Journal of Structural Geology, Vol. 2, No. 1/2, pp. 69 to 74.
Pergamon Press Ltd. 1980. Printed in Great Britain.

0191-8141/80/0601-0069 $02.00/0

Sinistral horizontal shearing as a dominant process of deformation in the Alpine Pyrenees

J. C. Soula
Laboratoire de Géologie-Pétrologie et de Tectonophysique, 38, rue des Trente-Six-Ponts, 31000 Toulouse, France
and
G. Bessiere
Laboratoire de Géologie Méditerranéenne, L. A. 145 CNRS, 38, rue des Trente-Six-Ponts, 31000 Toulouse, France

(*Received* 22 *June* 1979; *accepted* 21 *November* 1979)

INTRODUCTION

The Pyrenees are a straight, narrow and strongly deformed mountain chain consisting of a Hercynian basement covered by Mesozoic and Cenozoic rocks which are preserved in the north Pyrenean zone as autochtonous or subautochtonous units and over the central and western axial zone as parts of nappe structures. The chain is divided into narrower longitudinal structural zones limited by vertical major faults.

The present study is centered on the Ariège area where the different structural zones are well represented and the relationship between basement and its autochtonous cover is clear.

Two main phases, recognized first in the cover rocks, give rise to the major structures and local deformation on preexisting heterogeneities. They have locally given rise to sizeable structures such as kilometric thrusts and inclined or recumbent folds.

The first main phase is marked by development of 'en échelon' upright folds with subhorizontal axes which are oblique to the longitudinal structural zones containing them. These folds are best seen away from major preexisting heterogeneities and are found principally in Jurassic and lower Cretaceous carbonates and in synforms of middle to upper Cretaceous flysch. They show different characteristics depending on their degree of evolution, i.e. variations in fold shapes and angle of obliquity of fold axes to the shear zone. These variations depend on the rock type, on the Alpine metamorphic grade and on their proximity to major preexisting (Hercynian) discontinuities. These folds are illustrated by three examples taken from Jurassic and lower Cretaceous units.

EXAMPLES

The first example (Fig. 2) is the Pech de Foix area to the East of Foix, which forms an antiformal zone within the northern major 'flysch' trough. The individual folds are Ω shaped, with highly 'serrated' anticlines and wider synclines with a half-wavelength of some hundred metres. The angle of obliquity is about 15–20° (see below, Figs. 1–2). No minor folds are developed but stylolites indicate a homogeneous shortening prior to or during early stage buckling.

The second example (Fig. 1) is taken in the eastern cover of the north Pyrenean massif which form a 12 km wide antiformal area. The major folds are larger (2–3 km half-wavelength) than folds in the Pech de Foix area but show similar shape variations. Their angle of obliquity is roughly 15–20°. They are locally accompanied by hectometric minor folds with horizontal axes slightly oblique to the axial plane of the major folds. After graphical restoration of the original disposition of the folds by eliminating the later rotations the angle of obliquity was found to have been roughly 15–20°.

The third example (Fig. 3) is taken in the Vicdessos basin situated along the metamorphic north Pyrenean fault zone. The folds are there sub-isoclinal, regular, of hectometric size with large amplitudes (amplitude greater than two half-wavelength), and flattened hinges. They are accompanied by schistosity which is parallel to the axial planes of decimetric to metric folds deforming calcite veins in limestones. The angle of obliquity of major folds is about 10–15°.

In middle to upper Cretaceous synformal areas major 'en échelon' folds are found accompanied by minor folds. The angle of obliquity varies from 15–20° in the southern area (e.g. Nalzen basin, Fig. 1) to 25–30° in the northern area (e.g. "Zone Cénomanienne", Fig. 1).

Towards the contacts of basement massifs and towards the ends of the basins these folds become progressively more accentuated and parallel to the trend of the contacts or of the structural zone.

The scale of the second phase folds is controlled by the scale of the structures it deforms. This deformation is represented by NW–SE large kilometric fold bands (= rotation bands) with internal, vertical asymmetrical sinistral folds which appear to be one of the most characteristic features of the entire chain (Fig. 1). Internally the bands are made up of a central principal rotation sub-band bordered by lateral compensating rotation zones (similar to backward rotation zones in KB) (Fig. 4) (see details in Soula 1979). These lateral compensating rotation zones may be outlined by vertical brecciation or mylonite (fault) zones limiting the bands. The sense of principal internal rotation within the bands is systematically sinistral. The compensating rotation (or offset displacement) in lateral sub-bands is dextral (Fig. 4).

In areas where there are previously schistose or

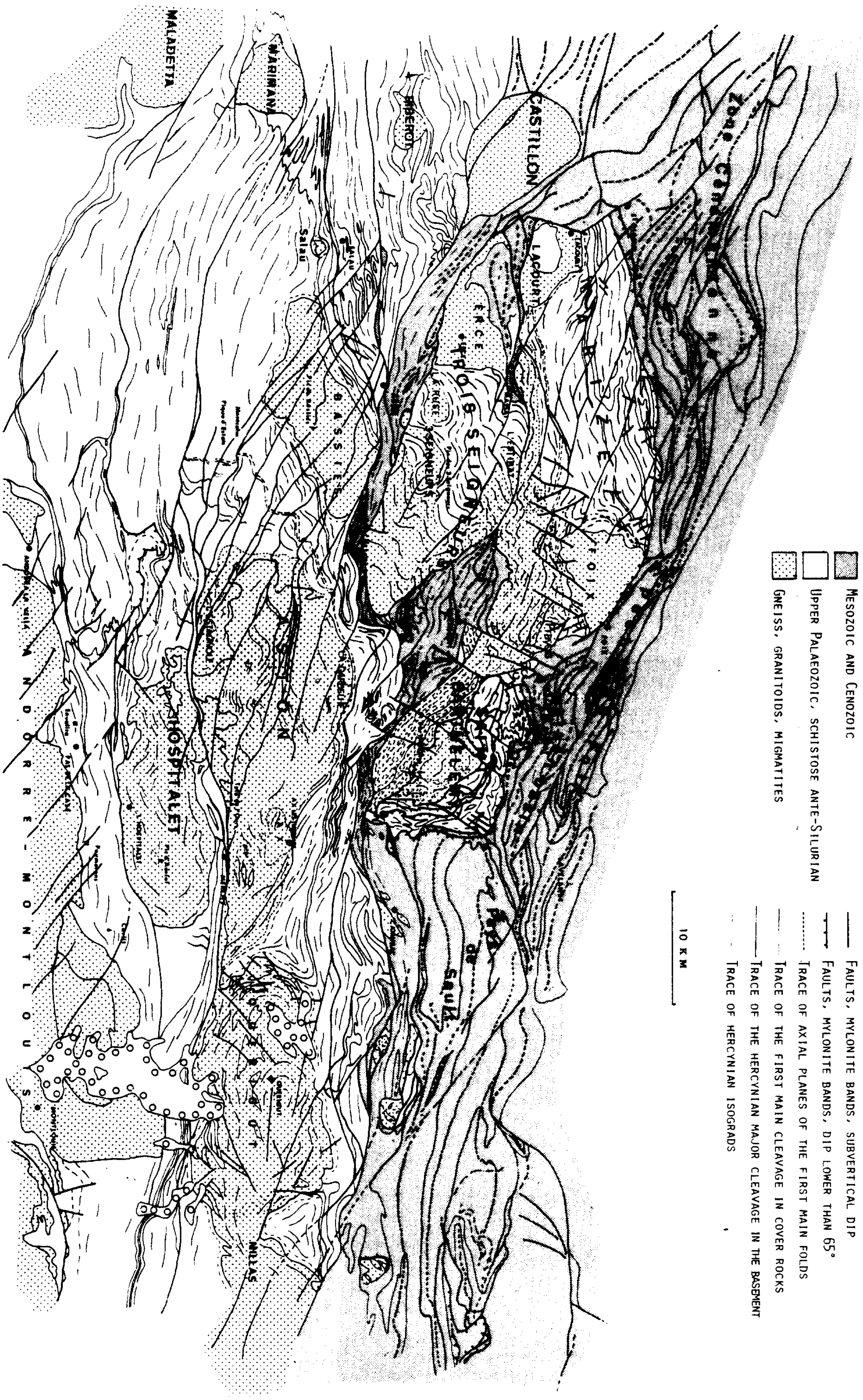

Fig. 1. Structural map of Ariège, Pyrenees.

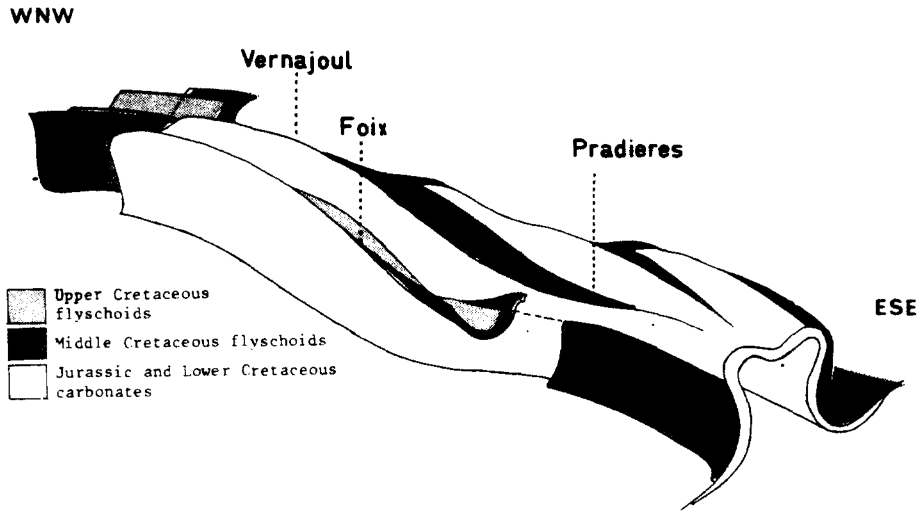

Fig. 2. The Pech de Foix antiform.

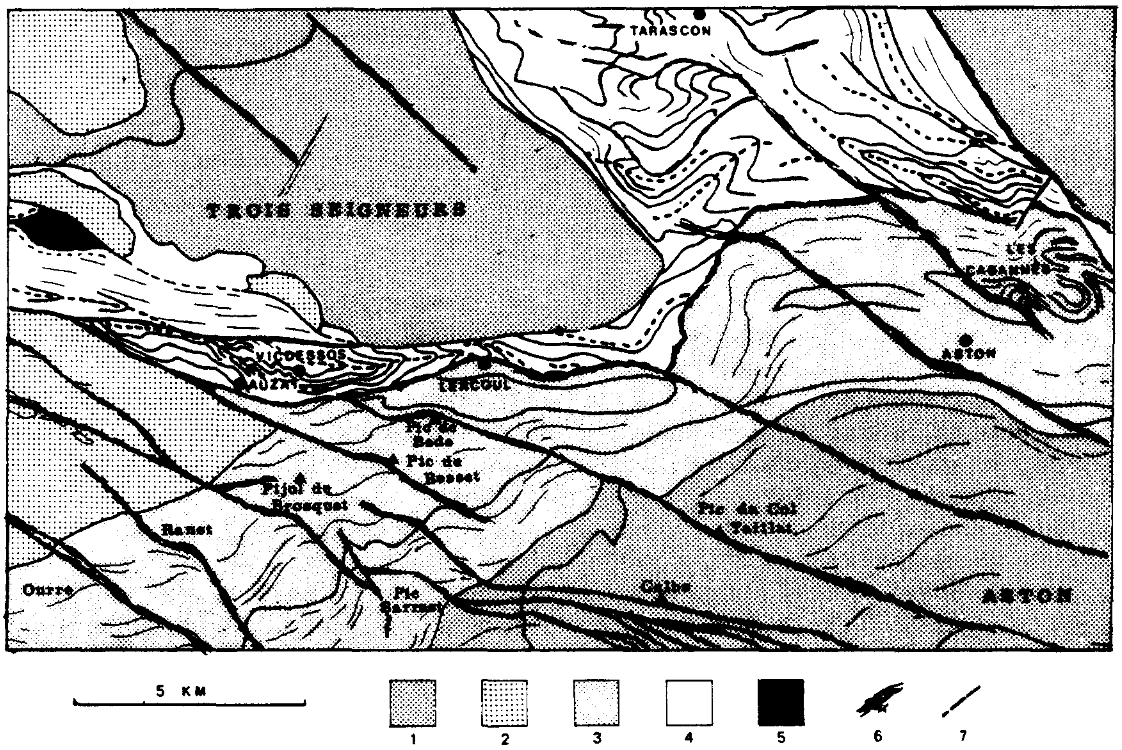

Fig. 3. Structures in the basement and cover between the Trois Seigneurs and Aston Massifs. 1: Gneiss and migmatites; 2: Granitoids; 3: Upper Palaeozoic and Ante-Silurian schistose terrains; 4: Mesozoic rocks; 5: Lherzolites; 6: Mylonite bands, faults (vertical dip); 7: Trace of the first main folds axial planes.

cleaved rocks there are involved in the second deformation several orders of fold band which have the same geometry as those seen in the major fold bands. They show successive generation of lower order (larger) bands within the megascopic bands. The lower order folds systematically deform the higher order (smaller) folds. The direction of these bands appears to have been originally NE–SW and longitudinal whatever best their order. The developed minor folds of this type are found in the Vicdessos basin where they were first observed by Choukroune (1976) (who however described them as first folds).

In the basement, NW–SE fold bands similar to those seen in the cover are found generally in continuity with them. They show similar internal rotation angles as those seen in the cover. This feature is especially clear at contacts between cover and basement (e.g. northern border of the Arize Hercynian massif (Fig. 1), or on both parts of the Vicdessos basin (Figs. 1–3). In these contact zones first Alpine folds in the cover are deformed together with the contacts and the Hercynian structures in the basement (Fig. 3). The NW–SE mylonite bands, widely represented in the basement, are related to the exaggeration of the reversal compensating rotation in lateral sub-bands.

In addition to these fold bands the Alpine deformation in the basement is marked by: (i) slip along and accentuation of penetrative Hercynian structures (Soula & Guchereau 1975); (ii) left lateral horizontal displacement (about 10–20 km) along major preexisting discon-

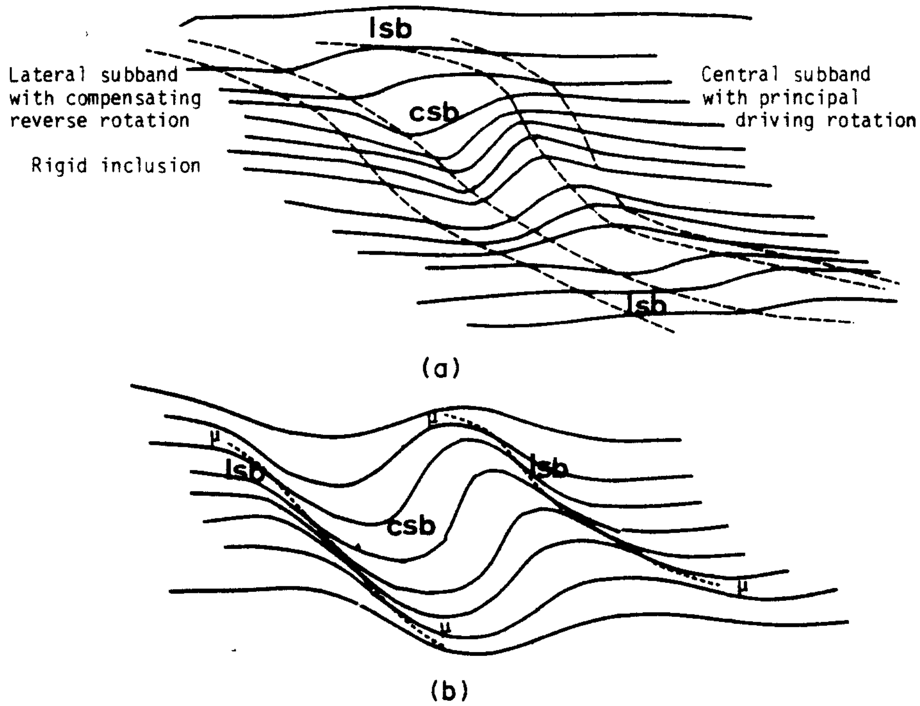

Fig. 4. (a) Formation of fold band induced by the rotation of a rigid inclusion in simple shear constructed from Ghosh & Ramberg's fig. 26 (1976). (b) Geometrical model for the development of mylonite band by the exaggeration of the reverse compensating lateral (backward) rotation caused by an increase in principal driving rotation (from a photograph of a minor fold in Vicdessos basin).

tinuities such as the Hospitalet, Merens, North Pyrenean or Col de Port faults, as shown from displacements of late Hercynian isograds or structural zones (see details in Soula 1979); and (iii) sinistral rotation of gneissic or granitic massifs, which behaved as competent inclusions in a more deformable matrix as documented in a companion paper (Lamouroux *et al.* 1980).

The development and evolution of the fold bands is directly related to this rotation of massifs as shown by the structural patterns of initially longitudinal structures which are similar to those of marker lines initially parallel to the shear plane in Ghosh & Ramberg's (1976) simple shear experiments (e.g. in particular the Bassies and Querigut massifs which are situated at, or near the contact of Mesozoic series). A similar pattern is seen in the Hercynian massifs in the western end of the chain, which rotated relative to the general direction of the structures of the chain, giving rise in the cover to the particular structures in these areas. This may be why the North Pyrenean Fault is absent in the western part of the chain.

It should be noted that longitudinal vertical faults are deformed within the NW–SE fold bands, which means that the development of the bands postdated, at least partly, the sinistral horizontal displacement along the longitudinal faults.

INTERPRETATION

As discussed in detail elsewhere (Soula 1979) all these deformation structures can be interpreted as due to a non coaxial strain with a sinistral horizontal (simple) shear component parallel to the direction of the longitudinal structural zones and of the entire chain with pure shear component with maximum shortening normal to it.

The first en échelon folds were formed by deformation acting on initially horizontal layers. They allow an estimate of the components of simple shear and pure shear. In the approach used here the folds were assumed to be parallel to the greatest extension axis of the finite strain ellipse, using a procedure of calculus similar to Ramberg's (1975) (Soula 1979; Rambach & Soula, forthcoming report). Fold shortening was estimated in cross sections normal to fold axes, using Sherwin & Chapple's method (1968) for estimating the early stage homogeneous shortening wherever possible. The data are shown on the diagram (Fig. 5) by a rectangular field corresponding to the limiting values for the folding shortening and for the angle of obliquity. For folds in the synformal flysch areas only minimum values could be estimated. The diagram shows that in all the areas studied the simple shear component is dominant, particularly in Jurassic and lower Cretaceous units but also in the synformal flysch areas.

The sinistral displacement along longitudinal faults may be interpreted as an exaggeration of this mechanism of longitudinal shearing on the boundaries of the structural zones considered as heterogeneous shear zones (Ramsay & Graham 1970).

The rotation of gneissic and granitic massifs corresponds also to a rotational strain with a sinistral horizontal simple shear component. However, in this case, the component of pure shear cannot be estimated. The simple shear component must be considered as the minimum shear, any component of pure shear shortening being opposite to the sinistral rotation of inequal inclusions so oriented. This minimum shear component may be estimated considering the massifs as rigid inclusions and using Ghosh & Ramberg's (1976) equations. However, this procedure gives also a minimum value for the simple shear component as the massifs behaved as competent but not rigid inclusions.

As deduced from their internal geometry and their relationship with the rotation of the massifs the development of the second deformation bands is also best explained by sinistral horizontal shearing. A simple analogical model was constructed considering that the band was initiated on an initial heterogeneity (or instability of any sort, such as an initial deflection) from which the band then will propagate. When a sizeable heterogeneity such as a granitic massif or a fold termination is present, the bands would develop and propagate by the rotation of the block.

This analogical model could be also used for estimating the minimum shear strain by considering the rotated central part of the layer (Fig. 4) as a rotated competent inclusion.

DISCUSSION AND CONCLUSION

The occurrence of horizontal longitudinal shearing in the Alpine Pyrenees was first proposed by Le Pichon *et al.* (1970) from geophysical studies, and this hypothesis was then developed after new geophysical and structural studies (see Choukroune *et al.* 1973, Choukroune 1976). In these interpretations, however, the shear strain was considered to be localized along the North Pyrenean Fault, the deformation outside this zone being considered as due to a non rotational strain with maximum shortening normal to the chain (Choukroune 1976). The hypothesis of the localization of the shear strain along the north Pyrenean fault zone is not supported by the present work. Our studies lead us to the conclusion that rotational strain has occurred over the entire width of the chain and that the simple shear component was an important component in all the structural zones. The North Pyrenean Fault is not considered as having more importance than the other major longitudinal faults such as the Hospitalet Fault, the Merens Fault or the Col de Port Fault. All these faults are considered as zones along which the strain is concentrated (see the value inferred from Fig. 5 for the Vicdessos basin). It should be noted that the observed displacements of Hercynian structures or isograds in the basement are of the same order of magnitude as that inferred from the estimated values for continuous deformation in the basins situated along the fault zones (Soula 1979).

The displacement inferred from minimum shear strain estimates over the entire width of the chain, i.e. $\gamma \approx 3$ to 4, is similar (210–280 km) to that obtained from the geophysical studies of Le Pichon *et al.* (1973), i.e. about 300 km, or Choukroune *et al.* (1973) (several hundred kilometres).

The time of occurrence of this shearing has been the subject of previous discussion. Choukroune (1976) has proposed a late Cretaceous age. The relations between the sedimentation and the fold development lead us to propose an age for the beginning of the shearing which is older than the Upper Albian in the north Pyrenean zone.

Studies on the relationships between tectonic structures and the development of Permian and Triassic basins have shown that sinistral horizontal longitudinal shearing was active during Permian and Triassic times (Soula *et al.* 1979). On another hand, it can be observed

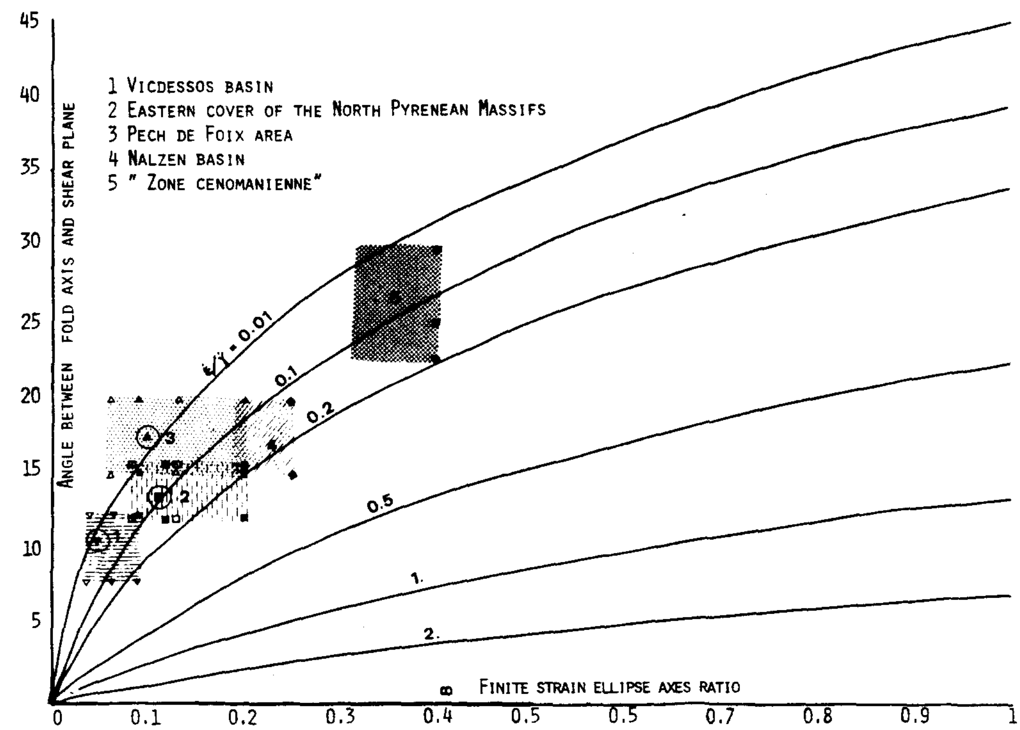

Fig. 5. Estimates of the ratio pure shear vs simple shear for F1 folds.

that in the Ariége region, the NW–SE fold bands are marked in Eocene terrains. Furthermore, at the western end of the chain, the structures accompanying the rotation of the Hercynian massifs, or deformed by this rotation, are post-Lutetian in age (Choukroune 1976). This thus implies that the shearing was still active at least in the eastern and western ends of the chain during (or after) Eocene time.

Acknowledgements—We thank D. Elliott, M. Lelubre, R. Mirouse, H. Ramberg and J. G. Ramsay for fruitful discussion on the results, D. Elliott and J. G. Ramsay have reviewed and annotated the English manuscript. J. Y. Guchereau and P. Viallard have contributed to the field work.

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