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Thrust tectonics in the south central Pyrenees

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Abstract—Surface structural data and published stratigraphies are combined to construct two balanced and restored sections through the Nogueras Zone of the south central Pyrenees. The allochthonous Nogueras Zone units are interpreted as the foreland-dipping margin of a major antiformal stack in the Palaeozoic rocks of the Pyrenean Axial Zone. Their structural evolution is summarized in a hangingwall sequence diagram. This reinterpretation of the Nogueras Zone is incorporated into a new N–S balanced and restored section from the centre of the Pyrenean Axial Zone to the Ebro Basin. A classical 'Rocky Mountains' piggy-back thrust model is employed and the resulting section is a significant departure from those previously published. It is argued that 'gravity gliding' has never been an important mechanism in the Alpine Pyrenees. Section restoration casts doubt on the correlation of the surface expression of the North Pyrenean Fault and the seismically detected Moho step beneath it.

GEOLOGICAL SETTING

THE PYRENEES form an almost linear mountain chain extending for approximately 1000 km from the Cantabrians in northern Spain to Provence at their eastern extremity (Fig. 1). There is a symmetrical distribution of structural zones about a central Axial Zone comprising Precambrian? and Palaeozoic rocks (Choukroune & Seguret 1973). In the north, post-Hercynian rocks of the North Pyrenean Zone and Northern Folded Foreland have undergone N-directed thrusting and are typified by N-verging asymmetric folds (Choukroune 1969). To the south of the Palaeozoic Axial Zone, the South Pyrenean Zone and Southern Folded Foreland have undergone S-directed thrusting. Décollement-tectonics are typical, with post-Triassic strata being thrust S for up to 50 km and showing little internal deformation (Seguret 1970).

Allochthonous units to the south of the Axial Zone are formed of Mesozoic and Tertiary strata detached from their basement and moved on a décollement level of Upper Triassic evaporites (Solé Sugrañes 1978). The Montsec Nappe (Seguret 1970) is the central unit of this southern allochthonous zone. Garrido-Mejias (1972) suggested that the Montsec Nappe was the oldest allochthonous unit of the south Pyrenees and that it 'glided' southward into a sedimentary basin to be covered by disconformable Cuisian sandy marls. This view was modified after data from deep oil wells became available proving that the Montsec Nappe was emplaced in the Late Eocene (Choukroune & Seguret 1973).

At the exposed rear of the Montsec sheet (Fig. 2), there exists a complex zone of Devonian to Triassic rocks called the Nogueras Zone (Dalloni 1910). This zone comprises several structurally distinct units that were originally thought to be allochthonous and thrust S (Dalloni 1910). Numerous later workers favoured an upfaulted and essentially autochthonous origin for the Nogueras Zone (Jacob *et al.* 1927, Misch 1934, Mey *et al.* 1968). It is now widely accepted that the Nogueras units are allochthonous and have been thrust S from the Palaeozoic Axial Zone (Seguret 1964, Choukroune & Seguret 1973, Zwart 1979).

In this paper, two new N–S structural sections from Axial Zone to Nogueras Zone are presented and a hangingwall sequence diagram for part of the Nogueras Zone is given. These, coupled with a long balanced and restored section from the Axial Zone across the Montsec thrust sheet to the Ebro Basin, are used to provide a thrust tectonics model for the south central Pyrenees. The term Montsec thrust sheet is preferred as 'nappe' has erroneous connotations of major overfolds.

STRATIGRAPHY OF THE NOGUERAS ZONE AND MONTSEC THRUST SHEET

The post-Hercynian stratigraphy of the Nogueras Zone is based largely on the works of Mey (1968) and Mey *et al.* (1968) and it is summarized in Fig. 3. The thrust units of the Nogueras Zone comprise pre-Hercynian, intensely cleaved rocks (Devonian and Carboniferous) and post-Hercynian cover rocks of Upper Carboniferous, Permian and Triassic age (Zwart 1979). The post-Hercynian Carboniferous rocks (Westphalian D and Stephanian) are only locally developed, are

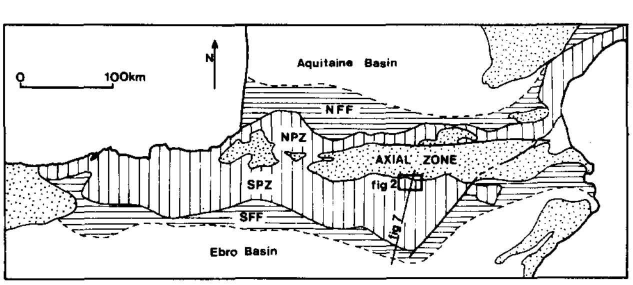


Fig. 1. Structural zones of the Pyrenees (after Choukroune & Seguret 1973). Location of Fig. 2 and cross section (Fig. 7) are shown. NFF, northern folded foreland; SFF, southern folded foreland; NPZ, north Pyrenean zone; SPZ, south Pyrenean zone. Hercynian basement stippled, north and south Pyrenean zones are vertically lined and the northern and southern folded forelands are horizontally lined.

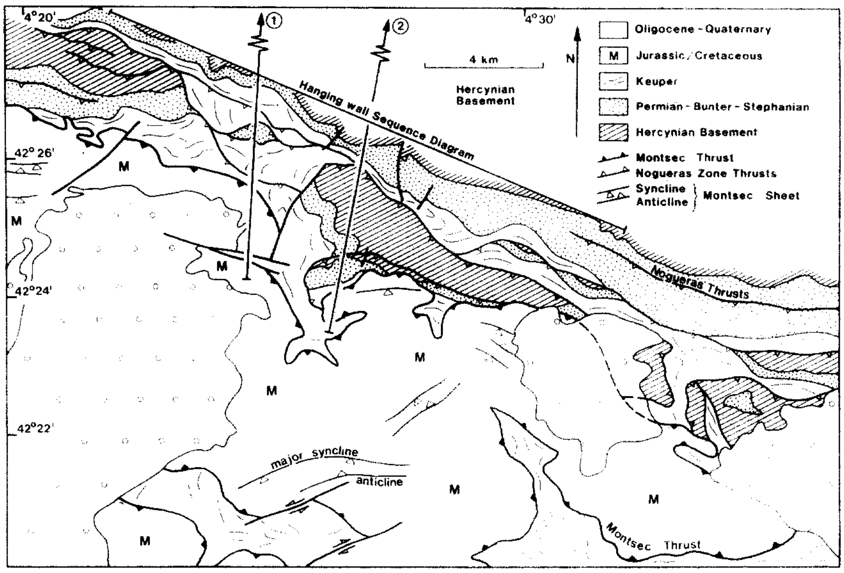


Fig. 2. Generalized geological map of part of the south-central Pyrenees to show location of Nogueras Zone sections Figs. 5(a) & (b) and the extent of the hangingwall sequence diagram. Map modified after Mey (1968).

strictly non-marine and largely fluvial. Volcanic strata occur above Westphalian D and below Stephanian age rocks. Permian rocks are monotonous grey or red calcareous mudstones, siltstones and sandstones that are locally developed and are overlain unconformably by fluvial red beds of the Bunter. The Middle and Upper Trias is a tectonic mélange comprising blocks of dark grey to black micritic limestone, dolomite, marl, cargneule and variously sized bodies of 'ophite'—a crystalline basic rock. These blocks are non-systematically oriented and set in a matrix of brecciated evaporite mylonite. This mélange is a zone of about 200 m average thickness, and it will be shown later that this is the floor thrust of the Montsec thrust sheet and roof thrust of the sub-Montsec duplex.

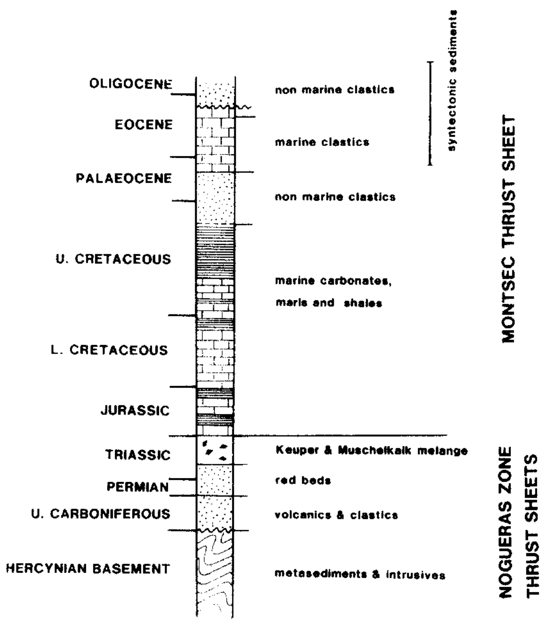


Fig. 3. Summary of the stratigraphies involved in thrust tectonics of the south central Pyrenees (after Mey 1968 and Mey *et al.* 1968). Stipple, siliciclastics; horizontal lines, marls and shales; block pattern, carbonates and calcarenites. Note that geological period or epoch boundaries do not usually coincide with major lithofacies changes.

In all structural sections, the Permian-Bunter is regarded as a marker unit of 250 m thickness and the Westphalian D-Stephanian unit is ignored because of its restricted development in localized basins. The Middle–Upper Triassic is regarded as a tectonic mélange of 200 m thickness.

The Montsec thrust sheet consists of post-Triassic rocks of Late Jurassic to Late Eocene age (Fig. 3). Along the line of section (the Ribagorzana Valley) there is an almost complete Cretaceous, Palaeocene and Eocene succession dominated by carbonate rocks and punctuated only by minor disconformities in the Lower–Mid Cretaceous (Solé Sugrañes 1978). It is interesting to note that Eocene sedimentation in the Tremp-Graus basin, on top of the Montsec thrust sheet, took place continuously and was controlled and modified by motion of the thrust sheet (C. Atkinson pers. comm.). The maximum thickness of Cretaceous and Palaeocene of the Montsec sheet (2500 m) occurs beneath the syntectonic Eocene sediments of the Tremp-Graus basin. The basin is controlled by the ramp-flat geometry of the Montsec thrust. Two kilometres south of the Montsec ramp the Cretaceous is dramatically thinned to only 500 m in the Milà anticline (Garrido-Mejias 1972).

STRUCTURE OF THE NOGUERAS ZONE

Seguret (1970) regarded the thrust units of the Nogueras Zone as a series of synformal anticlines and the downward facing 'noses' of fold nappes. It is for this reason that he coined the term 'têtes plongeantes de Nogueras'. The Nogueras Zone units were reported to have a S-dipping, Alpine-age cleavage in the Triassic rocks (Seguret 1970) and this cleavage passes gradually into a gently N-dipping spaced cleavage in the 'autochthonous' Axial Zone Palaeozoics. For this reason, Choukroune &

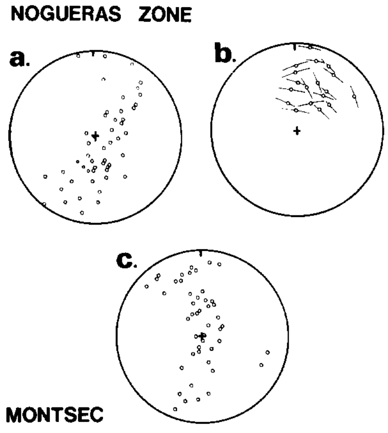
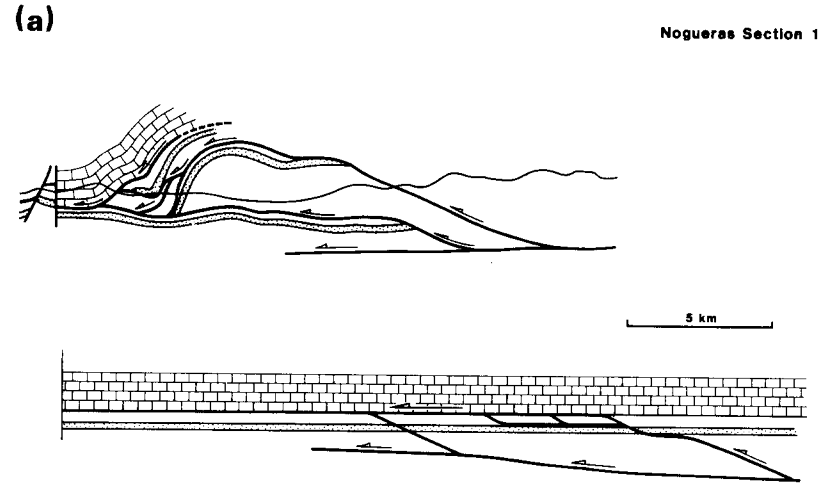


Fig. 4. Equal-area stereonets. (a) Poles to bedding in Permo-Triassic red beds of the Nogueras Zone. (b) Thrust faults (plotted on partial great circles) and associated slickenside striations. All thrusts cut through steeply dipping red beds of the Nogueras Zone. (c) Poles to bedding in the Montsec thrust sheet.

Seguret (1973) proposed that the emplacement and refolding of the Nogueras units correspond to a single, continuous deformation event—a view entirely supported in the present paper.

In plan view, the Nogueras units form a consistent pattern, with steep thrust faults on their northern margins overthrusting Axial Zone Palaeozoics and/or Permo-Triassic red beds above the Mid-Upper Triassic mélange (Fig. 2). The Permo-Triassic red beds provide abundant evidence of S-younging and this is corroborated by stratigraphic evidence. Superimposed on the downward-facing (Shackleton 1958) structures of the Nogueras Zone, steeply dipping red beds exhibit open folds with horizontal or gently plunging axes and gently dipping axial surfaces (Fig. 5). These folds occasionally exhibit a weak Alpine cleavage (Choukroune & Seguret 1973) in their axial planes. Bedding planes show slickenside striations approximately normal to fold hinges indicating a flexural slip fold mechanism (Ramsay 1967, p. 391) and the overall axis for the zone plunges at a shallow angle to the ENE (Fig. 4a). Thrust faults with



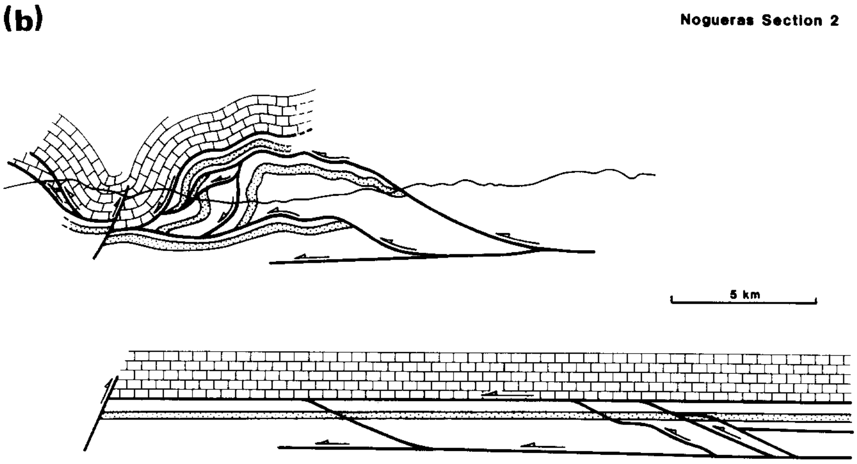


Fig. 5. (a) Nogueras Zone section 1 and restored section. (b) Nogueras Zone section 2 and restoration. For location of cross sections, see Fig. 2. The Nogueras Zone is interpreted as the foreland region of a major antiformal stack in the Axial Zone. Stipple, Permo-Triassic red beds; block ornament, Jurassic and Cretaceous.

associated slickenside striations commonly cross-cut bedding in the red beds, and these may be used to indicate approximately the direction of thrust transport (Fig. 4b).

Jurassic and Cretaceous limestones and shales visible in the exposed rear of the Montsec thrust sheet are deformed into major anticlines and synclines as a result of Nogueras Zone thrusting (Fig. 4c). In certain regions, 'out-of-sequence' thrusts (Butler 1982a) cut through the Montsec floor thrust. Further south in the Montsec thrust sheet, such deformation is absent. To the north of the Nogueras Zone, in the presumed autochthonous Axial Zone, small outliers of Permo-Triassic red beds are preserved in 'pinched-in' synclines that are asymmetric, verge S and have a N-dipping axial-planar cleavage. In other regions of the Axial Zone, Permo-Triassic red beds are overthrust by Palaeozoic rocks of the Axial Zone. These lines of evidence lead to the conclusion that the Nogueras Zone is the southerly region of a major antiformal stack (Figs. 5a & b) and as such represents a foreland-dipping duplex (Boyer & Elliott 1982). Similar structures have been observed on a small scale at Dundonnel in the Moine thrust zone (Elliott & Johnson 1980) and postulated on a much larger scale in the Aiguilles Rouges Massif of the Swiss Alps (Boyer & Elliott 1982). In order to accommodate the basement thrusting, and the building of the Nogueras antiformal stack, significant backthrusting must have taken place within the Montsec sheet. Similar intercutaneous thrusting has been described in the Alberta syncline by Jones (1982).

The presence of a major antiformal stack in the south of the Pyrenean Axial Zone with associated deformation of its cover (the Montsec thrust sheet) argues strongly for a piggy-back thrust sequence. Assuming piggy-back thrusting, a hangingwall sequence diagram (Fig. 6) may be constructed. The Montsec floor thrust is the highest in the sequence and was therefore first to move and it must ultimately root in the basement to the north. It is located within the Mid-Upper Triassic mélange which acts as a 200 m thick shear zone and is the classical décollement level of the south Pyrenees. Subsequent thrusts cut down along lateral or oblique ramps into Palaeozoic basement. Basement wedges are carried over frontal ramps on to flats and deform their cover accordingly. Deformation of the cover takes the form of major culminations and, in one instance, a hangingwall drop-fault (Fig. 6) (Butler 1982a, b).

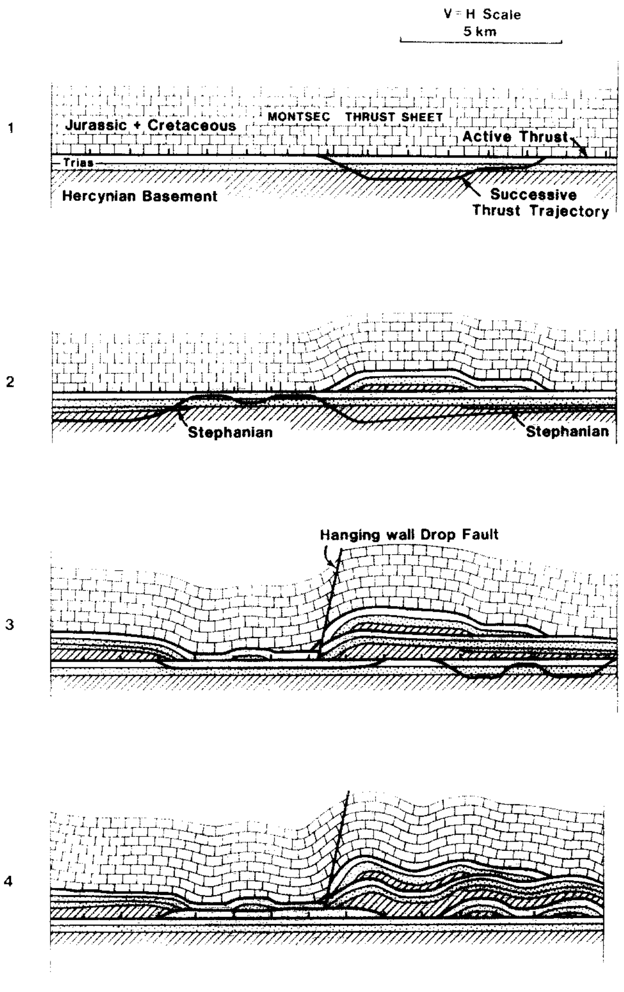


Fig. 6. Hangingwall sequence diagram for the thrust stack in the Nogueras Zone. Extent of this diagram is shown in Fig. 2.

STRUCTURAL SECTION—SOUTH CENTRAL PYRENEES

The cross section of the South Central Pyrenees (Fig. 7) is based on accurate field recording of surface data and subsurface interpretation based on techniques developed in areas of well-constrained thrust belt sections, e.g. the Canadian Rockies. Geometric reasoning based on present day knowledge of thrust systems (Boyer & Elliott 1982) has allowed an economical description of the observed structural geometry and the section presented is a significant departure from the classical sections of Choukroune & Seguret (1973). Numbers on the cross section (Fig. 7) are referred to at specific points in the text (below). The section has been restored by bed-length techniques from the pinline to P using the top Palaeocene as a horizontal datum and from P to Q using the top of the Bunter as a horizontal datum.

Thrusts 1 and 2 were active first, and emplaced Palaeozoic Axial Zone rocks over Triassic red beds at 2. These thrusts dip N and join at or near the postulated floor thrust. They were probably oversteepened during the formation of the Axial Zone antiformal stack (3), but it is essential that they truncate at depth the large Hercynian granodiorite pluton of Maladeta; this pluton, therefore, is entirely allochthonous as is the whole southerly portion of the Axial Zone. Thrust 2 at point Q cross-cuts Jurassic/Cretaceous rocks (projected along strike on to the present section). A splay from thrust 2 at 4 roofs into the Mid-Upper Triassic shear zone, and this activated movement of the Montsec thrust sheet on its floor thrust.

The Nogueras Zone duplex (5) is developed in only the uppermost levels of the Axial Zone and its Permo-Triassic cover (see Fig. 6) and all slip on its thrusts is

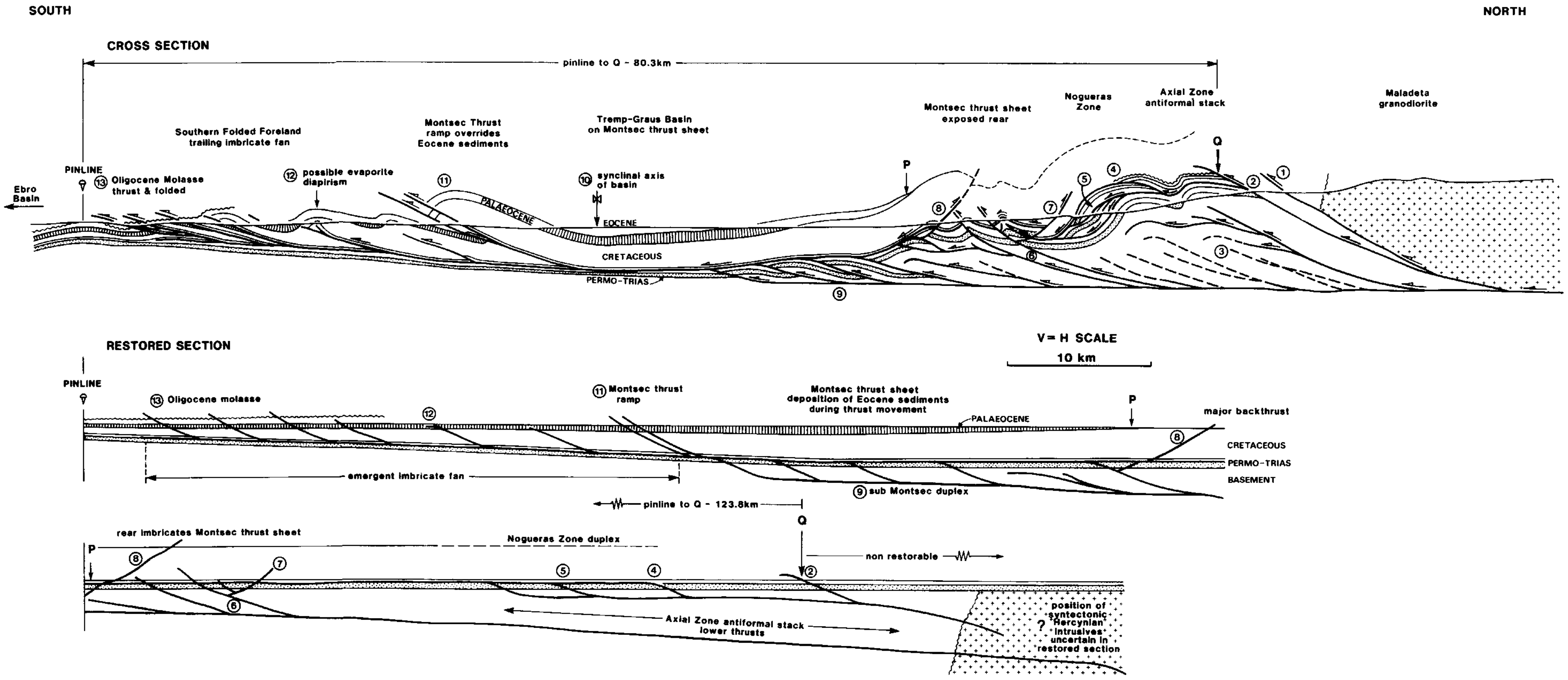


Fig. 7. Structural cross section and partial restoration of the South Central Pyrenees. Numbers and letters on this section are referred to in the text. Two stratigraphic markers are shaded; Permo-Triassic red beds are stippled and Palaeocene has orthogonal lines. The main sub-Montsec detachment is within a Triassic evaporite mélange.

transferred to the Montsec floor thrust. The Axial Zone antiformal stack (3) was developed by utilizing sequentially lower and more southerly thrust faults, the majority of which are blind, do not transfer slip into the Montsec floor thrust, and serve only to thicken the southerly portion of the Axial Zone.

Further southerly migration of thrusting (6) produced deformation at the exposed rear of the Montsec thrust sheet with the formation of the rear imbricate slices. Deformation at the rear of the Montsec thrust sheet includes asymmetric folds (Fig. 4c), and out-of-sequence thrusts that cross-cut the Montsec floor thrust. Two backthrusts (7 and 8) also cross-cut the Montsec floor thrust. A sub-Montsec duplex (9) is postulated to explain the southerly dip of the northern part of the Montsec thrust sheet, and all displacement is transferred into its roof thrust.

The gross geometry of the Montsec sheet and of the Tremp-Graus sedimentary basin above it is defined by the flat and ramp at the base of the sheet. Where the Montsec thrust cuts up section through Jurassic to Eocene rocks, a geometrically necessary syncline is developed, and this becomes the early to mid Eocene depocentre of the basin (10). Detailed sedimentological work has shown that Cretaceous rocks became exposed at the Montsec thrust ramp and sediment began to be shed back into the basin during the early Eocene. The Montsec thrust ramp involves two splay faults from the major ramp.

South of the Montsec ramp a trailing imbricate fan (Boyer & Elliott 1982) is developed, in the region classically known as the Southern Folded Foreland. Apparently intrusive relationships of Keuper evaporites coupled with omission of stratigraphy indicate possible evaporite diapirism (12). Deformation of Upper Eocene and Oligocene molasse signifies the presence of an emergent imbricate fan in this southerly region (13).

The current distance from the pinline to point Q is 80.3 km and on the restored section is 123.8 km. This shortening of 43.5 km must be regarded as a minimum and is almost certainly an underestimate for four main reasons. (1) A small amount of deformation may be observed to the south of the pinline in the Ebro Basin. Therefore this is not the true foreland. (2) The amount of transport on the Montsec thrust flat is very difficult to estimate and therefore, overthrusting at the Montsec ramp (11) is estimated and shown schematically. (3) Bed length restoration is impossible to the north of point Q as stratigraphic control is lost. A simple area balance shows that the formation of the Axial Zone antiformal stack accounts for at least 45 km shortening. The southern intrusive contact of the Maladetta granodiorite has been transported southwards for at least 88 km, therefore. (4) Intercutaneous thrusting associated with the Nogueras antiformal stack (cf. Jones 1982) involves shortening in basement sheets but not in the cover.

DISCUSSION

The interpretation of the south central Pyrenees in terms of a typical Rocky Mountains type, piggy-back thrust sequence provides an efficient way to explain the observed structural geometries. It is clear that all the thrust structures discussed are Alpine in age as all involve post-Hercynian rocks, and that these structures have significantly modified the Hercynian 'basement'. This fact is emphasized by the proposal that the late Hercynian Maladeta granodiorite is entirely allochthonous and has been thrust southwards by ~88 km.

The classical view of Alpine tectonics in the Pyrenees is that the upper thrust sheets were emplaced by gravity gliding on a décollement horizon of Triassic evaporites and that this period of nappe movement was followed by a compressive phase (Choukroune & Seguret 1973, Solé Sugrañes 1978). The present model argues against the initial phase of gravity gliding, as all sole thrusts were initiated as horizontal or hindward dipping surfaces. The presently observed foreland-dipping thrust faults are a result of sequential thrust development and the creation of a major antiformal stack in the southern part of the Axial Zone. It is this antiformal stack that causes Axial Zone uplift and simultaneously deforms the Montsec floor thrust.

The Alpine deformation front migrated downwards and southwards with time. The Montsec thrust ramp cuts Cuisian age rocks (~53 Ma), and at this time started shedding detritus back into the Tremp-Graus Basin. Deformation migrated southwards into the trailing imbricate fan and Mid Eocene rocks ~45 Ma old are thrust and folded. Eventually, in the Ebro basin, Oligocene molasse ~35 Ma old underwent slight deformation.

It is impossible to escape the conclusion that the Maladeta granodiorite and all points north of this in the Axial Zone have been transported southwards for a considerable distance. The North Pyrenean Fault, regarded as the margin between the Iberian and European plates (Choukroune & Seguret 1973) has recently been projected vertically down to a major seismically detected step in the Moho (Gallart *et al.* 1980). Present section restoration means that the North Pyrenean Fault has been cross-cut by Alpine thrusts and its upper portion must have been transported southwards by ~88 km to its present day position. Alternatively the North Pyrenean Fault is an early fault of listric form that has become reactivated as a steep reverse fault during Alpine deformation.

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