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A structural interpretation of a section of the Gavarnie nappe and its implications for Pyrenean geology

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Abstract—The Gavarnie nappe is a feature of the Tertiary Pyrenean orogen and is shown to consist of at least two thrust sheets of Palaeozoic rocks which are overlain by a southward-dipping sequence of Cretaceous and Eocene sediments, showing folded thrust structures. The Gavarnie nappe covers a basement and Mesozoic cover-rock sequence which is exposed in the tectonic windows of La Larri and the Troumouse Cirque. Here, previously unrecognized thrusts involving basement were responsible for folding the overlying Gavarnie nappe. These basement-involved thrusts climb up section westwards giving a westward lowering of the Gavarnie thrust along strike. The structural evolution of the Gavarnie nappe in a region extending from Heas in France to the Valle de Pineta in Spain can be explained in terms of a piggy-back thrusting sequence. On a regional scale, thrust-tectonic models may be used to explain the double vergence of the Pyrenean chain where early southward-directed thrusting was responsible for structures in the South Pyrenean zone. A later northward-directed back thrusting event, or rotation of southward-directed thrust sheets by the stacking of lower thrust horses, can explain the steepness of structures in the axial zone and the northward-verging North Pyrenean thrust zone. Both models suggest that prior to the Pyrenean orogeny, some of the Hercynian structures in the axial zone were flatter lying, and have been rotated to their present steepness during the Pyrenean orogeny.

INTRODUCTION

THE PYRENEES are a late Cretaceous to Palaeocene mountain belt separating France and Spain, and stretch from the Bay of Biscay to the Mediterranean sea. Structurally the Pyrenean chain is almost symmetrical and typically shows a fan-shaped structure, with opposed vergence such that thrusting is directed outwards from the central, upright axial zone. Choukroune & Seguret (1973) divide the Pyrenees into three structural zones from north to south (Fig. 1a). (1) The North Pyrenean zone comprises several satellite Hercynian massifs (e.g. Arize, Trois Seigneurs) and their folded sedimentary cover. This zone is bounded to the north by a northward-verging thrust zone which probably continues north beneath the sediments of the Aquitaine basin. In the south, the North Pyrenean zone is separated from the axial zone by the steeply dipping North Pyrenean fault. (2) The axial zone which dominantly consists of Palaeozoic rocks often showing upright folds and steeply dipping southward-directed thrusts. (3) The South Pyrenean zone consisting of Mesozoic and Tertiary rocks with southward-verging folds and thrusts (Deramond *et al.* 1980).

The Gavarnie nappe lies at the southern boundary of the axial zone (Fig. 1) and has long been recognized as a major thrust sheet of Palaeozoic rocks, displaced over a basement and Mesozoic cover-rock sequence (Bresson 1903, van Lith 1965, Seguret 1972, Deramond *et al.* 1980). It is overlain by a succession of Cretaceous and Eocene sediments commonly displaced by southward-dipping thrusts and structures, attributed to gravity gliding from the uprising axial zone by De Sitter (1954)

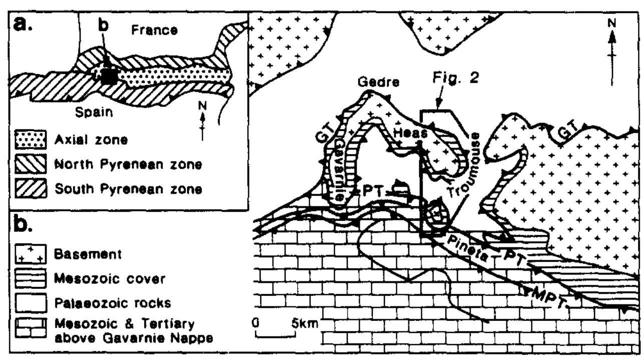

Fig. 1 (a) Main structural zones of the Pyrenees with location of Gavarnie area (b). (b) Simplified geological map of the Gavarnie area after Deramond (1980) and location of Heas–Pineta area shown in Fig. 2.

Rutten (1969) Seguret (1972) and Deramond (1979). Recent detailed mapping of the Gavarnie nappe in an area extending from Heas in France to the Valle de Pineta in Spain (Fig. 2) suggests an alternative interpretation for the structural evolution of this area. This paper aims to demonstrate that the major structures developed by a piggy-back thrusting sequence (Elliott & Johnson 1980) where thrusts originate from a floor thrust, and successively younger thrusts develop in front of older ones and climb structural sections in the direction of tectonic transport. As successively younger thrusts form they may climb structural sections to join an older higher-level thrust, isolating a fault-bounded horse which is accreted onto the hanging wall of the overriding thrust complex. The continuation of this process will form a duplex (Elliott & Johnson 1980). Alternatively the developing thrust may climb section and cut higher older thrusts (Coward 1980). In both cases older higher-level thrusts are passively carried forward and folded by the development of lower-level thrusts. This paper aims to deduce the relative ages of emplacement of thrust sheets in the Gavarnie region using folding and thrusting relationships.

LITHOSTRATIGRAPHY

The stratigraphy of the Gavarnie nappe has been described in detail by van Lith (1965), Joseph (1972) and Deramond (1979), and only a brief outline is presented here. This is summarized in Fig. 2 (b) which also serves as a key for all subsequent diagrams.

Stratigraphy beneath the Gavarnie nappe

The tectonic windows of La Larri and the Cirque de Troumouse (Fig. 2) expose beneath the Gavarnie nappe, a pre-Mesozoic basement unconformably overlain by Mesozoic sediments. The basement rocks consist of granitic gneisses, marbles and schists, showing N–S trending but vertically plunging Hercynian (H_1) folds and later E–W trending Hercynian (H_2) folds (Deramond *et al.* 1980). These folds are cross-cut by a later NW-trending mafic dyke complex, and intruded by post-tectonic, non-foliated Hercynian granites, locally forming an injection vein complex. In the La Larri window, basement rocks are overlain by 100 m of Permo-Triassic red beds, but these are absent northwards in the Cirque de Troumouse where Upper Cretaceous white limestones directly overlie the basement. This Upper Cretaceous limestone sequence is well bedded, often sandy near its base and is only 2 m thick in the Cirque de Troumouse (Fig. 2), but thickens to >100 m in La Plan de Larri. This southward thickening is due to the Gavarnie thrust climbing up section southwards in the direction of tectonic transport.

Stratigraphy of the Gavarnie nappe

The Gavarnie nappe consists of four thrust slices of Palaeozoic rocks (van Lith 1965), whose stratigraphies are described in order of ascending structural height.

(1) The lowest Gavarnie nappe unit (LGNU) consists of 125 m of black carbonaceous Silurian shales (van Lith 1965) overlain by a Lower Devonian sequence of 100–200 m of interbedded limestones and shales, locally named the Fourche de Sede Formation (Joseph 1972), followed by more than 300 m of massive, well-bedded, grey or white limestone forming the Sugar Marble Formation (van Lith 1965, Joseph 1972), overlain by more than 100 m of Rubanes (Joseph 1972) a sequence of calcareous shales with limestone beds. The uppermost rocks are the Bouneu Formation (van Lith 1965, Joseph 1972, Deramond 1979), a sequence of shales and calcareous shales with intermittent limestone and sandstone beds.

(2) The Sia thrust unit consists of the Gabideous limestone (Joseph 1972), a white to grey sequence of massive or locally well-bedded limestones of middle Devonian age (van Lith 1965). This is overlain by the Sia Series, a greenish weathering Upper Devonian turbidite

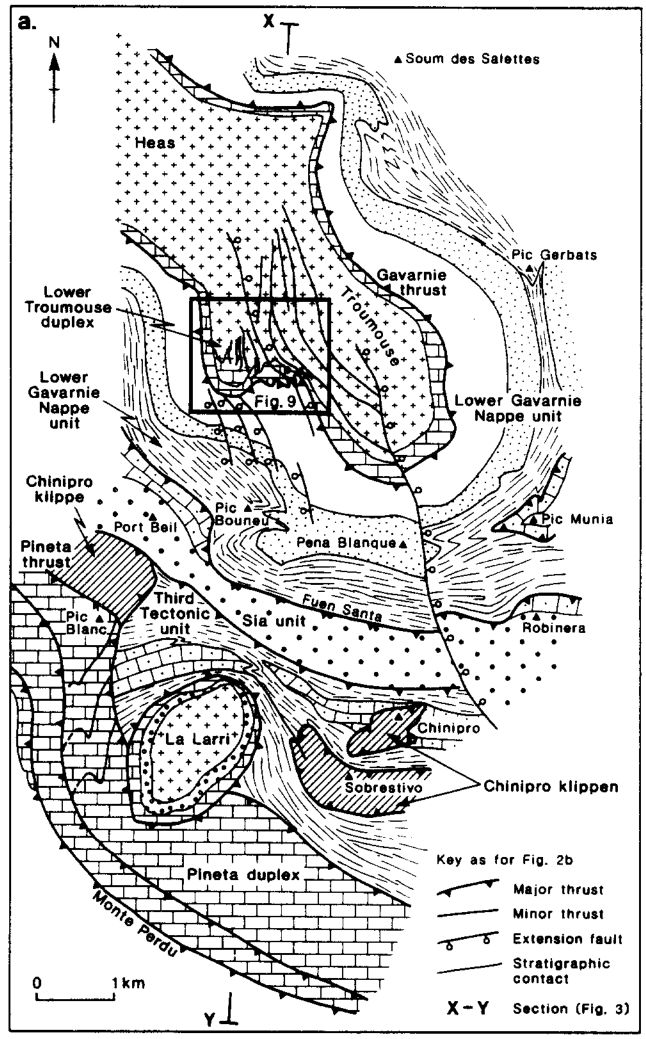

Fig. 2 (a) Detailed geological map of the Heas–Pineta area, showing location Fig. 9 and location of section *X–Y* (Fig. 3).

sequence (Joseph 1972, Deramond 1979).

(3) The Third Tectonic Unit, consisting of the Bounea shales and the overlying Mallo Rojo limestone (which is lithologically similar to the Gabideou limestone), was believed by van Lith (1965) to represent a back thrust slice of the Lowest Gavarnie nappe unit, thrusting Bouneu shales and Mallo Rojo limestones northwards over the Sia thrust unit. This interpretation is compatible with an observed northward décrease in thickness of the Third Tectonic Unit.

(4) The Chinipro klippes (Fig. 2) consist of interbedded shales, sandstones and red, grey or green fossiliferous and nodular limestones of Early Carboniferous age (van Lith 1965, Joseph 1972).

The Palaeozoic rocks of the Gavarnie nappe are overlain by a sequence of well-bedded white Upper Cretaceous limestones (van Lith 1965, Deramond 1979), forming the Pineta duplex. The floor thrust to this duplex (the Pineta thrust) contains pods of strongly tectonized Permo-Triassic conglomerate (cf. Seguret 1972). The Pineta duplex (Fig. 6) is overlain by a sequence of Upper Cretaceous white limestones, Maastrichtian sandstones (Gres du Marbore) and Eocene flysch, forming the Monte Perdu Nappe (Seguret 1972, Deramond *et al.* 1980).

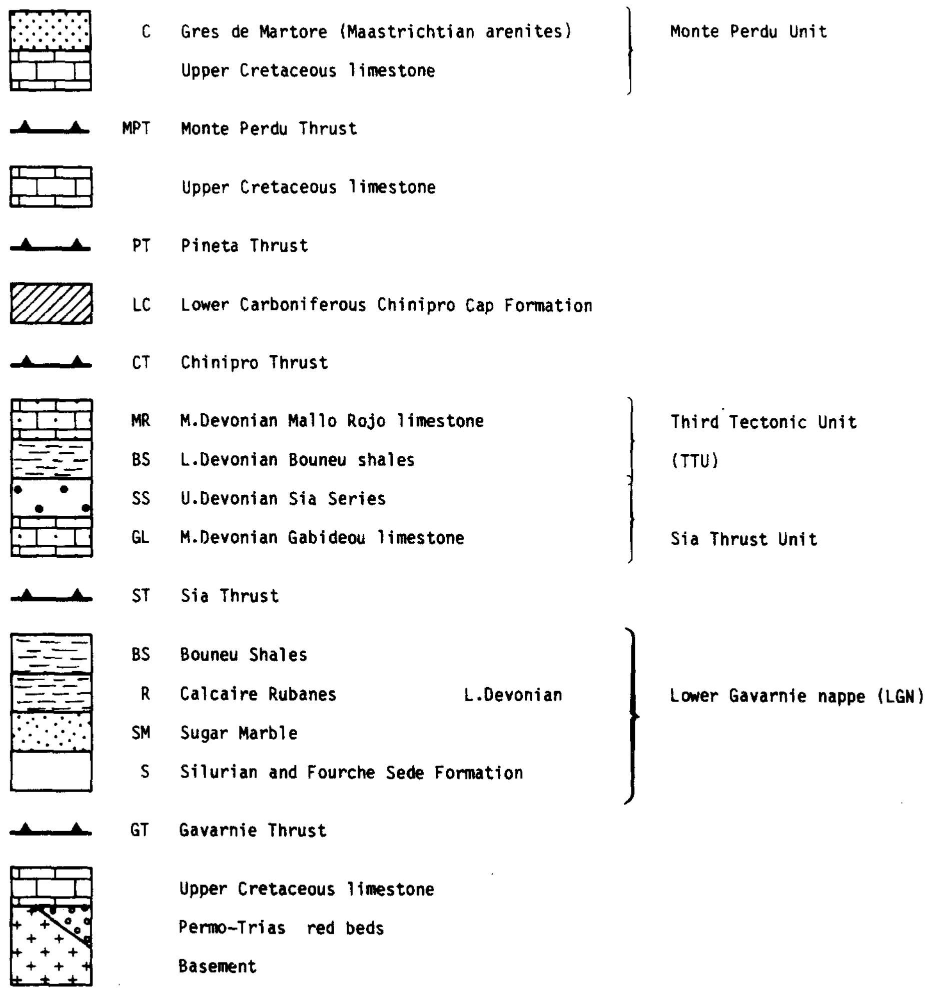

Fig. 2 (b) Summary of stratigraphy in its present tectonic framework and key for all diagrams unless otherwise stated.

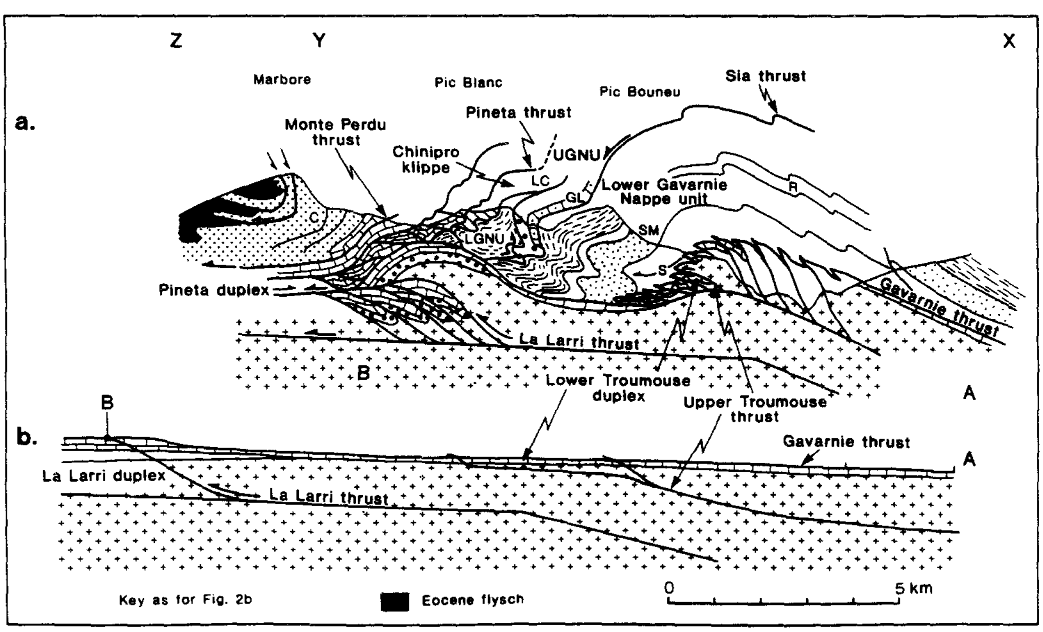

Fig. 3 (a) Cross-section *X–Y* with topographic profile as marked, section *Y–Z* after Deramond (1980). Legend as given in Fig. 2 (b). Thrusts shown by heavy lines, stratigraphic contacts by weak lines. Eocene rocks shown in black. (b) Lower sections *A'–B'* shows restored section *A–B* on section *X–Y*, of rocks underlying the Gavarnie nappe. These record a minimum shortening of 25%.

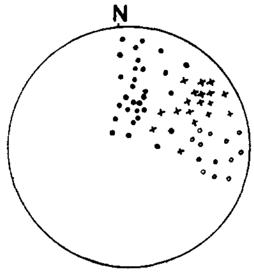

Fig. 4. Plot of axial plunges of folds within the Palaeozoic rocks of the Gavarnie nappe. Maximum concentrations: black circles, H_1 folds; crosses, H_2 folds; open circles, P_1 folds. See text for discussion.

STRUCTURE

The Palaeozoic rocks of the Gavarnie nappe display three dominant fold trends (Fig. 4) with N–S striking folds (H_1), showing variable plunge due to refolding by later E–W striking folds (H_2). Both of these fold sets are believed to be of Hercynian age (Joseph 1972, Joseph & Lucas 1972, Majeste-Menjoulas 1979, Deramond *et al.* 1980), and are cross-cut by both post-Hercynian, Pre-Pyrenean dykes and by the Permo-Trias, or Cretaceous unconformities. Both Mesozoic and Palaeozoic rocks are folded by WNW-trending southward-verging folds of Pyrenean age.

Pyrenean thrust tectonics of the Heas–Pineta area

The Heas–Pineta area (Fig. 2) is dominated by thrust tectonics with a regional southward tectonic transport direction evidenced by stretching lineations, sense of displacement on shear bands and southward-verging folds. However, the major Pyrenean folds strike WNW (Fig. 8) and are slightly oblique to the inferred movement direction; this may be due to differential thrust movement. Structures associated with the higher thrusts are discussed first; note, however, that these have often been folded by the development of lower level thrusts. Figure 5 depicts cross-section evolution diagrams for the Gavarnie thrust zone.

The Monte Perdu nappe forms the highest observed structural unit (Figs. 2 and 3) and consists of Upper Cretaceous white limestone, Maastrichtian sandstones (Gres de Marboré), Eocene flysch and Palaeocene limestones (Seguret 1972, Demarond *et al.* 1980). The Upper Cretaceous white limestones are absent in the south where the hangingwall rocks to the Monte Perdu thrust consist of the Gres de Marboré (Maastrichtian sandstones) (Fig. 6) as shown by Seguret (1972). This southward truncation of the Upper Cretaceous white limestone is due to the Monte Perdu thrust climbing stratigraphic section in a staircase trajectory, southwards in the direction of tectonic transport (Fig. 5). The Monte Perdu thrust is underlain by a sequence of bedding-parallel thrusts and the Pineta duplex, which consists of at least 200 m of tectonically thickened Upper Cretaceous limestones. These limestones are locally folded and

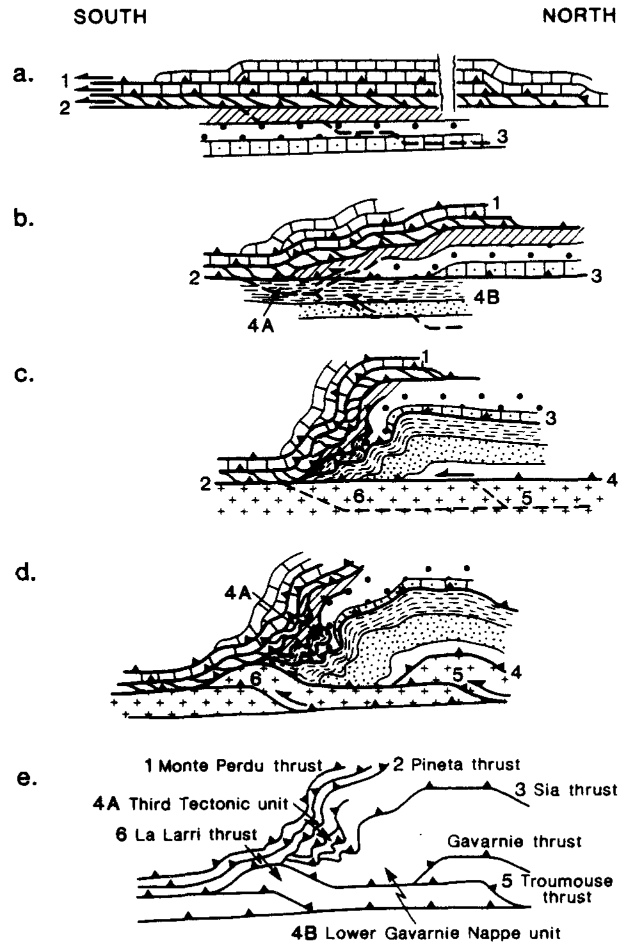

Fig. 5. Cross-section evolution diagrams for the evolution of the Gavarnie nappe. This diagram shows how the accretion of thrust-bounded horses on to the hangingwall of the overlying thrust, folds higher and earlier thrusts. This diagram depicts a piggy-back thrusting sequence where successively younger thrusts develop beneath higher and older thrusts, and as the younger thrusts climb ramps and join a higher décollement level the overlying thrusts are folded. Key as in Fig. 3. Heavy lines thrusts; broken lines incipient thrusts. Thrusting direction north to south. No exact scale is intended. (a) Formation of the Monte Perdu thrust (1); Pineta thrust (2). The Pineta floor thrust runs along a post-Hercynian unconformity, thus separating Mesozoic hangingwall rocks from previously deformed Palaeozoic rocks. Dashed line shows development of Upper Gavarnie nappe unit with Sia floor thrust (3) in footwall rocks. Note staircase trajectory of incipient thrust. (b) Accretion of upper Gavarnie nappe unit on to overriding Pineta thrust. Note folding of overlying thrusts by thrust (3) joining Pineta thrust (2). Incipient Gavarnie thrust (4) developing in footwall rocks. Horse 4A is back thrusted into the upper Gavarnie unit. Horse 4B is the Lower Gavarnie nappe unit. (c) Accretion of Lower Gavarnie nappe unit (4B), and back thrust (4A) onto the hangingwall of the overriding thrust sheet. Note the folding of all higher thrusts, and the development of a major frontal culmination wall. Thrust (4) is the Gavarnie thrust even though at point A the Gavarnie thrust joins with the Upper Gavarnie nappe floor thrust, and the Pineta thrust. The footwall rocks consist of basement and its Mesozoic cover. Dashed lines show the position of incipient thrusts (5), the Troumouse thrust, and (6) the Larri thrust. (d) Movement along the Troumouse thrust, and later movement along La Larri thrust has resulted in folding of the overlying older thrusts. This shows the present structure of the Garvarnie nappe. (e) Simplified sketch showing present relations of the major thrusts. Numbers denote sequence of thrust development with 1, Monte Perdu thrust; 2, Pineta floor thrust; 3, Upper Gavarnie nappe thrust (Sia thrust); 4, Gavarnie thrust; 4A, Third Tectonic unit backthrust; 5, Troumouse thrust; 6, La Larri thrust.

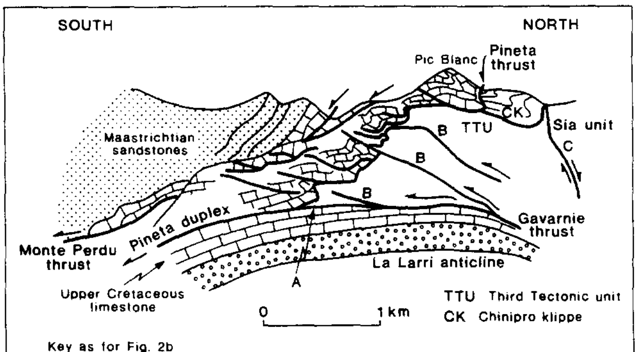

Fig. 6. View of Pic Blanc and frontal ramp fold in the Palaeozoic rocks (unshaded) of the Gavarnie nappe. Note that the Gavarnie thrust joins with the Pineta thrust at A. C, backthrust separating Upper Gavarnie nappe unit to the North and Third Tectonic Unit (TTU) to the south. Minor imbricates (B) truncate or fold the Pineta thrust illustrating that the emplacement of the Pineta duplex was prior to development of the Gavarnie thrust. The Gavarnie thrust is gently folded by La Larri anticline.

imbricated (Fig. 6) and form an intraformational foreland-dipping duplex between the Palaeozoic footwall rocks of the Gavarnie nappe, and the overlying thrusts associated with the Monte Perdu nappe. In the Pineta area (Fig. 2), the Pineta floor thrust forms a thrust flat following a post-Hercynian unconformity between Mesozoic and previously folded Palaeozoic rocks, giving an apparent geometry of truncated Hercynian footwall folds beneath the Pineta thrust. Décollement along the plane of unconformity as suggested by Deramond (1979) is supported by the presence of highly deformed pods of Permo-Trias basal conglomerate in the hangingwall of the Pineta thrust west of the Pineta area. Seguret (1972) suggests that the decoupling zone lies above the post-Hercynian unconformity, with the Pineta thrust climbing up stratigraphy westwards to lie within the Upper Cretaceous limestone succession. Imbricate thrusting within the Pineta duplex occurs on microscopic and macroscopic scales, with individual thrusts following staircase trajectories with ramp to bedding angles often less than 30°.

The Monte Perdu nappe and underlying Pineta duplex were later tilted southwards by the development of lower thrust sheets involving Palaeozoic rocks which subsequently formed the Gavarnie nappe (Fig. 5). A piggy-back thrusting sequence is suggested, as shown by the observations listed below. (1) The Pineta duplex is folded around the Gavarnie nappe, locally resulting in the reorientation of imbricates and southward-verging hangingwall folds such that at Pic Blanc (Fig. 6), the Pineta thrust is folded to a vertical attitude and shows downward-verging hangingwall folds and thrusts. Seguret (1972) also comments on an axial-plane cleavage to the Gavarnie nappe, which cross-cuts earlier formed folds in the Monte Perdu nappe. (2) Imbricate splays from the Gavarnie thrust cut the Pineta floor thrust rather than roofing into it (Fig. 6). These imbricates terminate as folds, imbricate the Pineta thrust and indicate that the Pineta duplex was emplaced prior to the development of the underlying Gavarnie nappe.

Structure of the Palaeozoic rocks of the Gavarnie nappe

The Palaeozoic rocks of the Gavarnie nappe form four distinct tectonic units (van Lith 1965) (Fig. 2). These four units are described in order of decreasing structural height.

The Chinipro thrust unit outcrops as folded thrust klippen of Lower Carboniferous rocks at Chinipro and Sobrestivo (Fig. 2). Here the sole thrust has been folded around a southward-verging, overturned fold which developed after the formation of the Chinipro thrust (Fig. 5). The Chinipro thrust overlies footwall rocks consisting of Bouneu shales and Mallo Rojo limestone which together form the Third Tectonic Unit (van Lith 1965). Beneath the Chinipro Summit (Fig. 2), the Chinipro thrust shows truncation of an easterly striking Hercynian fold in the footwall rocks. The lack of any hangingwall counterpart suggests that the Chinipro thrust trajectory may have run along a post-Hercynian unconformity (Fig. 5).

The Third Tectonic Unit (van Lith 1965) underlies the Chinipro thrust and overlies the Sia unit north of La Larri (Fig. 2) and the lowest Gavarnie nappe unit to the south. The Third Tectonic Unit thins northwards and consists of Bouneu Shales and Mallo Rojo limestone and hence its stratigraphy is similar to parts of the lowest Gavarnie nappe unit. The contact between the Third Tectonic Unit and the Sia unit follows poorly exposed ground, striking WNW from the northern face of Chinipro (Fig. 2), where it shows a nearly vertical attitude which becomes overturned with lower structural height. This is due to folding of a former flatter-lying contact by the later development of the Blancas anticline (Fig. 8), a major southward-verging overturned fold which post-dates the formation of the Third Tectonic Unit (Fig. 5). Since the Third Tectonic Unit thins northwards, shows similar lithologies to parts of the lowest Gavarnie nappe unit and because it appears to climb northwards up structural section, it is regarded as a backthrust (Fig. 5) or underthrust (cf. van Lith 1965), formed after the development of the Sia thrust unit but before the Blancas anticline.

The Sia thrust unit overlies the lowest Gavarnie nappe unit and consists of the Gabideou limestone sequence, which is overlain by the Sia turbidites. South of the Cirque de Troumouse the Gabideou limestone is absent from the hangingwall of the Sia thrust, with the Sia turbidites forming the hangingwall rocks overlying a footwall succession of Bouneu shales belonging to the Lower Gavarnie nappe unit. The Sia thrust unit occurs in the footwall to a backthrust involving the Third Tectonic Unit (Figs. 3 and 5); both structures are folded around a major southward-verging overturned fold (the Blancas anticline), with the Sia thrust cropping out in the overturned limb in the Fuen Santa valley (Fig. 2). Hence, the Blancas anticline postdates the development of higher, earlier-formed structures (i.e. the Sia thrust and Third Tectonic Unit). At Pic Munia (Fig. 2), the Sia thrust unit crops out as a klippe, and is believed to root

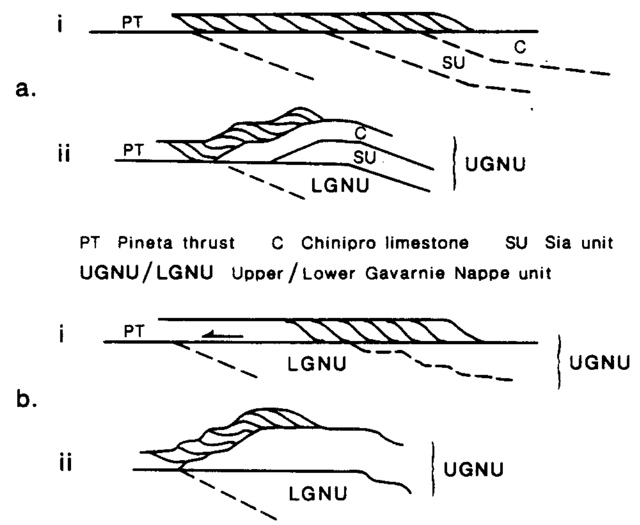

Fig. 7. Possible schematic evolution diagram for the Chinipro klippen and Sia Series Unit. In both models *a* and *b*, (i) represents the undeformed sequence and (ii) shows the geometry after thrusting. See text for discussion. (a) Separate horse model. (b) Model where Chinipro klippe and Sia unit represent Upper Gavarnie nappe unit.

further northwards towards the axial zone (Deramond 1979).

The relationship between the Chinipro Cap klippes and the Sia thrust unit is at present unclear since the contact between these units is inaccessible, and it was not possible to verify if the contact is tectonic or stratigraphic. It is suggested that these units may represent either; (model *a*) individual horses accreted onto the hangingwall of the overlying Pineta thrust (as shown in Fig. 7a) or; (model *b*) both units may be in stratigraphical contact representing the frontal portion of a thrust sheet with a floor thrust which has climbed stratigraphy from Middle Devonian rocks (Gabideou limestone) to Lower Carboniferous rocks in a ramp-flat trajectory. This thrust sheet has subsequently been accreted onto the hangingwall of the overlying Pineta thrust. This latter model (*b*) is schematically shown in Figs. 5 and 7 (b). As a greater amount of shortening is required with model *a* (Fig. 7a), model *b*, where the Chinipro klippe and Sia unit represent the frontal portion of an Upper Gavarnie nappe unit (UGNU), is preferred (see Fig. 3). In both models, back thrusting of the Third Tectonic Unit occurred after the formation of the Chinipro klippes and the Sia thrust unit.

The Lower Gavarnie nappe unit (LGNU) consists of Silurian and Lower Devonian rocks displaced for a minimum distance of 10.5 km southwards (Fig. 3, section *X–Y*) over a footwall of Upper Cretaceous limestone. The hangingwall rocks consist of Silurian shales which form an easy slip horizon but show variable thickness due to tectonic disruption. Exotic blocks of footwall granite and Upper Cretaceous limestone form tectonic inclusions within the shale and measure up to several metres in diameter. Hercynian structures within the lowest 15 m of the Silurian rocks are overprinted by later Pyrenean structures. But at higher levels north of Pic Bouneu (Fig. 2), the Silurian shales are locally metamorphosed to chiastolite slates, which possibly relate to a late-Hercynian thermal event, and show

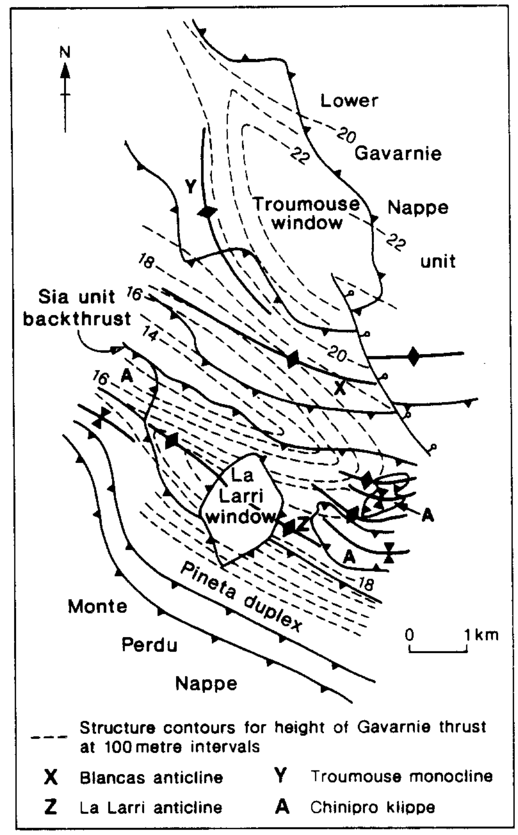

Fig. 8. Structural contour map for height of the Gavarnie thrust, map also shows major structural features of the Heas–Pineta area.

chiastolite porphyroblasts overprinting an earlier Hercynian cleavage. Extensional shear bands (cf. White 1980) formed late in the deformation history of the Silurian hangingwall rocks and crenulate earlier-formed fabrics; and may possibly relate to extensional tip effects in a ductile shear zone (Coward & Potts, 1983). The Blancas anticline (van Lith 1965) (Fig. 8) forms a major southward-verging overturned fold, possibly resulting from internal buckling during propagation of the Gavarnie thrust. This may be due to sticking of the hangingwall on a ramp due to a transition from ductile Silurian rocks to competent Lower Devonian limestone. Minor imbricate thrust faults are common within the Lower Gavarnie nappe unit but often terminate as folds rather than roofing into a higher thrust.

Basement thrusts underlying the Gavarnie nappe

The Gavarnie thrust is folded, as shown on a structural contour map (Fig. 8), with previously unrecognized thrusts exposed in the basement culminations forming the tectonic windows of La Larri and the Cirque de Troumouse (Fig. 2).

The Troumouse window (Fig. 9) exposes a sequence of thrust slices of basement and Upper Cretaceous limestone, which cut above the Gavarnie thrust and imbricate the Silurian rocks which form an early slip horizon at the base of the Gavarnie nappe. These relations describe a piggy-back thrusting sequence where basement-involved thrust slices developed after the formation of the Gavarnie nappe and have imbricated the earlier-

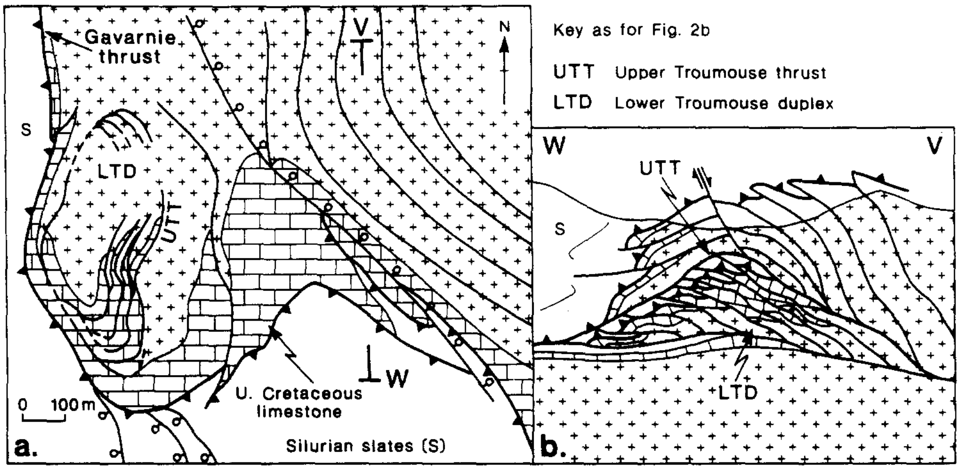

Fig. 9. Map and cross-section (*V–W*) of The Troumouse culmination. The map is located on Fig. 2. Section scale is half the map scale. Both map and section show that younger and lower level thrusts imbricate the older, higher Gavarnie thrust, hence the Silurian hangingwall rocks of the Gavarnie thrust are imbricated with the basement and Cretaceous rocks beneath the Gavernie thrust. Figure 10 shows the inferred cross-section evolution diagrams for the development of the Troumouse culmination.

formed and overlying Gavarnie thrust (Fig. 10). The Troumouse thrust sheet (Figs. 3 and 9) consists of an imbricated basement, Cretaceous limestone and Silurian slates displaced southwards, for a minimum distance of 600 m at its frontal horse over a footwall ramp (named the Upper Troumouse thrust) in the same lithologies. Collapse of this footwall ramp (Upper Troumouse thrust) formed the Lower Troumouse duplex (labelled LTD in diagrams) which is exposed as an imbricate stack in the unnamed Cirque (Figs. 2 and 9). The development of the Lower Troumouse duplex has folded the overlying Troumouse thrust sheet and the Gavarnie nappe, indicating a piggy-back thrusting sequence where the high-level old thrusts are passively carried and folded by the development of new, lower-level thrusts.

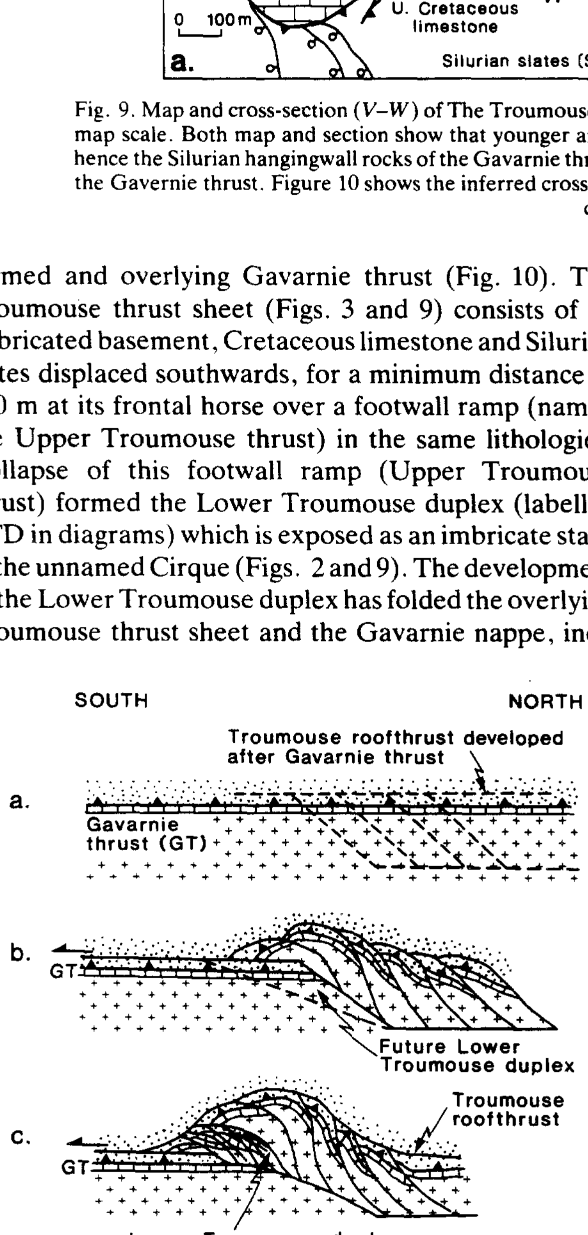

Fig. 10. Cross-section evolution diagrams for the Troumouse culmination. Heavy lines, thrusts; barbed heavy lines, Gavarnie thrust (GT); dashed line, incipient thrust. (a) Gavarnie nappe already emplaced along Gavarnie thrust, Silurian rocks (dotted) overlie Mesozoic cover and Pre-Mesozoic basement. Lower and younger incipient thrusts shown dashed, these climb section southwards and truncate the Gavarnie thrust. (b) Development of Troumouse thrust sheet imbricating into the Gavarnie nappe; collapse of its frontal ramp forms the Lower Troumouse duplex. (c) Present relationship after development of the Lower Troumouse duplex. Throughout each stage of thrusting the hangingwall rocks and overlying thrusts have been continually folded. A possible roof thrust to the Troumouse duplex is shown.

The Troumouse thrust and underlying imbricates have climbed stratigraphy westwards resulting in a westerly lowering of the Gavarnie thrust along strike. This has resulted in the formation of a NNW-striking monocline in the overlying Gavarnie nappe (Fig. 8), forming a ramp fold oblique to the movement direction. This monocline is associated with a set of N-trending listric normal faults which join the Gavarnie thrust (Fig. 11b). These may represent accommodation structures due to the development of extensional strain on lateral culmination walls (cf. Butler 1982).

Figure 11 is a hangingwall sequence diagram (cf. Elliott & Johnson 1980) viewed up dip, and summarizes the longitudinal changes and development of structures associated with the lateral climb of the Troumouse thrust sheet. It shows that movement along the Gavarnie thrust in the west was coeval with the successive development of lower, basement involved thrusts in the east.

The Gavarnie nappe and underlying Mesozoic and basement rocks are folded into a large scale WNW-striking open fold named the Larri anticline (Fig. 8) which is interpreted as overlying a deeper blind thrust ramp, named La Larri thrust in Fig. 3. An underlying duplex (La Larri duplex) is exposed eastwards along strike of the mapped areas (Fig. 2) in the Parzan valley. Figure 3 shows a balanced cross-section which suggests a minimum displacement of 1.6 km along the Larri thrust.

Thrusting sequence

The southerly dip of the Monte Perdu nappe and Pineta duplex which overlie the Gavarnie nappe was formerly attributed to gravity gliding during the development of the Gavarnie nappe by De Sitter (1954), Seguret (1972) and Deramond (1979). However, this paper suggests that the Monte Perdu nappe and Pineta duplex formed early high-level thrust sheets which have been

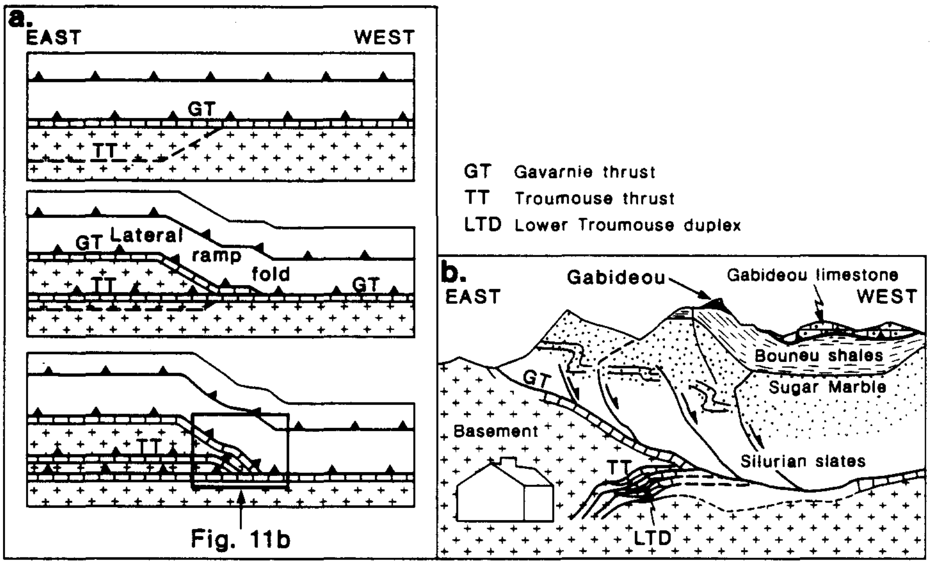

Fig. 11. (a) Hangingwall sequence diagrams (Elliott & Johnson 1980) of the Troumouse culmination viewed up dip (Harris 1970) showing the longitudinal changes and development along strike from east to west. Movement direction N–S. No exact scale is intended. (1) Emplacement of Gavarnie nappe along the Gavernie thrust, lower and younger incipient Troumouse thrust (TT) develops in basement rocks in the east, but joins the Gavarnie thrust (GT) in the west by climbing a lateral ramp. (2) Emplacement of the Troumouse thrust sheet, after the Troumouse thrust has climbed section southwards in the direction of tectonic transport. Movement on the Troumouse thrust in the east is coeval with movement on the Gavarnie thrust in the west. All structures overlying the Troumouse thrust sheet are folded, forming a monocline striking parallel to the transport direction. Lower developing imbricates shown by dashed lines. (3) Geometry after development of lower imbricates. Note that all structures overlying the Troumouse thrust sheet must be strained, this can be seen by comparing the original and final length of the Gavarnie thrust. In (3) the Gavarnie thrust datum line has been extended. (b) Detailed view looking south from the unnamed Cirque of locality shown as box B in Fig. 11 (a). This shows the lateral ramp fold overlying the Troumouse thrust sheet. This lateral ramp fold is associated with a set of N-striking listric normal faults, which accommodate the release of extensional strain overlying a lateral ramp. LTD, Lower Troumouse duplex.

reorientated by the stacking of lower, later thrusts developing in a piggy-back thrusting sequence (see Fig. 5). The Pineta unit is considered to represent an intraformational duplex underlying the Monte Perdu nappe, with the Pineta floor forming a prominent décollement horizon along a post-Hercynian unconformity. Westwards, however, this detachment surface climbs above the unconformity to lie within Upper Cretaceous limestones (Seguret 1972). The accretion of the Chinipro klippe and the Sia thrust unit either as an Upper Gavarnie nappe unit (Fig. 5), or as separate horses (Fig. 7a) on to the Pineta thrust, folded the overlying thrusts at each stage of thrust sheet accretion. The emplacement of the Lower Gavarnie nappe unit was coeval with the development of the Blancas anticline, which folded the Lower Gavarnie nappe unit and higher thrust sheets. The resultant southward-facing culmination wall developed from the stacking of these thrust sheets (see Fig. 5c) may have been sufficient to drive gravitational collapse structures south of the area mapped. The development of basement-involved thrusts in the east of the Gavarnie area was coeval with movement at a higher structural level on the Gavarnie thrust in the west. As the basement-involved thrusts climbed section southwards in the direction of thrusting, all overlying sheets were folded. The lateral climb of basement thrusts westwards to join the Gavarnie thrust led to the development of a lateral ramp fold, oblique to the tectonic transport direction. Thus in the Heas–Pineta area (Fig. 2) the major Pyrenean structures can be explained by a southward-directed piggy-back thrusting sequence as summarized in Fig. 5.

DISCUSSION

The Pyrenean development of the Heas–Pineta area can be explained by a piggy-back thrusting sequence, where the Monte Perdu and Pineta thrust units form high-level thrusts folded by the later formation of the Gavarnie nappe, which consists of at least two distinct thrust sheets of Palaeozoic rocks. Previously unrecognized basement thrusts account for a westward lowering of the Gavarnie thrust along strike and suggest that there was a basal decoupling zone at an unknown depth in the basement. Large-scale upper crustal shortening is believed to be important in the Heas–Pineta area. In Fig. 3, restoration of basement-involved thrusts suggests a minimum shortening estimate of 25%, with a line balance (Hossack 1979) on the present deformed length of 11 km of the post-Hercynian unconformity (Figs. 3a & b) restoring to 17 km (between A′ and B′, Fig. 3). The Lower Gavarnie nappe shows a minimum displacement of 10.5 km over Cretaceous footwall rocks, which is in agreement with estimates presented by earlier workers (Seguret 1972, Deramond 1979). Shortening within the Palaeozoic rocks of the Gavarnie nappe is more difficult to estimate due to Hercynian folding. The overlying Cretaceous and Eocene sediments show repeated duplication of stratigraphy.

On a more regional scale, a thrust tectonic model may be used to account for the relative steepness of structures in the Pyrenean axial zone. This steepness may be attributed to (1) the stacking of lower and younger southward-directed thrusts, causing back rotation of higher earlier thrusts as shown in Fig. 12 (a), and/or (2)

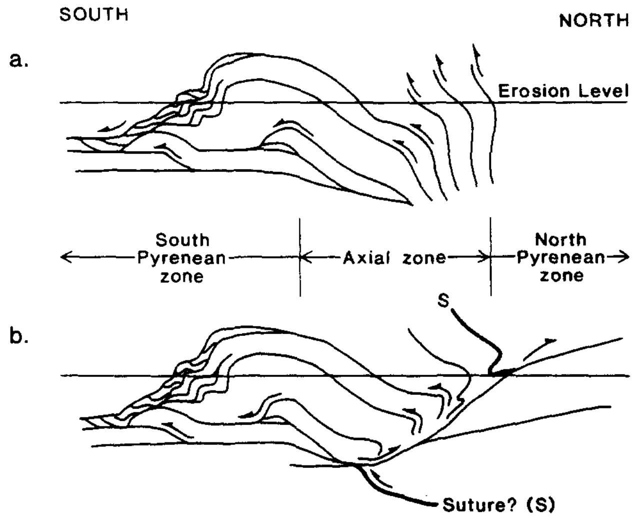

Fig. 12. Two suggested interpretations to explain the structure of the Pyrenees. (a) A piggy-back thrusting model where the steepness of axial zone structures is attributed to the progressive stacking of lower, younger thrusts; and rotation of older higher level thrusts. (b) Back-thrusting model where early southward-transported thrusts have been back folded and thrust towards the north. This backthrusting may be attributed to layer-parallel shortening at the tip of a propagating thrust, possibly at depth in the crust. This model explains the lack of any surface Pyrenean suture.

folding of the early southward-directed thrusts by a later northward-directed back thrusting event, locally back folding parts of the axial zone. The formation of a second phase fracture cleavage with a gentle southward dip reported in parts of the axial zone (Choukroune & Seguret 1973) may be related to the latter events. More importantly, the back thrusting model may explain the lack of a Pyrenean suture level at the present level of erosion, although one may occur at depth (Fig. 12b). Of great importance to any model for the evolution of the Pyrenees is the relevant timing of thrusting in the different zones. The North Pyrenean thrust zone migrated northwards from the late Cretaceous to the Eocene (R. Graham, pers comm.). Southward thrusting also started during the late Cretaceous and propagated southwards until the Miocene, and was possibly accompanied by back rotation (Fig. 12a) or back thrusting (Fig. 12b) causing the present relative steepness of the axial zone. Both of the models suggested in Fig. 12 indicate that prior to the Pyrenean orogeny the Palaeozoic rocks of the axial zone were originally gently dipping. This is important to the interpretation of all Hercynian structures in this zone such as diapirs, mantled gneiss domes and shear zones (Soula 1982).

A foreland-propagating thrust complex as described in this paper suggests that folding in thrust belts is diachronous and lateral changes in thrust geometry may give rise to oblique folds. Regional correlation of fold phases is therefore felt to be ambiguous.

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