

Deformation and metamorphism in the Trois Seigneurs massif, Pyrenees – evidence against a rift setting for its Variscan evolution

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Abstract

Low grade metamorphic rocks in the Trois Seigneurs massif characteristically exhibit steep foliations axial planar to tight folds, indicating horizontal shortening. An older deformation phase is indicated by a considerable spread of intersection lineations with bedding on the steep foliations. The steep foliations have been folded into a kilometre-scale inclined fold, which has a crenulation cleavage subparallel to the axial plane. Rotation sense of porphyroblasts, in medium to high grade rocks, is different in each limb of this fold. The fold is argued to result from late Variscan vertical shortening and horizontal extension following crustal thickening. The massif is transected by the Cap de las Costes fault, inferred to be a strike-slip fault with 5–6 km sinistral offset.

Variscan metamorphism in the Trois Seigneurs massif started after the shortening phase and reached peak temperatures after the extensional phase. It is not related to a rifting event, as proposed by Wickham & Oxburgh (1985), but to late orogenic extension after considerable crustal thickening.

Introduction

The Trois Seigneurs massif forms part of the North Pyrenean Zone (Fig. 1). It is separated from the Axial Zone of the Pyrenees by the North Pyrenean Fault, considered by many authors (e.g. Vielzeuf & Kornprobst, 1984) to be a sinistral strike-slip fault active in Cretaceous times.

This massif consists of Cambro-Ordovician to Silurian metasediments, which have been deformed, metamorphosed from low to high grade and intruded by several types of intrusives during the Variscan orogeny (Allaart, 1959).

Recent investigations in the Trois Seigneurs massif (e.g. Wickham & Oxburgh, 1985, 1986, 1987a) have led to the hypothesis that the Variscan

Pyrenees developed in a rift setting. Main arguments for this hypothesis are:

- (i) absence of evidence for continental collision at the time of metamorphism,
- (ii) exceptionally high thermal gradients and
- (iii) circulation of seawater before peak metamorphism.

This interpretation was challenged by Matte & Mattauer (1987), who mentioned a strong shortening in the Variscan Pyrenees, resulting in poly-phase deformation. According to Matte & Mattauer (op cit.) metamorphism in the Variscan Pyrenees is related to crustal thickening and not to crustal thinning. In their reply Wickham & Oxburgh (1987b) mentioned the possibility of a trans-extensional regime with shortening and extension at different levels.

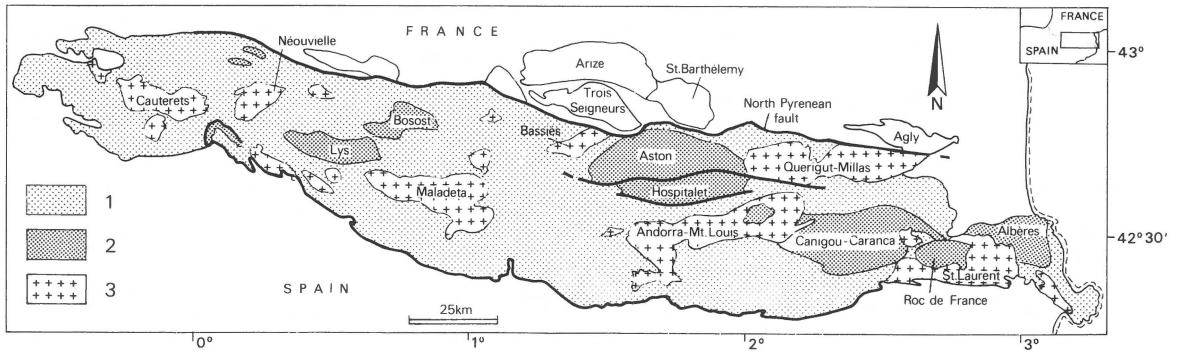


Fig. 1. Structural domains in axial zone and northern massifs of Pyrenees, after Van den Eeckhout & Zwart (Geology, 16, pp. 135–138, 1988) with kind permission. 1 = Paleozoic metasediments of suprastructure; 2 = Paleozoic and older metasediments and gneisses of infrastructure; 3 = late Variscan batholiths.

This paper aims to contribute to the discussion on the tectonic setting of Variscan metamorphism in the Trois Seigneurs massif. A detailed structural cross-section is presented, together with new structural data from other parts of the massif. A new interpretation of the Variscan tectonometamorphic evolution of the Trois Seigneurs massif is given. The discussion focuses on the work of Wickham and co-workers.

Lithology

In the Trois Seigneurs massif a rather monotonous sequence of pelitic and psammitic phyllites and schists with quartzites and quartzitic marbles crops out. These metasediments have been assigned to the Cambro-Ordovician (Allaart, 1959).

It is not certain whether all occurrences of quartzitic marbles belong to the same stratigraphical level, but some certainly do, as shown by mapping (Fig. 2). Henceforth it will be assumed that all occurrences belong to the same stratigraphical level, 500–1000 m below Silurian black shales. This implies that large-scale folds can be inferred from the outcrop pattern of these quartzitic marbles, e.g. near Pic de la Ruse (Fig. 2).

Deformation

Four deformation phases were distinguished on the

basis of overprinting and the relations between deformational phenomena and mineral growth.

D1. This phase has been identified from the observation that in subareas of constant S2 a spread in intersection lineations between bedding and S2 exists (Fig. 3), although the number of measurements is limited. Locally a foliation has been found which is not bedding and which is crenulated by S2. Observations of D1 fabric are restricted to the rock sequence above the quartzitic marbles.

D2. D2 consists of tight to isoclinal folds with penetrative axial plane foliations, S2. West of Pic de Bernès, S2 is subvertical with an E-W strike (Fig. 4). Close to the Cap de las Costes fault S2 rotates to become parallel with the fault trend at its contact. At many places, notably south of the Pic de la Journalade, upright tight D2 folds have been found, indicating considerable N-S horizontal shortening. The outcrop pattern of quartzitic marble implies kilometre-scale D2 folds (Fig. 2).

D3. In the central part of the area studied, on the eastern flank of the Pic des Trois Seigneurs, a kilometre-scale inclined fold exists with a steep N-dipping limb, a gentle SW dipping limb and an interlimb angle of 80° (Fig. 5). In both limbs tight folds were observed, while a quartzitic marble could be traced around the fold hinge and was not seen to change its vergence relation with the main foliation (Fig. 5). Hence this fold represents a post-

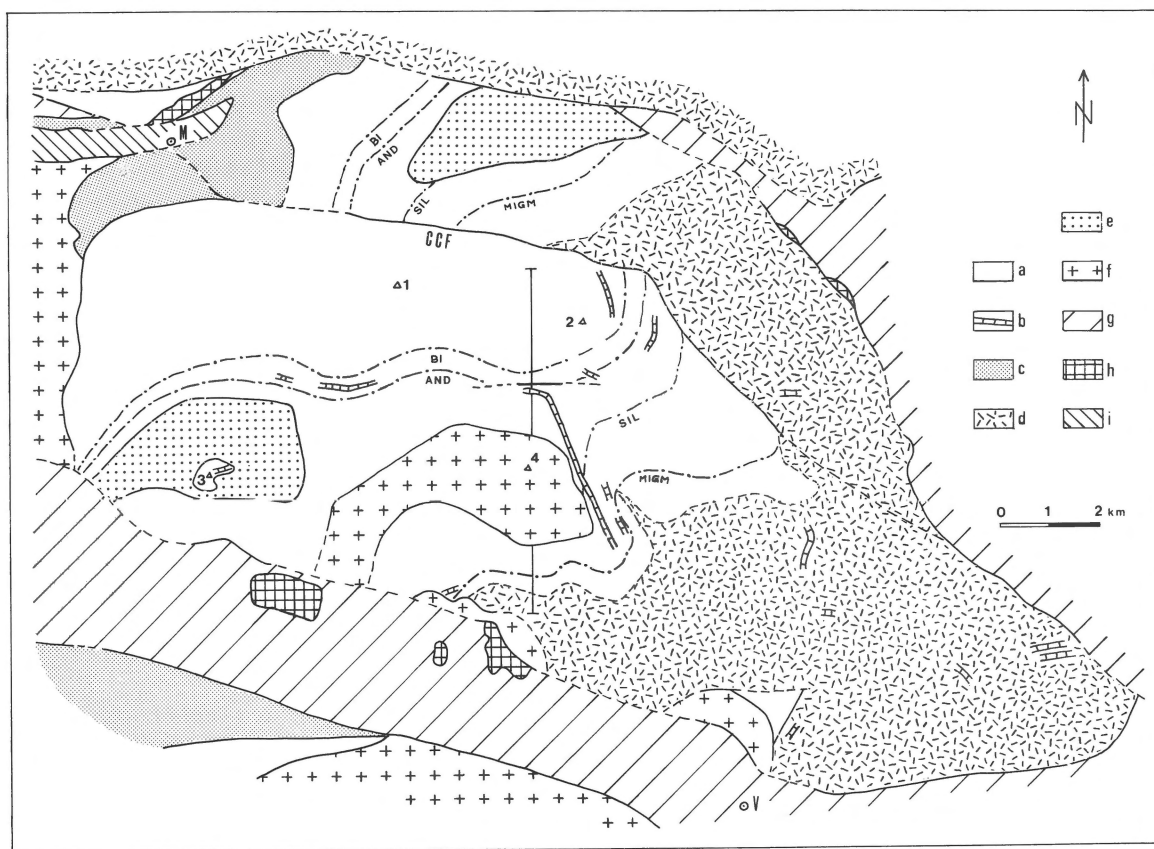


Fig. 2. Sketch map of the Trois Seigneurs massif, modified after Allaart (1959), De Sitter & Zwart (1959) and Wickham & Taylor (1985). The profile line of Fig. 5 and mineral isograds are indicated (migm = migmatite front). a = Cambro-Ordovician metasediments; b = quartzitic marble; c = Silurian and Devonian metasediments; d = quartz diorite; e = two-mica granite; f = granodiorite; g = Jurassic and Lower Cretaceous sediments; h = Lower Cretaceous ophite and lherzolite bodies; i = Cenomanian and Upper Cretaceous sediments. M = Massat; V = Vicdessos. 1 = Pic de Bernès; 2 = Pic de la Journalade; 3 = Pic de la Ruse; 4 = Pic des Trois Seigneurs.

D2 deformation phase (D3).

The axial plane orientation was calculated from its trace along the east flank of the Pic des Trois Seigneurs together with the post-D2 fold axis given by the pole to a girdle defined by poles to S2 within the fold. The result, 328/43 (dip direction and dip angle) is consistent with small scale crenulation cleavages, frequently observed in pelitic layers, especially within the andalusite zone, which have an average attitude of 349/45 ($n = 15$).

Looking west along the F3 fold axis (280/35, plunge azimuth and plunge angle), andalusite and cordierite porphyroblasts with straight inclusion trails show dextral rotation with respect to the external foliation in the steep limb and sinistral rota-

tion in the shallow limb. This indicates that porphyroblast rotation is related to the F3-fold and that the fold formed by flexural slip.

Stretching lineations defined by strain shadows around porphyroblasts have been observed throughout this F3 fold. They plunge moderately W, subparallel to the F3 fold axis.

Another F3 fold may be inferred to exist because moderately N-dipping foliations E of the Pic des Trois Seigneurs project onto the cross-section (Fig. 5) at deeper structural levels. A fold hinge has not been found due to a lack of exposure E and S of the Pic des Trois Seigneurs. From the foliation measurements it is evident that the interlimb angle is smaller than the angle for the other F3 fold. This

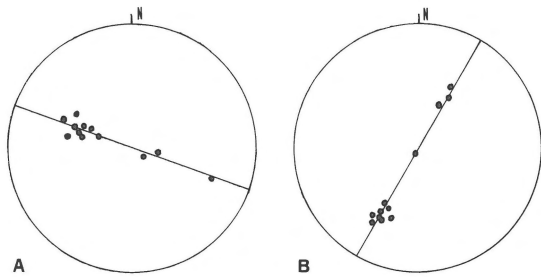


Fig. 3. Intersection lineations of bedding and S2 in two small areas of the Trois Seigneurs massif. Measurements in area with average S2 020/90 (A) and in area with average S2 120/90 (B). The distribution in B can be obtained from the distribution in A by a sinistral rotation of 80° about a vertical axis looking down. Lower hemisphere equal area projection.

may point to increasing deformation with depth.

Mineral isograds are subparallel to the F3 axial planes (Fig. 5). Hence, shortening during D3 was perpendicular to the isograds. Assuming these isograds to have formed with a subhorizontal attitude or a gentle dip, D3 constitutes a phase of subvertical shortening.

D4. All postmetamorphic deformation has been assigned to D4. Structures are mostly brittle and include E-W trending faults, locally marked by up to 5 m thick breccias with a quartz matrix, and some N-S trending faults.

The Cap de las Costes fault bisects the Trois Seigneurs massif (Fig. 2). It trends NW-SE in the eastern part of the massif but swings to E-W and becomes difficult to trace near Massat. SE of Massat its presence could be deduced from brittle deformation in Silurian slates. As this fault does not cut the Oust granodiorite in the west, its strike probably swings again to a NW-SE azimuth near Massat.

From a general E-W trend, the strike of S2 swings to N-S close to the Cap de las Costes fault, to parallel the fault trend at its contact (Fig. 4). The maximum of intersection lineations with bedding on N-S striking S2 can be obtained from the maximum on E-W striking S2 by rotation about a vertical axis (Fig. 4), indicating essentially horizontal movement. If this localized folding of S2 is a drag effect of fault movement, a sinistral offset of

5–6 km is implied. Restoration of this displacement gives a pre-fault WSW-ESE alignment of the mineral isograds, quartz diorite outcrops and the two large bodies of two mica granite.

As the E-W trending Cenomanian deposit does not show any offset (Fig. 2), the Cap de las Costes fault must have been active before the Cenomanian. This fact and the inferred sinistral offset make it plausible that the Cap de las Costes fault forms part of the North Pyrenean Fault System, active in the Lower Cretaceous (mainly Albian; Vielzeuf & Kornprobst, 1984).

The moderate westerly plunge of F3 fold axes and the moderate northerly dip of the isograds is attributed to block rotation of the entire massif during D4.

Metamorphism and its relation to deformation

Allaart (1959) has divided metamorphism in the Trois Seigneurs massif into a chlorite zone (1), biotite zone (2), andalusite zone (3) and sillimanite zone (4) (Fig. 2). The sillimanite zone grades into quartz diorite, which Allaart (1959) considered to have formed by in-situ melting of sillimanite-gneiss. Wickham & Oxburgh (1986) have subdivided the sillimanite zone into a subzone with and a subzone without andalusite. These authors also noted a zone of partial melting between the sillimanite zone and the quartz diorite (biotite granite of Wickham & Oxburgh, 1986). Isograds dip gently to moderately NNW, subparallel to the axial planes of the F3-folds (Fig. 5).

Observations

Observations of porphyroblast-matrix relations along the cross-section (Fig. 5) are mainly restricted to the biotite and andalusite zones. In these zones biotite has locally grown after D2 but before D3, as shown by deformed biotites in fold hinges of D3 crenulations. Other biotites have their basal traces parallel to S2.

Andalusite and cordierite occur as two types. Type 1 has straight inclusion trails making an angle with the external foliation, indicating rotation. As rotation directions – looking W along the D3 fold

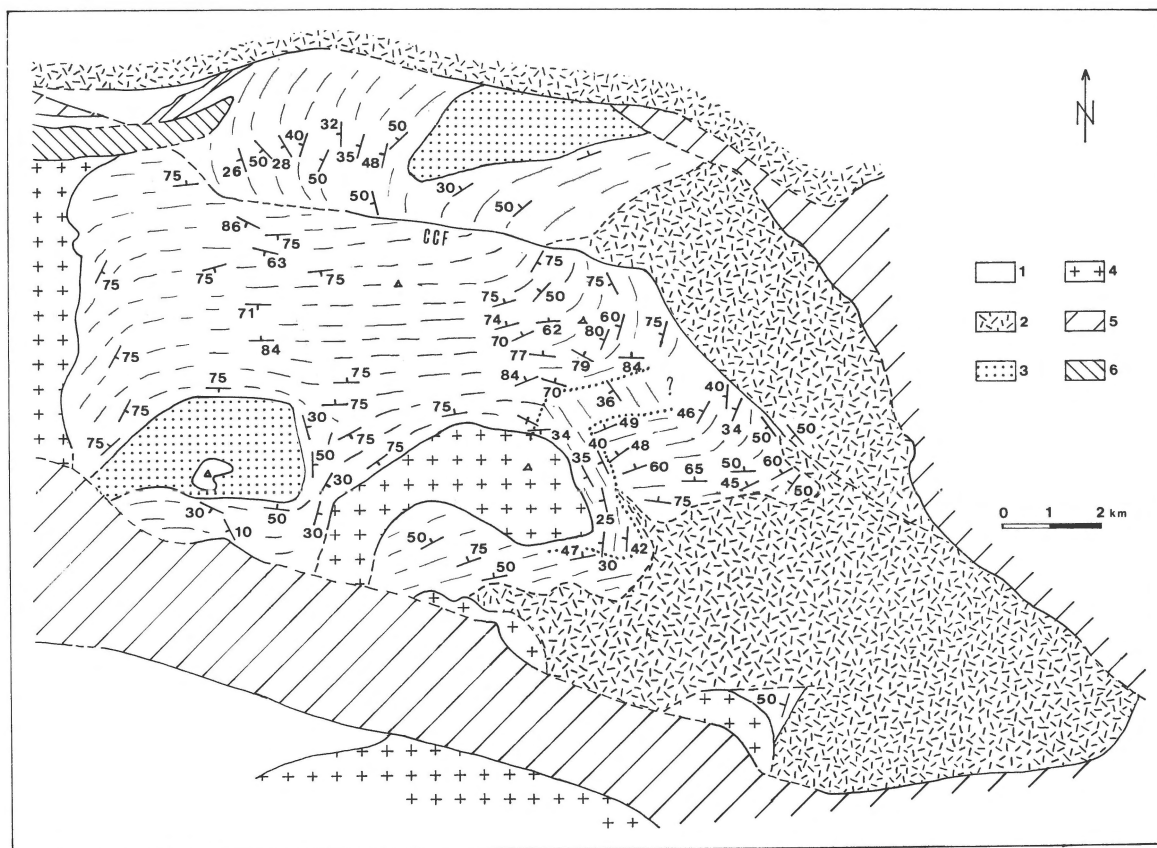


Fig. 4. Trends (broken lines) and attitude of main foliations, all regarded as S2, in the Trois Seigneurs massif. Based on measurements by Allaart (1959) and the present author. Note the swing in foliation trends near the Cap de las Costes Fault (CCF), also that the Cenomanian sediments are unaffected by movement along this fault. Dotted lines denote interpreted trace of F3 axial planes. 1 = Cambro-Ordovician to Devonian metasediments; 2 = quartz diorite; 3 = two-mica granite; 4 = granodiorite; 5 = Jurassic and Lower Cretaceous sediments and intrusives; 6 = Cenomanian and Upper Cretaceous sediments.

axis – are dextral in the steep limb of this fold and sinistral in the shallow limb, rotation is interpreted to be the effect of flexural slip folding during D3. Type 1 andalusite and cordierite are therefore concluded to have grown post-D2 and pre-D3. Type 2 andalusite and cordierite contain crenulated inclusion trails but they are undeformed, indicating post-D3 growth. They mostly occur near the sillimanite-in isograd and in the contact aureoles. Syn-D3 growth of andalusite and cordierite has not been observed.

Large muscovite crystals resulting from prograde breakdown of andalusite are undeformed. Hence, both the andalusite-out and the muscovite-out isograd are post-D3.

Subdivision of metamorphism

The observations indicate two phases of metamorphism, the first, M1, post-D2/pre-D3, the second, M2, post-D3. This is consistent with Allaart's (1959) subdivision of metamorphism into a syn- and a postkinematic phase. Allaart (op cit.) also considers the sillimanite zone to have formed during the synkinematic phase (M1), while he attributes the quartz diorite to the postkinematic phase (M2). Timing of the quartz diorite is confirmed by its undeformed nature.

Two-mica granites in the Trois Seigneurs massif and in the Pyrenees in general are believed to result from anatexis of water-rich sediments (e.g. Zwart, 1979; Wickham, 1987). Boudinage of two-mica

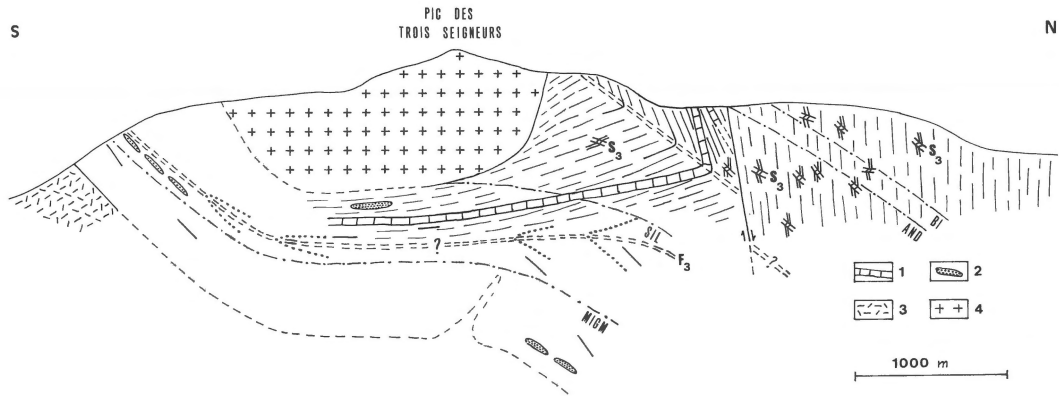


Fig. 5. N-S cross-section through the Trois Seigneurs massif (see Fig. 2 for location). Main foliation S2 is deformed into an inclined F3 fold on the eastern flank of the Pic des Trois Seigneurs with an axial plane (double broken line) subparallel to S3. Most data have been projected from the east along the F3 fold axis, 280/35. Another F3 fold at depth is inferred from the presence of N-dipping foliations at depth. Intrusion of the granodiorite may have caused deflection of the sillimanite-in isograd and the migmatite front (migm), as well as tightening of the lower F3 fold. Note the near parallelism between isograds and F3 axial planes. 1 = quartzitic marble; 2 = boudins of two mica granite; 3 = quartz diorite; 4 = granodiorite.

granite in the central part of the massif (Allaart, 1959; Wickham, 1987; Fig. 5) points to anatexis before D3 deformation, hence during M1. It is not certain whether the present migmatite front was affected by D3 deformation. If it was not, then the M1 migmatite front must lie at a deeper level. This would imply a rising of the migmatite front during M2.

It is concluded that M1 took place between D2 and D3 and led to formation of the biotite-in, andalusite/cordierite-in and sillimanite-in isograds, as well as anatexis at deeper levels.

M2 occurred after D3 and resulted in new growth of andalusite and cordierite, breakdown of andalusite and muscovite, possibly a rising of the migmatite front and in-situ formation of quartz diorite out of the highest grade metamorphic rocks. In situ formation of the quartz diorite out of previously formed migmatites is also proposed by Wickham (1987).

P-T conditions of metamorphism

Andalusite and cordierite appear together within the biotite stability field. Hence, a suitable reaction for the formation of these minerals is: chlorite + muscovite + quartz = cordierite + andalusite + biotite + water. Winkler (1979) mentioned $525 \pm$

10°C at 2 kb water pressure and $535 \pm 10^\circ\text{C}$ at 4 kb water pressure for this reaction. Prograde breakdown of muscovite did not occur during M1. Hence, pressures at anatexis during M1 were greater than 3.0–3.5 kb (after Winkler, 1979).

Boudins of two-mica granite point to anatexis during M1, as argued above. A possible reaction for anatexis during M1 is: albite + muscovite + quartz + water = melt + sillimanite. This takes place at 660°C and 3 kb or 640°C and 6 kb (Winkler, 1979), which is the appropriate pressure range in the absence of kyanite.

The distance between the andalusite/cordierite-in isograd and the migmatite front is now 1.5–2.0 km (Fig. 5). It is uncertain whether this migmatite front is due to M1 or to M2, since it may have risen during M2. However, it gives at least the minimum distance during M1. This distance must be corrected for D3 deformation. As the interlimb angle of the upper D3 fold is $\pm 80^\circ$ and the isograds are subparallel to the axial plane of the D3 folds (Fig. 5), a minimum of 35% shortening perpendicular to the isograds is inferred. Hence, the original distance between the isograds mentioned was 2.5–3.0 km, corresponding to a pressure difference of slightly less than 1 kb.

At 2 kb for the andalusite/cordierite-in isograd

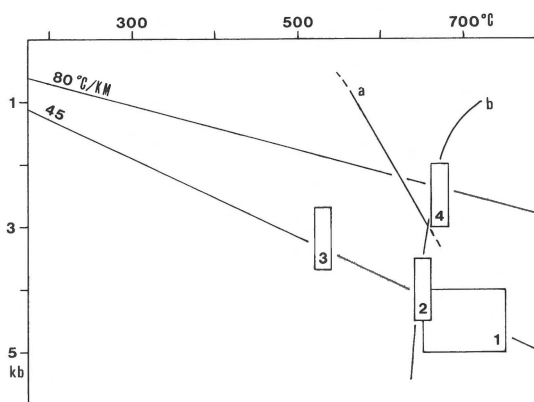


Fig. 6. P-T conditions of metamorphism in the Trois Seigneurs massif. 1 = garnet bearing gneisses in the southeastern part of the massif (after Zwart, 1979 and Vielzeuf, 1984); 2 = anatexis during M1; 3 = andalusite/cordierite-in isograd during M1; 4 = anatexis during M2. a: muscovite + quartz = kalifeldspar + sillimanite + water; b: beginning of anatexis at water pressure equal to total pressure (after Winkler, 1979).

and 3 kb for the beginning of anatexis, the temperature difference amounts to $135 \pm 15^\circ\text{C}$. At 4 kb and 5 kb, respectively, the temperature difference is only $115 \pm 15^\circ\text{C}$. Hence, the field P-T array shows a gradient of $35\text{--}50^\circ\text{C}/\text{km}$ during M1 (Fig. 6).

During M2 muscovite became unstable and reacted with quartz to form alkali feldspar and sillimanite. Hence, pressures during M2 have dropped to below 3.0–3.5 kb at this level. Anatexis at lower pressures requires higher temperatures (e.g. Winkler, 1979). This implies that M2 was characterized by lower pressures and higher temperatures than M1. Consequently, the metamorphic gradient during M2 was also higher than during M1.

Tectonometamorphic evolution of the Trois Seigneurs massif

Combining the structural and metamorphic observations the following scheme for the Variscan tectono-metamorphic evolution of the Trois Seigneurs massif is proposed:

1. Horizontal shortening (D1 ?, D2) causing formation of tight folds with steep axial plane foliations;

2. regional metamorphism (M1) with formation of biotite-in, andalusite/cordierite-in and sillimanite-in isograds and anatexis in the presence of muscovite ($P > 3.0\text{--}3.5\text{ kb}$, Fig. 6);
3. subvertical shortening (D3), causing formation of kilometre-scale inclined folds and crenulation cleavages S3 (Fig. 5);
4. peak regional metamorphism (M2) with breakdown of muscovite, anatexis ($P < 3.0\text{--}3.5\text{ kb}$, Fig. 6), in-situ formation of quartz diorite and intrusion of large bodies of two-mica granite;
5. intrusion of the Trois Seigneurs granodiorite by shouldering aside the metasediments, causing a deflection of the sillimanite-in isograd, the migmatite front and the lower F3 axial plane (Fig. 5).

Tectonic setting of D3 and metamorphism

Sonder et al. (1987) have concluded from tectono-thermal modelling that crustal extension may follow crustal thickening when a Moho-temperature of $\pm 750^\circ\text{C}$ is reached. In the Trois Seigneurs massif, peak temperatures after crustal thickening, during M1, exceeded 640°C . Hence, the Moho-temperature is likely to have reached 750°C . M1 was followed by D3, which is interpreted as a phase of subvertical shortening. Assuming constant volume deformation, vertical shortening implies horizontal extension. It is therefore postulated that D3 represents a phase of horizontal extension. Attenuation of the overlying rock sequence during the extensional phase, together with erosion at the surface, may explain the pressure decrease between M1 and M2.

Discussion

A recent model for the evolution of the Variscan Pyrenees proposed a rift setting (Wickham & Oxburgh, 1985, 1986, 1987a; Wickham, 1987). The main arguments of Wickham and co-workers for this model are derived from their study of the Trois Seigneurs massif. These arguments are summarized and evaluated below.

A. Unimportance of horizontal shortening

Wickham & Oxburgh (1985) only mentioned extensional deformation in the Trois Seigneurs massif. They stated that no evidence of continental collision is present and that nappe-type folding and thrusting are absent in the Variscan Pyrenees. In their reply to a critique by Matte & Mattauer (1987) Wickham & Oxburgh suggested that heterogeneous deformation in a strike-slip regime might provoke shortening in the upper crust and extension in the middle crust.

Interpretation of the structural history of the Trois Seigneurs massif depends on the original attitude assumed for the main phase foliation (S2 in this paper, S1 in Wickham, 1987). Wickham (1987) implicitly assumed this foliation to have originated in a horizontal position. However, mineral isograds are subparallel to the D3 axial planes (Fig. 5) and have consequently formed nearly perpendicular to S2. This suggests that S2 had a steep to subvertical attitude before the onset of metamorphism and probably originated in that orientation. Hence, the upright tight folds mentioned in this paper indicate considerable horizontal shortening.

In other parts of the Pyrenees early Variscan thrusting (e.g. Losantos et al., 1986) and later tight to isoclinal folds at all scales with predominantly steep penetrative axial plane foliations (e.g. Zwart, 1979; Kriegsman et al., 1989, this volume) have been described. In this paper it is argued that horizontal shortening was followed by an event of horizontal extension (D3). Evidence for Late Variscan extension after crustal shortening has also been put forward by Van den Eeckhout & Zwart (1988).

B. Very high geothermal gradients

Wickham & Oxburgh (1985, Fig. 3) have shown a P/T array from $\pm 400^\circ\text{C}$ to $\pm 700^\circ\text{C}$ with a slope of $80\text{--}100^\circ\text{C}/\text{km}$, the distance across being about 3 km. According to Wickham and co-workers, such high gradients are strong evidence for a rift setting.

The lower temperature mentioned by Wickham & Oxburgh (1985) is possibly based on the assumption that andalusite formed out of pyrophyllite, which takes place at $\pm 410^\circ\text{C}$ (Winkler, 1979). In this paper, however, it is argued that andalusite formed with cordierite out of muscovite, chlorite

and quartz at $\pm 525\text{--}535^\circ\text{C}$ (Winkler, 1979). This is in accord with the mineral reactions given by Wickham (1987) for the first appearance of andalusite and cordierite.

Absence of staurolite is taken by Wickham & Oxburgh (1985) to indicate low-pressure metamorphic conditions. However, from the 40 chemical analyses of pelites, migmatites and quartz-diorite/biotite granite mentioned by Wickham (1987), it is evident that Mg/(Mg + Fe) ratios are higher than 0.25 in all these lithologies. According to Winkler (1979) such a high Mg/(Mg + Fe) ratio of the original sediments prevents the growth of staurolite and leads to growth of cordierite instead. Besides, staurolite is a major constituent in some other Pyrenean massifs, where otherwise metamorphism is quite similar (e.g. Lys-Caillaouas massif: Kriegsman et al., 1989, this volume).

In this paper it has been argued that metamorphism can be subdivided into two phases, M1 and M2, separated by a phase of subvertical shortening and subhorizontal extension (D3). Shortening perpendicular to the M1 isograds and possibly transgression of M2 isograds over M1 isograds, due to a rising metamorphic front, have led to exaggerated metamorphic gradients. Thus the isograd sequence from sillimanite-in through muscovite-out to anatexis is a combined M1 and M2 effect; the sequence muscovite-out to anatexis and the stability of biotite during melting (Wickham & Oxburgh, 1986) do indicate low pressures, but only after the extensional D3 deformation.

Vielzeuf (1984) has calculated prograde P-T conditions of the Saint-Barthélemy granulites at 4.5 ± 0.5 kb, $700 \pm 50^\circ\text{C}$. These garnet-bearing gneisses constitute the shallowest basement granulites in the Pyrenees. Hence, the average gradient in the Paleozoic cover sediments during prograde metamorphism can be calculated from the peak metamorphic conditions in the granulites. The result is $44 \pm 6^\circ\text{C}/\text{km}$. At such a gradient a 1000–1500 m thick migmatite zone may be expected to form on top of the granulites (after data from Winkler, 1979). Similar garnet-bearing gneisses also occur at depth in the southeastern part of the Trois Seigneurs massif (Allaart, 1959), approximately 1.5 km below the migmatite front. Hence, the mig-

matite front may be related to prograde metamorphism (M1). A reasonable estimate for the pressure at anatexis during M1 is 4.0 ± 0.5 kb (Fig. 6). This is consistent with the stability of muscovite + quartz at anatexis during M1. Consequently, the field P-T array for M1 extends from $530 \pm 10^\circ$ C and 3.0 ± 0.5 kb at the andalusite/cordierite-in isograd to $\pm 650^\circ$ C and 4.0 ± 0.5 kb at the migmatite front (Fig. 6), which is $\pm 120^\circ$ C instead of the $\pm 300^\circ$ C of Wickham & Oxburgh (1985).

C. Circulation of seawater during Variscan metamorphism

According to Wickham & Oxburgh (1985, 1986, 1987a) metamorphism in the Trois Seigneurs massif was contemporaneous with marine sedimentation on top of this massif. These authors postulated that metamorphism was associated with circulating seawater, reaching down as far as 12 km (Wickham & Taylor, 1985).

Zwart (1979) mentioned Lower Namurian as the age of the youngest pre-Variscan sediments in the North Pyrenees. In the Upper Namurian and Westphalian these rocks were affected by a major thrusting event with tectonic transport probably to the south (e.g. Losantos et al., 1986). According to Raymond (1987) thrusting was accompanied by syntectonic sedimentation to the south. Lucas (1977) concluded from his study of Permian and lower Triassic sediments that the North Pyrenees formed a palaeo-high during these times. Hence, the surface of the North Pyrenean massifs was above sea level at least from the Upper Namurian until the Lower Triassic.

Vielzeuf & Kornprobst (1984) mentioned prograde granulite facies metamorphism of rocks found near Lherz (directly S of the Trois Seigneurs massif) dated at ± 300 Ma, or Westphalian D. Retrograde metamorphic assemblages containing andalusite (Vielzeuf & Kornprobst, op. cit.) imply considerable decompression of these granulites. As Late Westphalian and Early Permian deposits are not voluminous in the Pyrenees (e.g. Lucas, 1977), this decompression implies extension. Hence, peak metamorphism in the basement granulites occurred before the extensional phase, whereas peak metamorphic conditions in the Trois

Seigneurs massif were only reached after extension. It is therefore concluded that peak metamorphism in the Trois Seigneurs massif (M2) is younger than Westphalian D. This fact, together with the palaeogeographic data mentioned, indicates that the palaeozoic metasediments cannot have been flushed by seawater during Variscan metamorphism.

Conclusions

1. The Variscan evolution of the Trois Seigneurs massif can be summarized as penetrative N-S shortening (D1, D2) with subsequent metamorphism (M1), followed by a phase of subvertical shortening and subhorizontal extension (D3) and finally peak metamorphism (M2).
2. Variscan metamorphism in the Trois Seigneurs massif is not related to a rifting event, but to late orogenic extension (D3) after considerable crustal thickening (D1, D2).

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