3 phase of vertical shortening and horizontal extension.

Discussion

Comparison of our deformation scheme with the scheme proposed by De Bresser et al. (1986) for the western Lys-Caillaouas massif shows that their D1 corresponds to our D2 and their D3 to our D3. Lateral continuity of structures confirms this conclusion. In the area studied no evidence has been found for a deformation phase similar to D2 of De Bresser et al. (1986).

Suprastructure was formed during D2 and was subsequently deformed during D3, leading to formation of infrastructure in the highest grade metamorphic parts of the area. As proposed by Verhoef et al. (1984) and Van den Eeckhout (1986), crenulation and transposition play a major role in this process. We, however, want to emphasize the importance of the rotation of originally subvertical foliations to a gentle dip in the Lys-Caillaouas massif.

The porphyritic biotite granite intruded during D3, which we interpret as a phase of vertical shortening and horizontal extension. This is in contrast with the mechanism of intrusion during N–S shortening, proposed by Soula (1982) for the Variscan plutons in the Pyrenees.

The relation between the extensional phase and regional metamorphism is consistent with the existence of a synmetamorphic low-angle extensional shear zone at depth, as postulated by Van den Eeckhout & Zwart (1988) for the late-Variscan Pyrenees.

D2 and D3 are of Variscan age, because they are pre- to para-metamorphic and because metamorphism in the Axial Zone is attributed to the Variscan event (Zwart, 1979). D4 took place after peak metamorphism and is considered to be late- or post-Variscan.

Conclusion

The Variscan structural and metamorphic history of the eastern Lys-Caillaouas massif can be summarized as N–S shortening (D2, suprastructure formation), followed by regional metamorphism (M1), horizontal extension (D3, infrastructure formation) and subsequent intrusion of a porphyritic biotite granite with contact metamorphism (M2) and finally peak regional metamorphism (M3).

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References

Clin M. 1959 Etude géologique de la haute chaine des Pyrénées Centrales entre le cirque de Troumouse et le cirque du Lys – Thèse Fac. Sci., Nancy: 397 pp

De Bresser J.H.P., F.J.M. Majoor & M. Ploegsma 1986 New insights in the structural and metamorphic history of the western Lys-Caillaouas massif (Central Pyrenees, France) – Geol. Mijnbouw 65: 177–187

Den Brok S.W.J. (this volume) Evidence for pre-Variscan deformation in the Lys-Caillaouas area, Central Pyrenees, France – Geol. Mijnbouw. 68: 379–382

Lister G.S. & P.F. Williams 1983 The partitioning of deformation in flowing rock masses – Tectonophysics 92: 1–33

Lister G.S., N.J. Boland & H.J. Zwart 1985 Step-wise growth of biotite porphyroblasts in pelitic schists of the western Lys-Caillaouas massif (Pyrenees) – J. Struct. Geol. 8: 543–567

Soula J.C. 1982 Characteristics and mode of emplacement of gneiss domes and plutonic domes in central-eastern Pyrenees – J. Struct.Geol. 4: 313–342

Van den Eeckhout B 1986 A case study of a mantled gneiss antiform, the Hospitalet massif, Pyrenees (Andorra/France) – Ph.D. thesis, Univ. Utrecht, Geol. Ultraiectina 45: 193 pp

Van den Eeckhout B. & H.J. Zwart 1988 Hercynian crustalscale extensional shear zone in the Pyrenees – Geology 16: 135–138

Verhoef P.N.W., R.L.M. Vissers & H.J. Zwart 1984 A new interpretation of the structural and metamorphic history of the western Aston massif (central Pyrenees, France) – Geol. Mijnbouw 63: 399–410

Wennekers J.H.N. 1968 The geology of the Esera valley and the Lys-Caillaouas massif, Central Pyrenees, Spain, France – Ph.D. thesis, Univ. Leiden: 57 pp

Winkler H.G.F. 1979 Petrogenesis of metamorphic rocks (5th ed.). Springer, Berlin: 348 pp

Zwart H.J. 1979 The geology of the central Pyrenees – Leidse Geol. Meded. 50: 1–74