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Phil. Trans. R. Soc. Lond. A 1976 **283**, 271-280
doi: 10.1098/rsta.1976.0084

Phil. Trans. R. Soc. Lond. A. **283**, 271–280 (1976) [271]
Printed in Great Britain

Strain patterns in the Pyrenean Chain†

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The Pyrenean Chain is a deformed part of the crust, fan-shaped in cross section, in which we can define the main characteristics of the major deformation as follows:

(*a*) East–west folds always have their axial planes nearly vertical; the *B* axes of these folds have gentle plunges;
(*b*) in the domain where schistosity is present (dominent flattening), the direction of maximum apparent elongation on cleavage planes, i.e. the *X* deformation axis, is nearly parallel to the geometric *A* axis of the folds.

Inside the domain of strong flattening, a very narrow zone is present (less than 2 km wide on some cross sections) bounded by discontinuities, one of the most important is the North Pyrenean fault. This narrow zone is fundamentally different from the rest of the chain:

(i) here, the deformation has the highest intensity and the rocks are metamorphosed;
(ii) the *B* axes of the folds are curved and display steep plunges;
(iii) the *X* deformation axis is parallel to the *B* geometric axis.

We imagine that these anomalies have been created by sinistral horizontal displacement on the North Pyrenean fault during the folding.

In addition to these facts, a brittle-deformation analysis permits the drawing of deformation trajectories in the flat northern foreland up to 400 km from the chain itself.

Introduction

The Tertiary Pyrenean tectogenesis includes several tectonic phases: the first phase of deformation is the major one and is responsible for the most obvious tectonic structures at any scale in the field. In this paper, we will only discuss elements pertaining to this major phase of deformation. These data are mostly qualitative as a first step, and concern the spatial distribution of elementary modes of deformation, the geometry of folding, and the orientation of the principal strain axes.

This information could be gathered quickly enough in the Pyrenean chain and proved sufficient to establish the main structural characteristics of the deformed domain. It also enabled us to define the anomalous character of the eastern North Pyrenean zone which appears radically different from the rest of the chain. We will first discuss the main tectonic features of the Pyrenees, then show the originality of the eastern North Pyrenean zone and try to explain it.

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† This paper is a partial synthesis of several contributions by the Laboratory of Structural Geology at U.S.T.L. Montpellier (France): Choukroune (1971, 1974), Choukroune & Seguret (1973), Choukroune, Seguret & Galdeano (1973) Arthaud & Choukroune (1972), Seguret (1972).,

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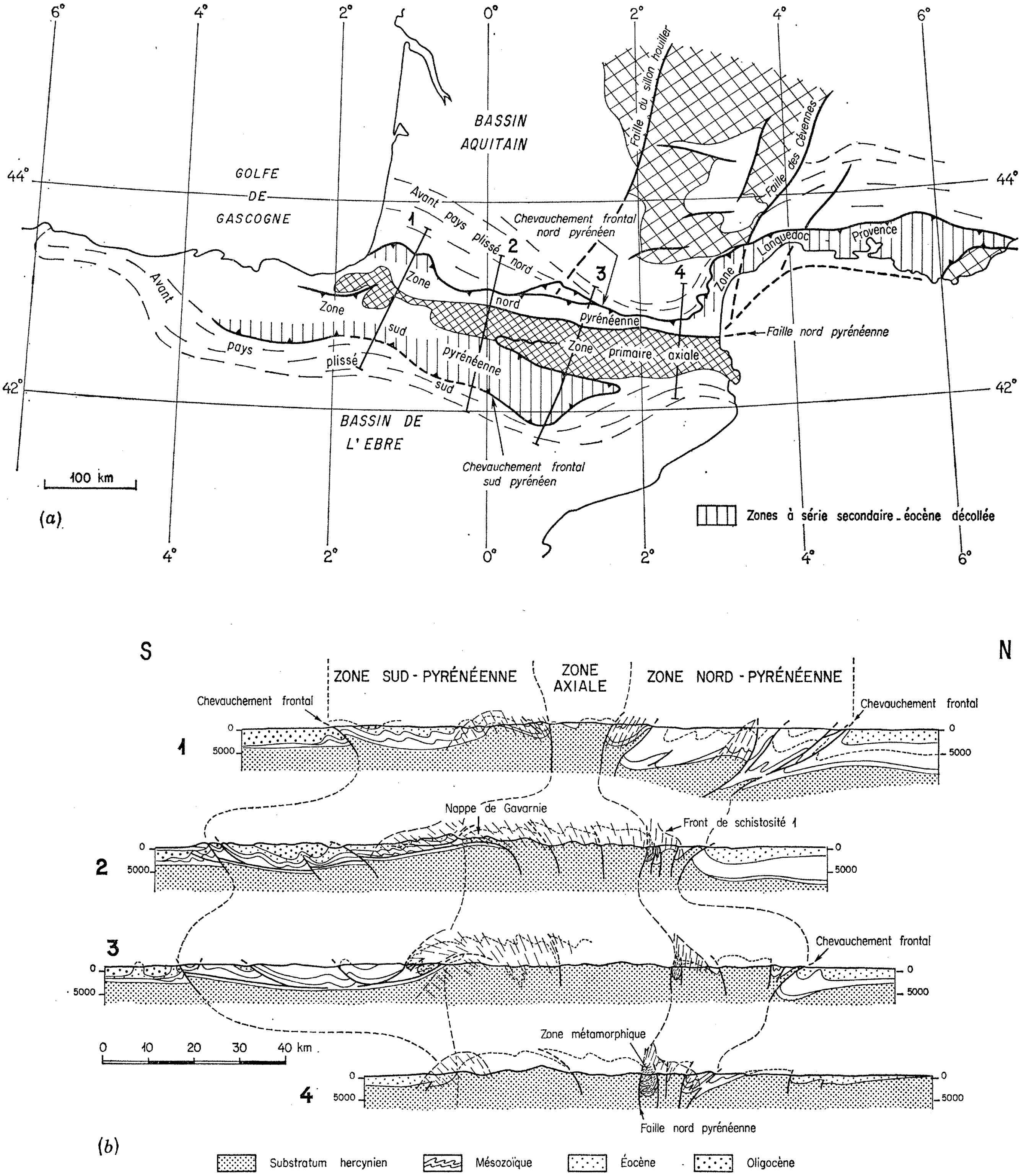

Figure 1. The main structural zones of the Pyrenees. Cross sections show the general fan shape of the folded domain (modified after Mattauer & Henry 1973).

The main structural characteristics of the Pyrenees

Cross sections of the Pyrenees are typically fan-shaped, most of the overthrusts being divergent towards the external zones (figure 1). This fan-shape is almost symmetrical, and we were able to distinguish three major structural zones (figure 1):

(i) The 'Hercynian axial zone' essentially made up of Palaeozoic rocks is approximately located along the symmetry axis between the centrifugal overthrusts.

(ii) South of the axial zone, the 'south Pyrenean zone' where Mesozoic and Cenozoic series, 'decollées' in the Triassic, have suffered important translations towards the South (40 km) without any intimate deformation of the transported masses (Seguret 1972). The only noticeable deformation was observed in the root zones of the thrust sheets. There, strong shortening is associated with nappes in Palaeozoic terrains (Gavarnie nappe, Plunging noses of Nogueras...).

The overthrusting south Pyreneans unit rides over an unfolded molassic foreland.

(iii) North of the Hercynian axial zone, in the so called 'North Pyrenean zone', the Mesozoic rocks have suffered *in situ* deformation. They are locally metamorphosed and affected by deep vertical faults, the most important of which is the north Pyrenean fault which marks the boundary between the axial zone and the north Pyrenean zone.

Frontal overthrusts occur to the north over the Mesozoic and Cenozoic aquitanian foreland which is affected by brittle deformation.

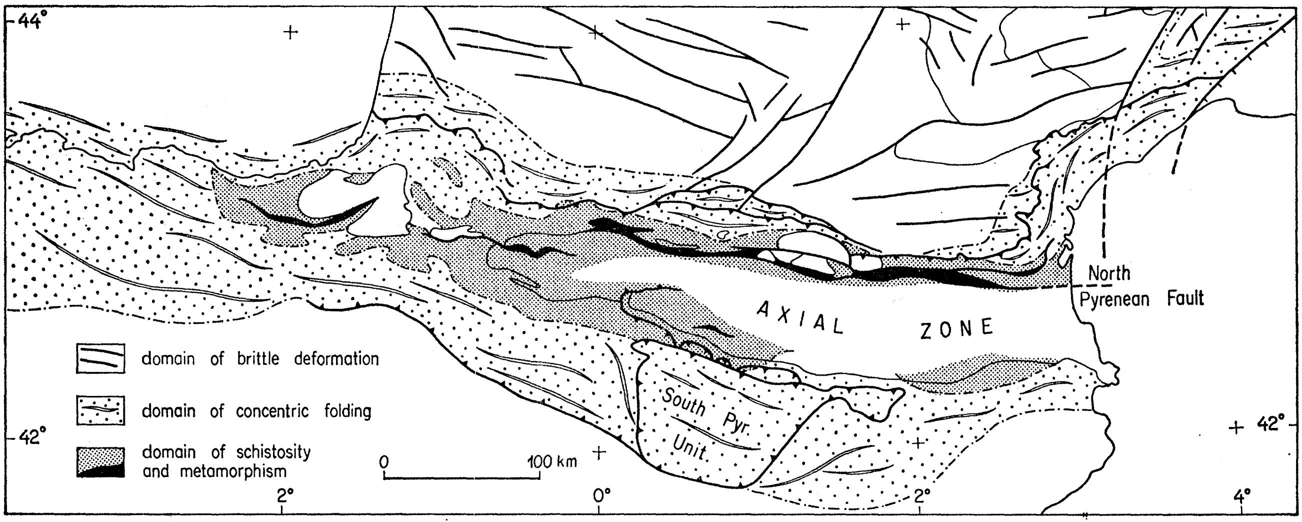

Figure 2. The extent of the upper, intermediate and deepest structural levels in the Pyrenean chain. Note the close coincidence between the north Pyrenean fault and the metamorphic zone.

The distribution of the elementary modes of deformation

In the structural setting that we have just described, we shall now distinguish several domains according to the prevalent modes of deformation. In each domain, we have compared the modes of deformation with reference to similar types of rocks with similar mechanical properties. We were thus able to define three principal deformation domains which are not simply superimposed with the structural domains but depend of course, on the physical conditions under which the deformation took place (Arthaud & Mattauer 1969).

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(1) Rocks deformed in the upper structural level are well represented in the north Pyrenean foreland; the deformation there is essentially brittle with no folding to speak of, except for gentle undulations of broad wavelength.

(2) Rocks deformed in the intermediate structural level show mainly concentric folding, and are characteristic of the northern part of the north Pyrenean zone and most of the south Pyrenean zone.

(3) Rocks deformed in the deepest structural level are observed in a belt roughly centred in the Hercynian axial zone. They show strong cleavage and, in a narrow zone spatially linked with the north Pyrenean fault, low pressure and high temperature syntectonic metamorphism.

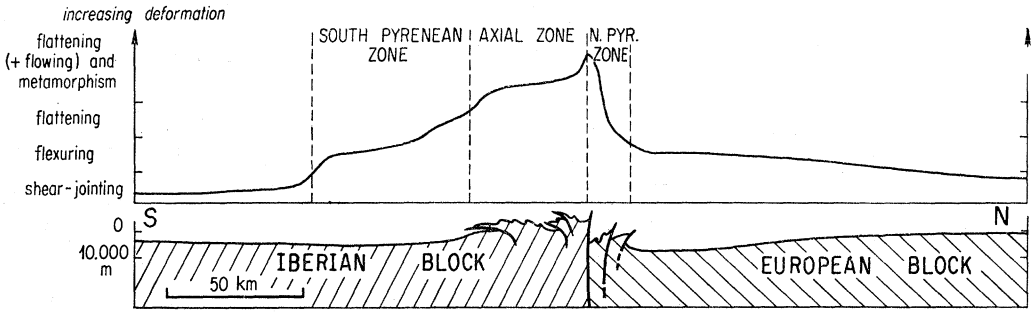

Figure 3. Schematic diagram depicting the predominant mechanisms of deformation in cross section. The extent of these mechanisms gives a good idea of the increasing deformation (after Choukroune & Seguret 1973.)

Figure 2 shows clearly the extent of these three domains. They correspond, in a first approximation, to areas of increasing deformation.

In figure 3, we represent schematically the variation of the intensity of deformation across the chain. Striking features in the diagram are: the narrowness of the maximum near the north Pyrenean fault, the steepness of the deformation gradient to the north, and the gradual decrease of this deformation to the south.

Geometry of the major Pyrenean folding phase

On the average, the folds trend east–west, parallel to the mean direction of the chain and have very steep axial planes. Similarly in the cleavage domain, where flattening is the dominant mode of deformation, S_1 planes are nearly vertical. This geometry which is to be expected for the axial fan-shape of the chain, has been considered by many authors as the typical characteristic of the Pyrenean chain (Fourmarier 1951; Mattauer 1968; Mattauer & Henry 1973). The B_1 axes of the folds and the intersection lineations usually have gentle plunges in the cleavage plane.

Locally, the general east–west trend of the folds is disturbed; these disturbances have been explained in terms of the heterogeneous nature of the deformed material and the role of pre-existing discontinuities (Choukroune 1974).

On the southern slope, bends in the general trend of the folds occur along the edges of two main translated units and are due to the different rates of displacement of these two units (Seguret 1972).

ORIENTATION OF THE PRINCIPAL STRAIN AXES

Strain trajectories in the northern Pyrenean foreland

The main preoccupations in the study of an orogen usually tends to be restricted to the analysis of continuous deformation in the regions of intense shortening. Here however we stress the importance of the effects of the tectonics on adjacent regions which have been little affected and generally described as 'stable plateforms'.

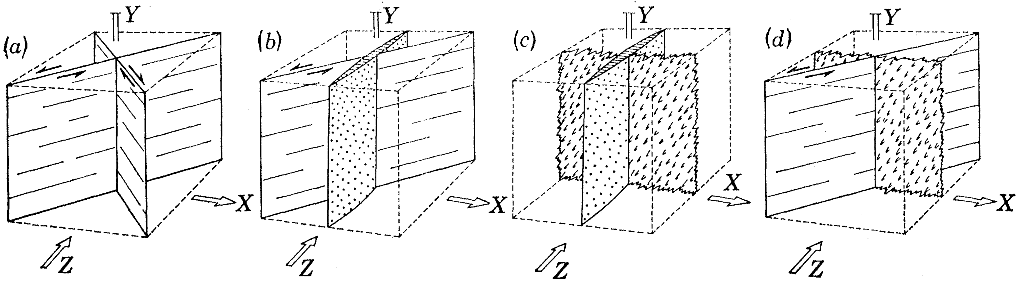

FIGURE 4. Determination of the principal axis of deformation in the brittle domain with a simple system of microfractures (micro-wrench – faults stylolitic joints and tension gashes) (after Arthaud & Choukroune 1972).

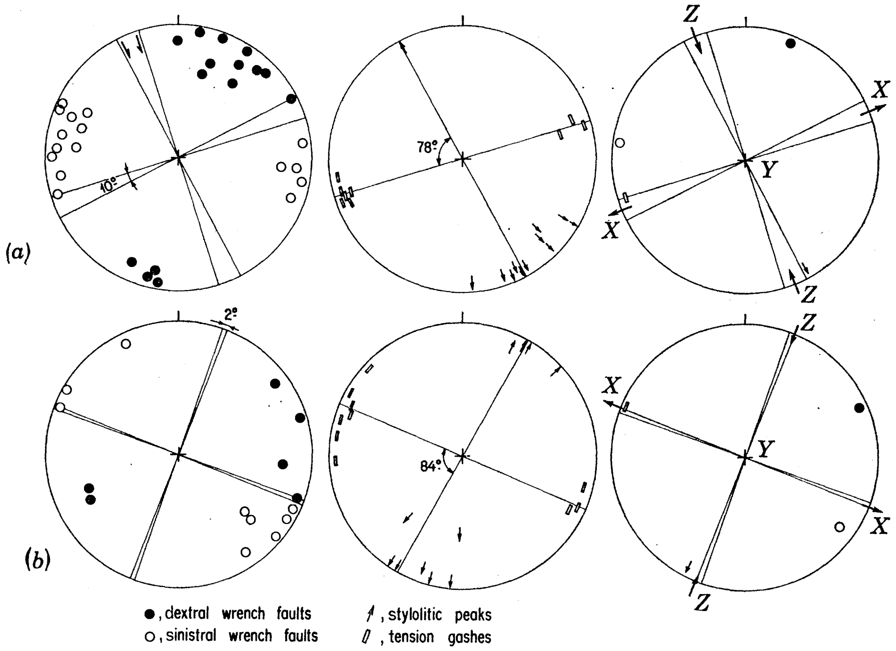

FIGURE 5. Examples of the punctual determination of X, Y, Z for two stations in the Aquitanian foreland (after Arthaud & Choukroune 1972).

In the Aquitanian plateform, for instance, the effects of Pyrenean tectonics can be observed as far away as 400 km from the chain itself. The deformation in this plateform, is of a brittle type and expressed by the presence at any scale of remarkable fracture patterns. At the scale of the outcrop, detailed microfracture analysis enables a local determination of the mean shortening direction; three kinds of micro-fractures can be used in this type of analysis and provide useful crosschecks (figure 4).

(i) Stylolitic joints allow a rough determination of the shortening direction which is usually found to be parallel to the stylolitic peaks.

(ii) Tension gashes, when not sigmoidal, open normal to this same direction of shortening. However, syntectonic crystallized fibres of quartz or calcite inside the gashes, give more accurate information in some cases (Durney & Ramsay 1973).

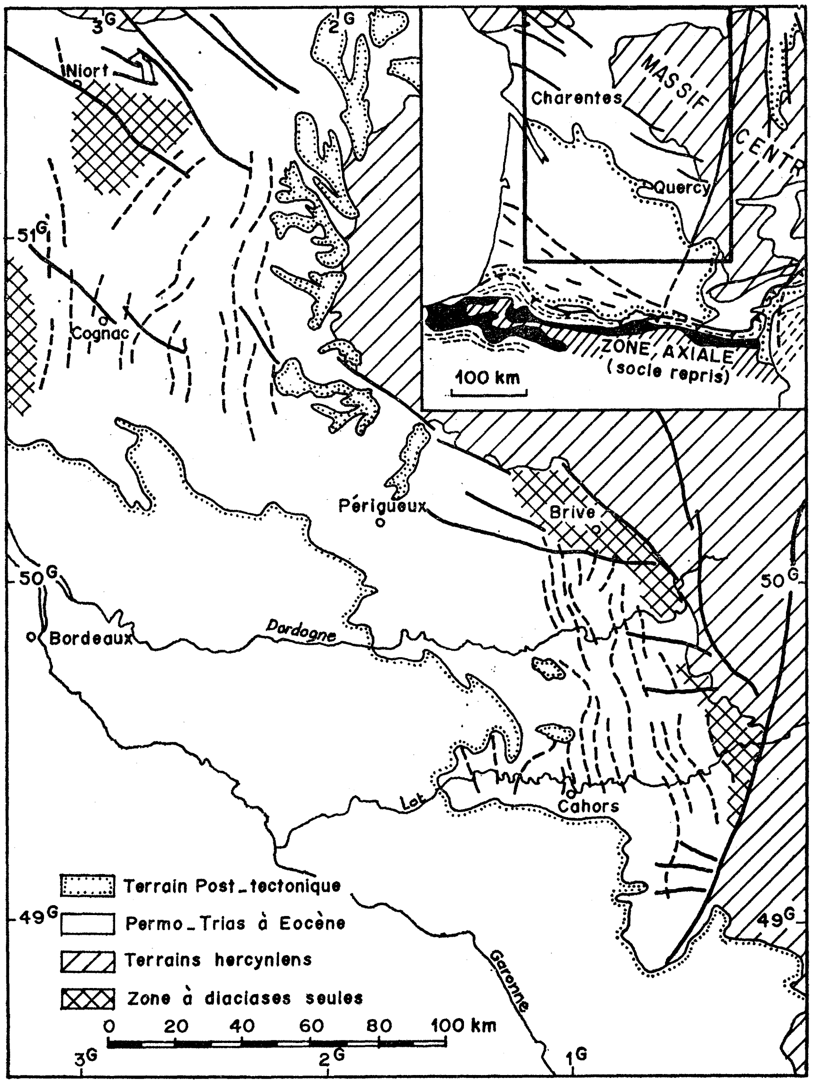

FIGURE 6. The results of the brittle deformation analysis in the north Pyrenean plateform: strain trajectories in the Aquitanian foreland.

(iii) Micro-strike slip-faults: in this area of weak and simple brittle deformation these faults could be grouped in two distinct classes (right lateral and left lateral). Statistically, the direction of shortening could therefore be bracketed.

In a single station, we found good agreement between the results given by the three types of micro-fractures which strengthened our confidence in the accuracy of the shortening direction determined with this method (Arthaud & Choukroune 1972) (figure 5).

A great number of stations allowed the determination of the strain trajectories as the envelope of the shortening directions. These trajectories were found to trend roughly NNW in the south (Quercy) and NNE in the north (Charentes) of the platform (figure 6).

Orientation of the principal strain axes in the deepest structural level

In this domain, where the rocks are affected by penetrative cleavage, we first tried to measure the direction, in each station, of the maximum apparent elongation (X) without measuring accurately the exact shape and orientation of strain ellipsoid.

This method, although incomplete, was the best way to gather information quickly enough on the geometry of deformation over a widespread area.

Criteria for the determination of the orientation of X are well known (Ramsay 1967): Stretching lineations, shape of boudinage, elongation of deformed pebbles, deformation of pretectonic minerals, and syntectonic crystal growth (gashes and pressure shadows).

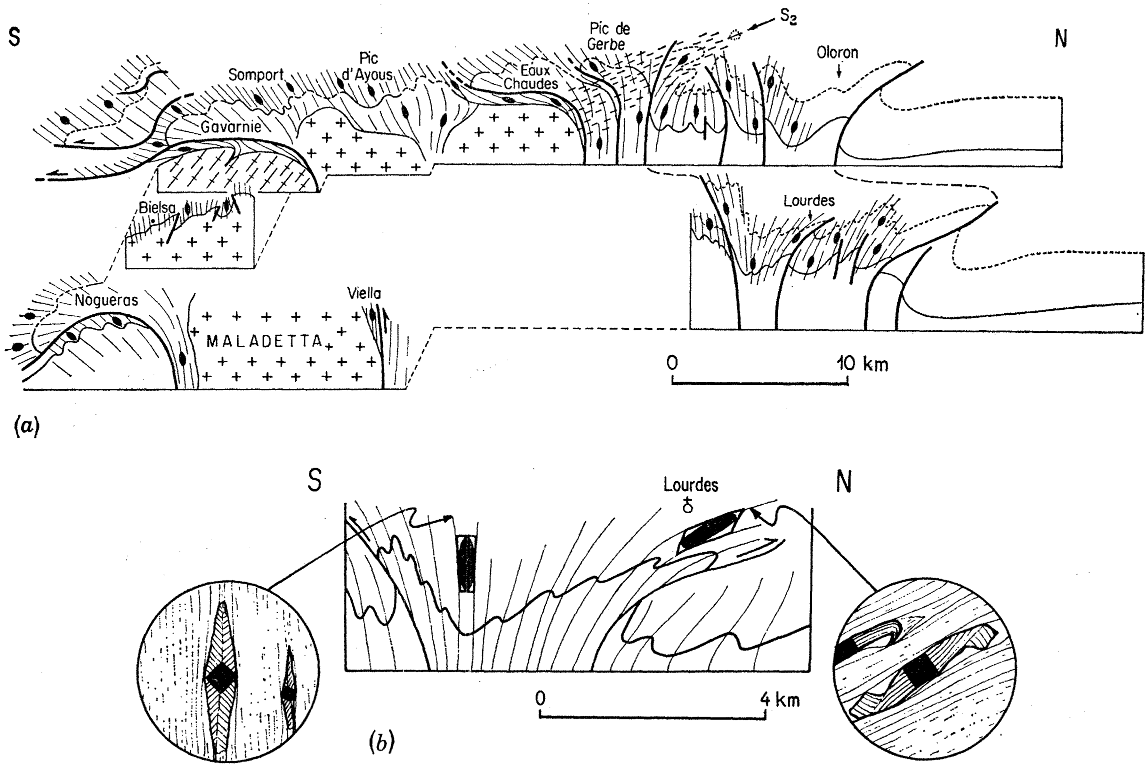

FIGURE 7. (*a*) Composite sections depicting the aspect of cleavage in central and western Pyrenees. The X elongation axis is parallel to the A geometric axis of folds. (*b*) Pressures shadows used as indicators of the continuous deformation processes in the Lourdes region.

The results of this preliminary study can be summarized as follows: X was found to have, on the average, a 90° pitch in the cleavage plane. This information together with the overall geometry of folding allows us to assert that the Pyrenees may be considered as a type of chain where the elongation is parallel to the A geometric axis of the folds.

The main characteristics that we just described are summarized in figure 7*a*. Cross sections are from the central and western part of the chain where the fan-shaped structures are particularly well defined.

In the region near Lourdes, in the central part of the north Pyrenean zone, pressure shadows are remarkably well developed. These pressure shadows are fundamental in untangling the succession in time of strain increments (Durney & Ramsay 1973; Choukroune 1971):

The shape of the shadows immediately gives the orientation and shape of the finite strain ellipsoid.

Crystallizations inside the shadows zone recorded the successive position of the actual X axis during the increments of deformation.

Moreover, these microstructures allow determination of the external rotation component in the deformation process, if any (figure 8).

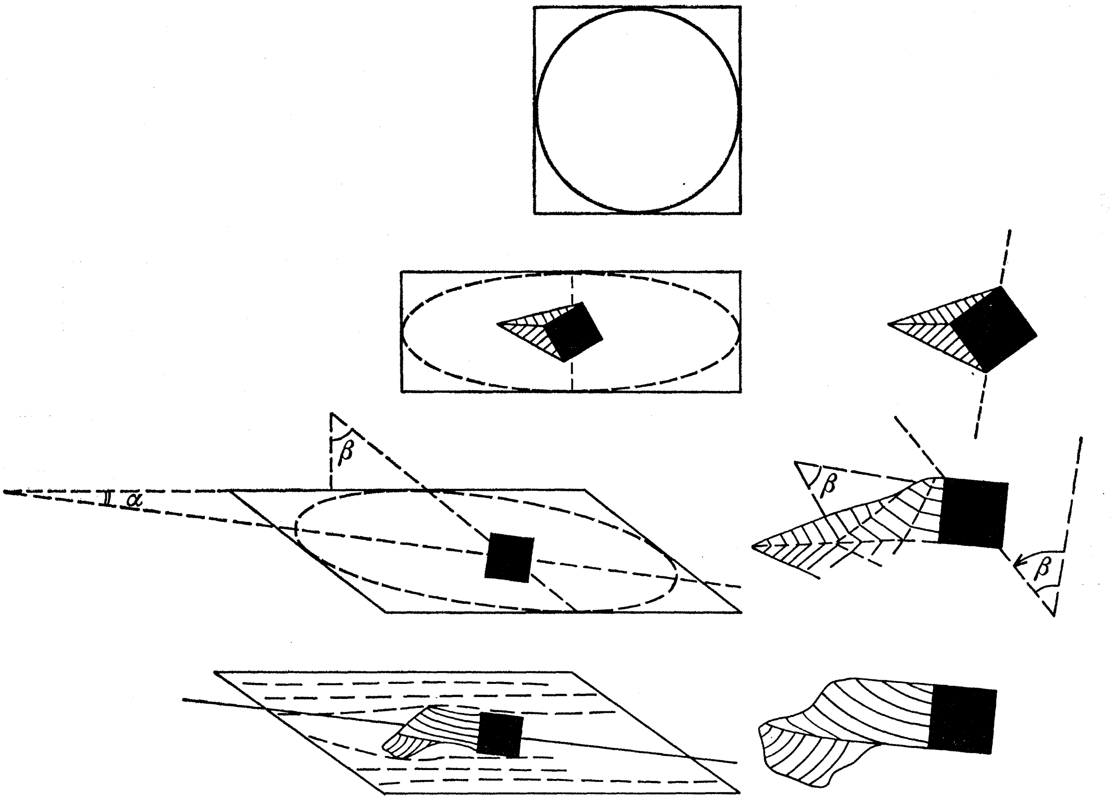

Figure 8. In pressure shadows, syntectonic crystal growth records the position of the successive X axis during the increment of deformation. In this example from the Lourdes region, the external rotation (β) and the angle between the last X and shear plane (α) can be estimated.

In the Lourdes region, syntectonic quartz–muscovite crystallizations in pressure-shadows around pyrite crystals proved to be antitaxial (Durney & Ramsay 1973). The longest axis of the shadows zones was the direction of mineral lineation on the cleavage plane and was always normal to the B intersection lineation. All the observations were carried out in three mutually perpendicular planes (XY cleavage plane, XZ and YZ planes). The main results can be summarized as follows:

Y was invariant during the deformation, both in orientation and magnitude; the overall deformation can therefore be considered as plane strain.

Moreover we were able to separate two domains with radically different strain mechanisms: in one domain, which coincides with the region in which the cleavage is almost vertical, pure shear strain was dominant; the crystallizations in pressure shadows contained in the S_1 plane, have recorded no variations of the position of the principal strain axes during the process. In the other domain, on the other hand, which coincides with the region where the cleavage is nearly horizontal, sigmoidal crystallizations always show clearly that the shear is accompanied by external rotation (figures 7*b* and 8). The global result is a northward simple shear along S_1 planes.

The eastern north Pyrenean zone; a structural anomaly linked to the north Pyrenean fault

In the folded domain, there is a zone within which the main structural characteristics which have been just described are no longer valid. It constitutes a narrow zone of metamorphic terrains, trending east–west, with a width of 500 m to 5 km, located just north of the north Pyrenean fault (figure 2). In fact, its extension is positively linked to the presence of this major crustal discontinuity; it is worth noticing that when the north Pyrenean fault ceases to be individualized as a unique discontinuity and when it is relayed westwards by a series of less important faults, this specific domain can no longer be recognized.

First, this zone is made up of rocks affected by intense deformation and syntectonic metamorphism in strong contrast with neighbouring terrains which show no metamorphism and are less deformed. The abrupt appearance of metamorphism, its small extent, and the presence of nearly vertical isograds with narrow spacing parallel to the north Pyrenean fault show the presence of a very strong temperature gradient during the deformation and the strict localization of a thermal anomaly related to the fault.

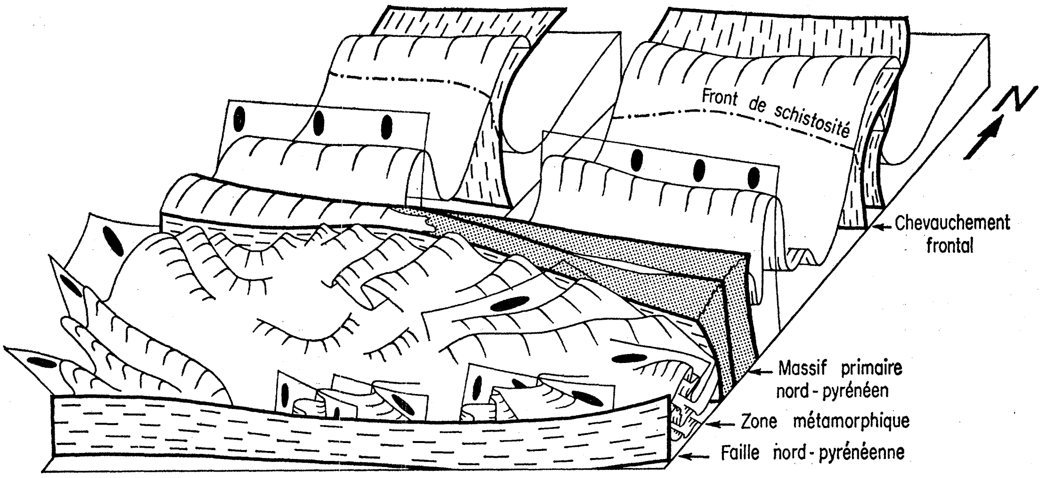

Figure 9. Perturbations of the major deformation in the Eastern north Pyrenean metamorphic zone: curved *B* axis of folds parallel to the *X* elongation axis and steep fold axis near the discontinuities such as north Pyrenean fault.

Secondly, there is, in this domain, important deviations in the folding geometry such as virgations accompanied by variations in the dip of the axial planes of the folds. The axes of the folds, curved in the foliation plane, become very steep near the limits of the metamorphic terrains and in particular near the north Pyrenean fault. Lastly, and this constitutes another essential difference with the rest of the chain, the maximum apparent elongation of the rocks is parallel to the B_1 axes of the major folds (figure 9).

Shear zone hypothesis for explaining the metamorphic north Pyrenean zone

The north Pyrenean fault appears to be a major feature of the structure of the Pyrenean Chain: concentration of a thermal anomaly and the radical changes in the deformation processes, in the vicinity of the fault, bring out this fact.

Moreover, it is clear that there is a causal link between the motion along the north Pyrenean fault and the specific type of deformation which is spatially related to the fault. It is suggested that the hypothesis of synmetamorphic strike-slip faulting is particularly satisfactory to explain the abrupt appearance of strong deformation, the perturbation in the geometry of folding and the B position of the X elongation axis. One can note, in this context, that direct proofs of wrench faulting exist such as horizontal striations on fault plane and systematic asymmetry of folds with vertical axes along the fault. These last observations seem to prove that the wrench faulting has been sinistral during folding.

To conclude, the methods of rapid structural investigation have been sufficient to characterize this special type of chain: the Pyrenees. Of course, this has been made possible by an exceptionally rapid spatial evolution of deformation which occurs very rarely in other orogenic segments. We have also distinguished two regions of different deformation within the folded domain: the narrowest one is probably related to intense deformation at the boundary between Iberian and European plates. It constitutes a good example of the complex relationship between deformation and wrench faulting at a deep structural level. The second zone, which is broader, could correspond to further late deformation within the plates themselves.

A quantitative study of the deformation is needed: it will certainly given some important precisions on what has been described and on the speculations which have been made.

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