Journal of Structural Geology, Vol. 6, No. 6, pp. 721 to 726, 1984
Printed in Great Britain.

0191-8141/84$03.00 + 0.00

Thrust tectonics in the North Pyrenees

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(*Received* 25 *November* 1983; *accepted in revised form* 28 *February* 1984)

Abstract—Balanced and restored cross-sections through the central and eastern Pyrenees, constructed using both surface and borehole data, demonstrate the presence of *c*. 18km of shortening above a flat lying, N-directed Alpine décollement surface. Hangingwall diagrams show how the North Pyrenean satellite massifs are culminations within this thrust system. Pre-thrusting structures such as subhorizontal stretching lineations in the North Pyrenean Fault zone became rotated above these culminations as the North Pyrenean Fault was cut by Alpine thrusts. Stratigraphic evidence demonstrates that N-directed thrust movements occurred between mid Eocene and Oligocene time, and this is similar to the age of major S-directed thrust movements on the south side of the Axial Zone. The N-directed thrust system probably originated as a series of backthrusts to the dominant S-directed structures.

INTRODUCTION

Until recently, the Pyrenees have been regarded as a very symmetric Alpine mountain chain, with major thrust zones to the north and to the south. These zones are separated by a central belt of pre-Alpine (Hercynian) basement (the Axial Zone) (Choukroune & Seguret 1973, Solé Sugrañes 1978). Classically, both N- and S-directed thrust structures were considered to root into the North Pyrenean Fault (N.P.F.), which has been suggested as the boundary between the European and the Iberian microplates (Van der Voo & Boessenkool 1973, Choukroune 1974) (Fig. 1). Recent work in the Pyrenees has used the concept of balancing and restoring cross-sections (Hossack 1979) to demonstrate the large amount of shortening (100 km of S-directed transport, Williams in prep.), and the previously unrecognised degree of basement involvement in the S-directed structures (e.g. in the Nogueras area, Williams in press, and in the Gavarnie area, Parish 1984). This work has invalidated previously drawn sections (Fig. 1), and has demonstrated that the Axial Zone, together with the N.P.F., must be allochthonous, having been translated over the Spanish foreland by some 100 km. This work has further demonstrated that the seismically observed Moho 'step' (Daignières *et al.* 1982) cannot be related to the present day surface trace of the N.P.F., and that the interpretations put forward by these authors for the structure and geological evolution of the Pyrenees need modification. This paper aims to quantify the amount of shortening within the N-directed thrust sheets, to the north of the N.P.F., and to discuss the possible relationships between the N- and S-directed structures.

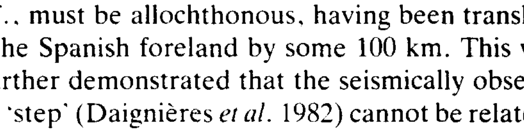

Fig. 1. Section through the Pyrenees (after Choukroune 1974) showing N- and S-directed thrusts rooting steeply into the North Pyrenean Fault (NPF). Hercynian basement is decorated.

STRUCTURE OF THE NORTH PYRENEES

The subvertical North Pyrenean Fault separates the Axial Zone from the North Pyrenean Zone (Fig. 2). It is marked by a wide (up to 5 km) zone of mylonites, generally showing a distinctive high *T*–low *P* metamorphism (Ravier 1959). This metamorphism has been dated (Albarede & Michard-Vitrac 1978) at 110 Ma. This age, together with the ages obtained from lherzolite bodies emplaced into the fault zone (Albarede & Michard-Vitrac 1978), and stratigraphic data (Choukroune 1974), suggest that the N.P.F. was active until mid-Cretaceous time, and had ceased to move as a strike–slip fault by Cenomanian times. As will be demonstrated later, this is earlier than the active thrusting, which only started during the Eocene. In some areas the N.P.F. zone is wide and complex. For this reason, the section lines cross the fault zone where the structures attributable to movement along the fault can be separated from those due to Eocene thrusting. Obviously, any deformation due to the strike–slip movement cannot be accounted for on the restored cross-sections, and hence this broadly synclinal structure has been left unrestored, and restoration has been restricted to the area north of the N.P.F. where stratigraphic continuity of the Mesozoic–Tertiary sequences exists. The North Pyrenean Zone consists of folded and thrust Mesozoic sediments with local windows into the Hercynian basement—the so-called satellite massifs (Barousse, Milhas, Trois Seigneurs, Arize and St. Barthélémy massifs). In some areas where the basement massifs are absent the North Pyrenean Zone consists of a wide zone of N-vergent asymmetric folds and local thrusts, although where the more rigid basement massifs occur this folded and thrust zone is much narrower. The northern margins of the massifs, with the exception of the St. Barthélémy massif, are marked by a post-Hercynian unconformity and almost continuous stratigraphic sequences from the Permo-Triassic through to the Upper Cretaceous. The northern margin of the St. Barthélémy massif is generally marked by a thrust that transports the Hercynian

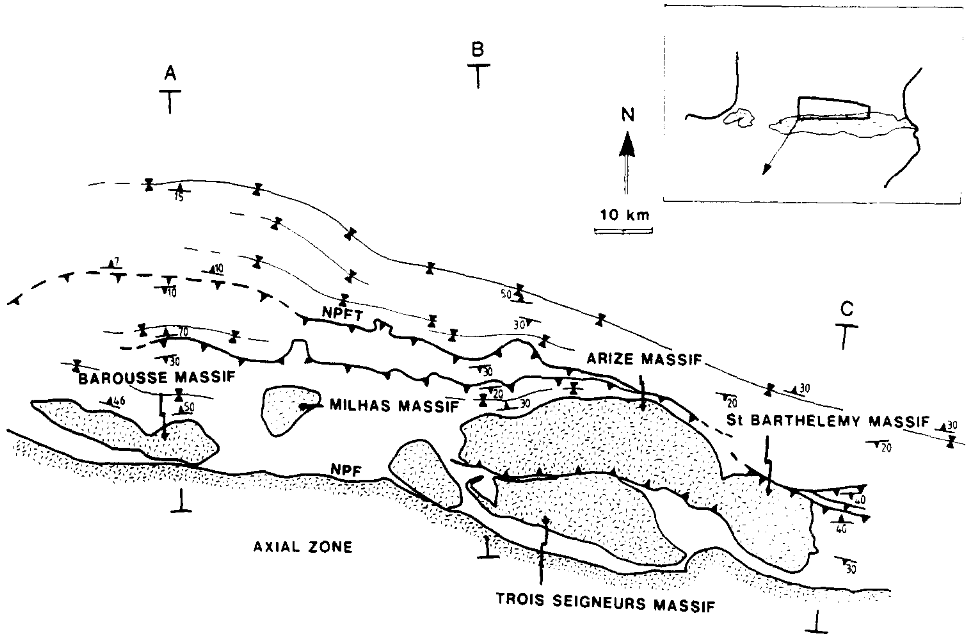

Fig. 2. Location map of the North Pyrenees showing structural subdivisions and section lines. Hercynian basement is decorated. NPF, North Pyrenean Fault; NPFT, North Pyrenean frontal thrust.

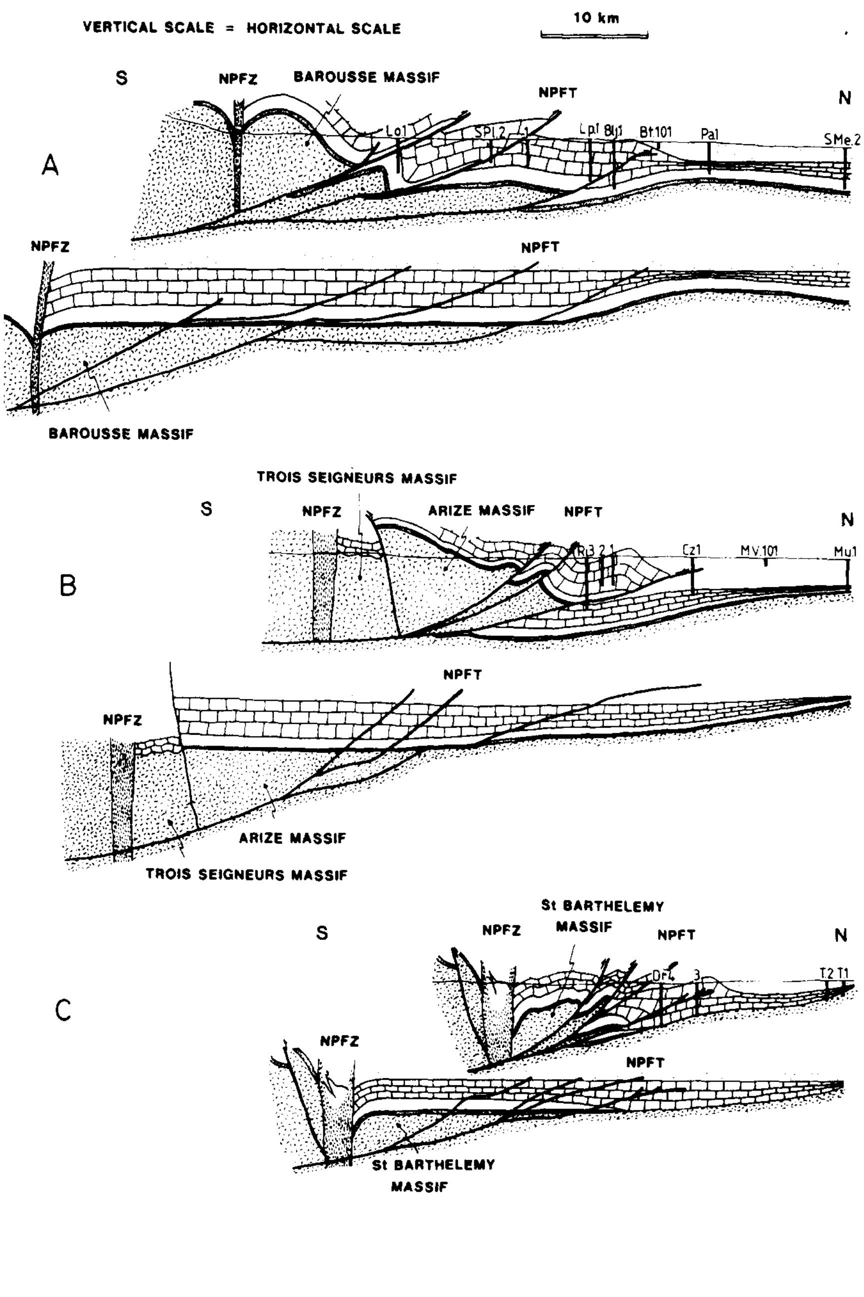

Fig 3. Balanced and restored sections along lines A, B and C (locations as in Fig. 2). The reference horizons, which are assumed to be horizontal in the restored sections, and from which the templates have been constructed are: Sections A and C, base of the Palaeocene; Section B, base of the Eocene. NPFZ, North Pyrenean Fault Zone. Lo 1, etc., boreholes.

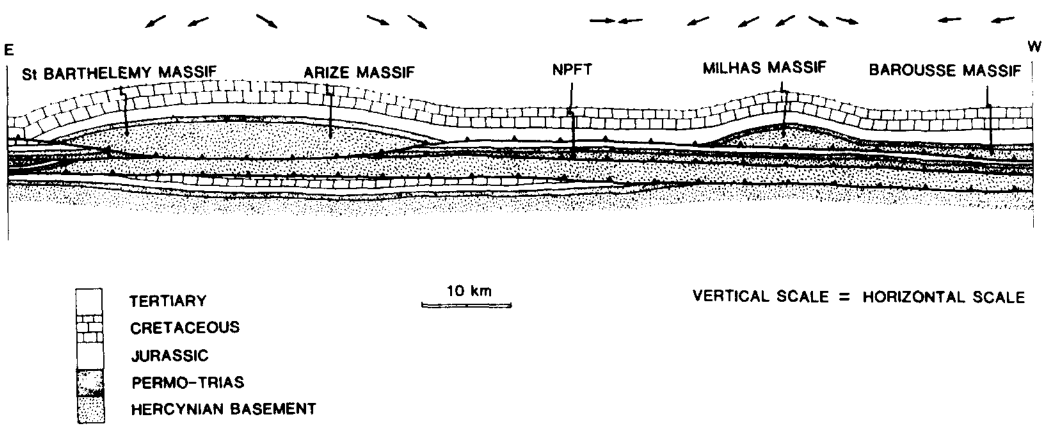

Fig. 4. Hangingwall diagram through the North Pyrenean Zone. Arrows indicate the plunge of stretching lineations on the North Pyrenean Fault.

basement and its Triassic–Jurassic cover over Mesozoic sediments. The North Pyrenean Zone is separated from the Northern Folded Foreland by the North Pyrenean frontal thrust and this generally marks the southernmost limit of exposed Tertiary rocks. The Northern Folded Foreland consists of folded and thrust Mesozoic and Tertiary sediments and pre-Mesozoic rocks are absent at the surface. The vertical limbs of asymmetric folds often form distinct topographic ridges, which are known as the Petites Pyrenees. Deformation dies out northwards into the Aquitaine basin, which consists of a Tertiary sedimentary fill.

DESCRIPTION OF CROSS-SECTIONS

Three major cross-sections (up to 70 km in length) are considered (Fig. 3). They run from the Axial Zone into the Aquitaine basin, to the north of the limits of recognized deformation (Fig. 2). The section lines are approximately 50 km apart, and have been linked with a hangingwall diagram (Fig. 4). Each of the section lines was mapped in detail, at a scale of 1 : 10,000. Well exposed section lines were chosen, generally along road sections, and practically complete coverage of structural data was obtained. Projection along strike of data was minimized as much as possible, and was never more than 0.5 km. The average spacing of surface data points along the section lines was in the order of 500 m, and for this reason details of this data have been omitted from Fig. 3. Published borehole data (B.R.G.M. *et al.* 1973) were used to constrain further the geological structure at depth. The position of these boreholes is indicated on Fig. 3, and data have not been projected along strike from boreholes by more than 1 km.

Thrust transport direction

Structural orientation data (Fig. 5) for the three section lines show a remarkably consistent mean fold axis direction, approximately E–W. The spread of points is due to the locally steep (up to 40°) plunges on individual folds, either W or E. Because data were collected over a large area, and are remarkably consistent, the mean fold vergence direction is taken to be the approximate thrust transport direction (that is due N). Local slickensiding of thrust surfaces is consistent with this interpretation.

Section restoration

Line-length balancing techniques (Hossack 1979) were used to construct the restored cover sequences. Area balancing was then used to constrain the shape of the basement wedges. Permo-Triassic and Jurassic sequences show a relatively consistent thickness over the area but this is not the case with the Cretaceous sequences. Local, abrupt thickening of the Cretaceous succession (e.g. at borehole Blj1, section A, Ri3 section B and Dr3 and Dr4, section C) may be interpreted in terms of tectonic thickening by repetition of the Cretaceous. It is obvious, however, that the large degree of thickening from north to south in each section cannot be satisfactorily explained by this method, particularly when unthrust stratigraphic sequences can be measured at the surface as in the North Pyrenean Zone, and compared with the measured thicknesses in boreholes to the north. These large-scale variations in stratigraphic thicknesses which occur over the north Pyrenees are assumed to be due to variations in pre-thrust thicknesses,

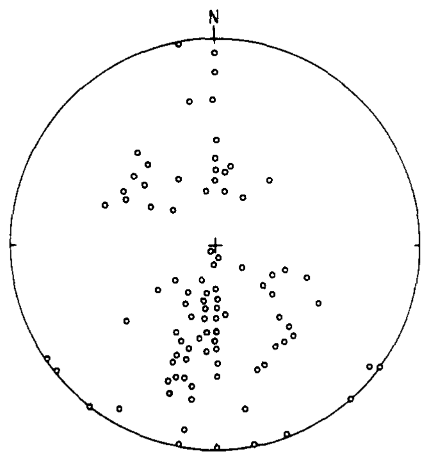

Fig. 5. Wulff net showing poles to bedding for all section lines. Mean fold axis is east–west.

and have been taken into account in the construction of templates for section restoration. For the purpose of these sections, this variation in stratigraphic thickness has been regarded as a gentle thickening, although it seems possible that this change took place through the development of discrete growth faults defining deeper sedimentary basins during a period of subsidence in the Cretaceous. Borehole data from section C shows the absence of large parts of the Cretaceous, Jurassic and Triassic successions. This again could be related to the formation of localized sedimentary basins during the early Mesozoic. These features have been accounted for in the restored sections.

In each section, the sole thrust necessary to produce deformation to the north of the frontal thrust is not exposed at the surface. This thrust must either 'die' into a region of ductile thickening or folding within the lower Tertiary units (cf. Jones 1982), or it became emergent and was subsequently covered by post-thrusting sediments. In the construction of the sections the former model is assumed.

In each section, the difference in length between the pin line and the North Pyrenean Fault Zone in balanced and restored sections, and thus the amount of shortening, is in the order of 18 km. This shortening is relatively well constrained by the borehole data, and the continuity of surface data. Major uncertainties occur in the position of footwall cutoffs to the sole thrust. Footwall cutoffs have been constructed to produce compatible linelengths, and area balancing values for the ductile bead (Elliott 1976a) in front of the sole thrust tip.

The hangingwall diagram (Fig. 4) is a $V = H$ scale section drawn parallel to the strike of the thrust belt, looking down the movement direction. It demonstrates how individual thrust surfaces cut up and down stratigraphic section along their strike. It also demonstrates the lateral continuity of individual thrust sheets, which is probably a result of the relatively small degree of transport of each sheet. From the unrestored sections it can be seen how the displacement on individual thrust faults varies along strike (Fig. 6). In the absence of major lateral or oblique ramps on which the displacement could be transferred to a higher level, the change in the amount of displacement can best be explained in terms of a 'bow-and-arrow' type model (Elliott 1976a). Displacement on a single thrust fault is at a maximum at the centre of Elliott's 'bow', and dies out laterally towards the fault tips.

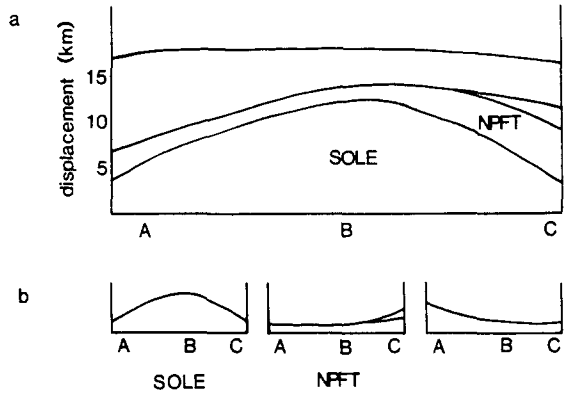

Fig. 6. Strike distance: displacement plots; (a) cumulative plots showing similar total displacements, (b) plots for individual thrust sheets showing 'bow-and-arrow' geometries.

DISCUSSION

Age of thrusting

Inclusion of lowermost Oligocene rocks in the northernmost folds indicates that deformation was active at this position during the early Oligocene (*c*.37 Ma), and possibly continued until late Miocene time (Crouzel 1965). Local unconformities, however, suggest that deformation was occurring in the Northern Folded Foreland during the mid-Eocene (*c*.45 Ma), and that the deformation front migrated from south to north (a distance of about 16 km) over this period. This yields a mean propagation rate of the deformation front of around 0.1 cm a^{-1}.

Relationship between thrusting, the N.P.F. and the satellite massifs

Restored sections (Fig. 3) show that the sole thrust to the N-directed thrust sheets must cut the N.P.F. at a depth of approximately 12 km. Thus the N.P.F. has been carried piggy-back on these thrusts, and the present surface expression of the fault represents its position within the uppermost thrust sheet. Culminations and depressions (Dahlstrom 1979) are produced by the transport of thrust sheets over lateral or oblique ramps as shown on the hangingwall diagram. Mylonites generated along the N.P.F. during the early strike–slip phase of deformation have generally subvertical foliation and subhorizontal E–W stretching lineations, defined by the elongation of calcite grains, and the alignment of metamorphic minerals (notably scapolite and tremolite) that grew during the strike–slip event. Only rarely are these lineations perfectly horizontal, however, and they commonly plunge at up to 40° W or E. These plunge variations, when superimposed on the hangingwall diagram (Fig. 4), show a pattern that relates closely to the position of lateral/oblique culmination walls and thrust flats. Originally horizontal lineations have been rotated over culminations to produce the observed plunge variations. This is further evidence that the N.P.F. is cut at depth by the N-directed thrusts.

The presence of culminations and depressions within the N-directed thrust system caused folding of the post-Hercynian unconformity over the culminations. Erosion through the northern thrust sheets has produced 'windows' into the basement, which are known as the basement massifs. It should be noted, however, that the basement massifs form an integral part of the thrust complex and are totally allochthonous.

Relationships between the N- and S-directed structures

Recent work has suggested that many of the steep faults with dip–slip movement in the Axial Zone are Alpine in age. This has been partly confirmed by dating of the movement of one such fault, the Merens Fault (McCaig, abstract presented to the Tectonic Studies Group, Cardiff, December 1982). In view of the Alpine age of these faults, it seems possible that these steep dip–slip faults are oversteepened S-directed Alpine thrusts. In the N.P.Z., the steep fault between the Arize and Trois Seigneurs massifs (section B) and a steep dip–slip fault on the north side of the Axial Zone (section C) are possible candidates for oversteepened Alpine thrusts. The restored sections demonstrate that the steep faults must be cut by, and hence predate, the N-directed structures. A corollary of this is that the N-directed thrusts postdate the oversteepening of the S-directed thrusts.

Three possible models for the generation of the N-directed structures are considered here (Fig. 7). (1) A topographic high (the Axial Zone), possibly generated by ramp climb on S-moving thrusts, will have a tendency to spread gravitationally (Elliott 1976b). This will induce both northward movement and further southward movement. (2) Accommodation structures may be induced by the oversteepening of S-moving thrusts (cf. out of the syncline thrusts, Dahlstrom 1970). These are necessary to conserve bed lengths in deformed and restored sections. (3) At some time late in the southward thrusting event a system of backthrusts may have initiated. These would propagate northwards, and cut through already oversteepened, S-directed thrusts, and indeed may have been partly responsible for their oversteepening.

All three models imply a close relationship between the two thrust zones, and necessitate similar ages of movement. Thrusting in the south Pyrenees was demonstrably active from mid Eocene to Oligocene time (Mattauer & Henry 1974), which is comparable with these models. The gravity spreading model (1) necessitates the development of a surface slope simultaneously with the thrusting. The presence of marine Pliocene at *c*.2000 m in the E. Pyrenees suggests that the uplift of the Pyrenees did not occur until at least end-Pliocene times, which is considerably later than the cessation of thrusting in both the north and south. Thus, it is unlikely that major relief was present during the Palaeogene, and hence the necessary conditions for gravity spreading were lacking. The amount of N-directed thrusting (18 km) is almost certainly too great for them to be accommodation structures induced by oversteepening of S-directed thrusts (model 2). The generation of backthrusts is therefore considered the most likely model. This predicts both the correct order of events, and the observed relationship between the oversteepened S-directed thrusts and the later N-directed back thrusts.

In view of this conclusion, the Pyrenees must be reconsidered as having formed mainly as a result of N–S shortening on a linked thrust system. The approximate geographic correlation between the present day trace of

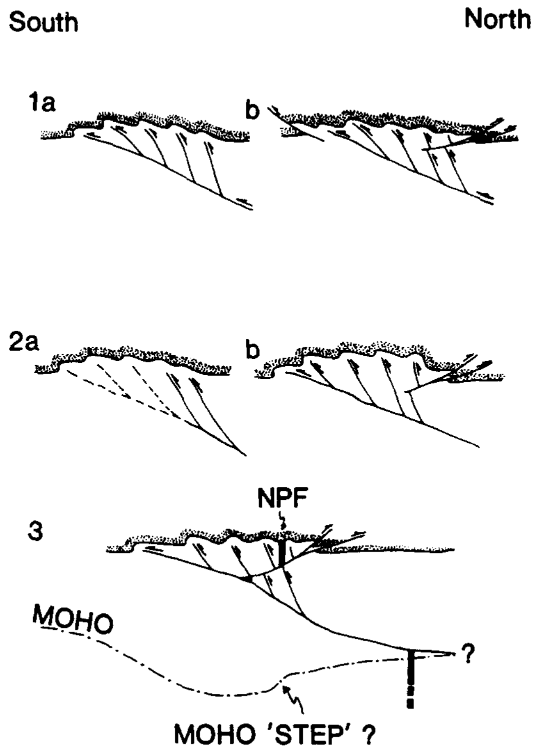

Fig. 7. Models for the formation of the N-directed thrusts: (1) gravity spreading from an Axial Zone culmination; (2) accommodation caused by oversteepening of early S-directed structures, necessary to preserve linelengths and (3) backthrusts on a dominantly S-directed linked thrust system. In this model the Axial Zone is interpreted as a large-scale 'pop-up' structure. Unless the MOHO is regarded as the basal décollement of the thrust system, the lithosphere must have been subducted northwards under Europe.

the N.P.F. and the Axial Zone 'pop-up' may be more than coincidental however, and the strike–slip event may have resulted in a major crustal or lithospheric weakness which was subsequently exploited during the Eocene compressional phase. During this compressional phase the crust was shortened by thrusting, whilst the lithosphere must have been subducted under the European continent.

CONCLUSIONS

(1) Total translation on the N-directed thrust structures is of the order of 18 km. (2) The N-directed thrusts must cut the N.P.F. and cannot root into it. (3) N-directed thrusting occurred during mid-Eocene to Oligocene time. (4) The North Pyrenean satellite massifs are culminations over N-directed thrusts. (5) Early structures in the N.P.F. zone have been rotated over these culminations. (6) The most likely origin of the N-directed thrusts is as backthrusts on the dominant S-moving system, the displacement on which is of the order of 100 km.

Acknowledgements—The constructive criticisms of Dr G. D. Williams of an early draft of the manuscript were greatly appreciated. Comments by Dr N. J. Soper and an anonymous referee were of much assistance in subsequent revisions. The work was carried out during tenure of NERC grant GT4/81/GS/108.

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