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The Ansó transect of the southern Pyrenees: basement and cover thrust geometries

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Abstract: A balanced geological section through the western central Pyrenees allows the Alpine geometry of Hercynian basement to be determined. This shows marked differences with other transects of the southern part of the chain. Basement-involved thrust sheets do not form an antiformal stack, but are imbricated and define steps separated by frontal culmination limbs. Basement thrusts propagate upwards and have formed distinct thrust systems in the cover. In this transect, the North Pyrenean Zone is bounded to the south by gently dipping thrusts of large displacement, and the Axial Zone massif, at its western termination area, is a flat-topped culmination caused by a single thrust fault, the Gavarnie thrust. This thrust emerges to the south in the interior of the syntectonic Jaca Basin, the geometry of which is also controlled by underlying basement thrusts. Various generations of structures can be correlated with distinct episodes of syntectonic sedimentation. A sequential restoration of the section illustrates how successive foreland sedimentary wedges were generated and progressively involved in deformation. Tectonic shortening is 48 km, almost half of that estimated further to the east for the southern Pyrenees. The structure deduced at the ECORS-Pyrenees seismic section cannot be translated to this transect.

Keywords: Pyrenees, thrusting, basement, sedimentary cover, syntectonic processes.

The Pyrenean orogenic belt shows well exposed deformation structures and exceptionally well preserved syntectonic sedimentary rocks. These features make the Pyrenees one of the best areas to undertake studies of thrust tectonics and of deformation-sedimentation relationships. The Pyrenean mountain range formed during late Cretaceous to earliest Miocene times at the collisional boundary between the Iberian and European plates. Being the result of a broadly N–S crustal contraction, it can be divided into a northern belt, dominated by north-vergent folds and thrusts (North Pyrenean Zone), and a southern belt characterized by south-vergent folds and thrusts (Fig. 1) (Choukroune & Séguret 1973). The latter includes the basement outcrop of the Axial Zone and the south Pyrenean cover thrust sheets (incorporating the earliest foreland basins), and will be referred hereafter as 'southern Pyrenees'.

One of the challenging problems of Pyrenean geology concerns the nature of basement–cover relationships and the Alpine (Tertiary) deformation structure of the Axial Zone. This is because it is commonly difficult to separate the effects of the older Hercynian (Palaeozoic) orogeny from the Alpine deformation when post-Hercynian rocks are absent. In addition, the relationships between the southern Pyrenees and the North Pyrenean Zone, separated along most of the range by steep structures of controversial significance (Choukroune 1976), are poorly understood.

This paper presents a new transect located in the western part of the central Pyrenees (partly near the valley of Ansó), where there had been no previous attempts to construct and restore balanced cross-sections. The section integrates the south-vergent belt of the Pyrenees, from the southern edge of the North Pyrenean Zone to the foreland, and includes the area of the western termination of the Axial Zone, where the basement outcrop disappears under a Mesozoic cover (Fig. 1). Because of this, the section has the advantage of being constructed using the structures of the cover rocks, and the Alpine geometries of basement can be determined. The cross-section includes the western south Pyrenean foreland basin (Jaca Basin) where many sedimentological and basin models have been developed (Mutti 1977, 1984; Puigdefàbregas & Souquet 1986; Hirst & Nichols 1986; Labaume *et al.* 1987; Friend 1989; Barnolas *et al.* 1991, among others), and this study provides a tectonic framework for the basin development. In addition, this work has thrown new light on the southern boundary of the North Pyrenean Zone, which, in this location, is little affected by later deformations.

The cross-section presented can be compared with the ECORS-Pyrenees seismic section located some 160 km to the east (Choukroune *et al.* 1989; Muñoz 1992; Fig. 1b). The results of the present study indicate significant lateral changes in structural geometry and shortening with respect to that and other well-documented traverses to the east in the Pyrenean belt, and illustrates the crucial role of basement involvement in the geometrical evolution of the Jaca Basin.

The Ansó transect

The dominant trend of folds and thrusts along the traverse is ESE (Figs 1 and 2), and the vergence is to the south. The deformation structures correspond to upper crustal levels with low-grade or no metamorphism; cleavage is locally developed, especially in incompetent rocks in the more deeply exhumed northern area.

The transect may be divided into four zones. From N to S, these zones are (Fig. 2): (1) the Lakora thrust sheet (North Pyrenean Zone), characterized by Palaeozoic and Mesozoic rocks; (2) the area of the western termination of the Axial Zone, where Hercynian basement is overlain by an Upper Cretaceous cover defining a large antiformal fold; (3) the Jaca Basin, a deformed Palaeogene foredeep, and (4)

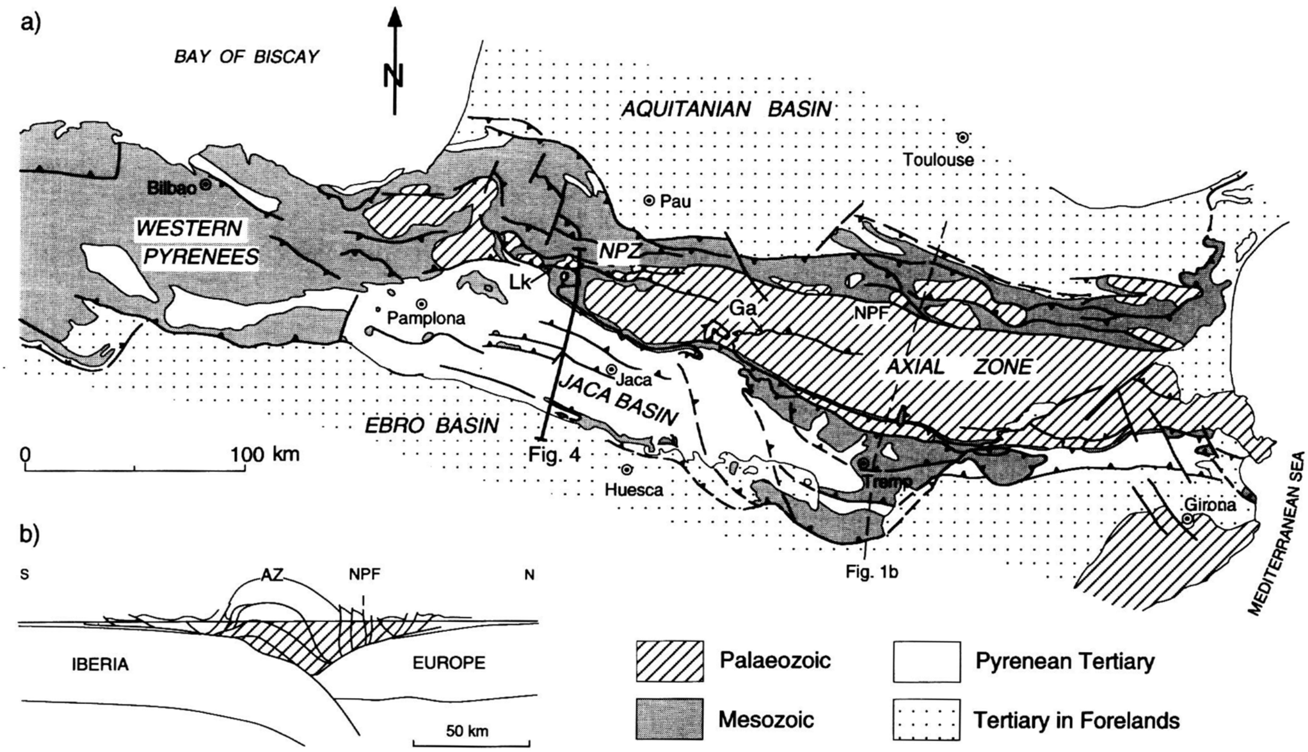

Fig. 1. (**a**) Location map of the Pyrenees in northern Spain and southern France showing the location of the Ansó cross-section presented in this work (Fig. 4). Lk, Lakora thrust; Ga, Gavarnie thrust; NPZ, North Pyrenean Zone. (**b**) Crustal-scale section based on the ECORS-Pyrenees seismic profile (simplified from Muñoz 1992).

the External Sierras, a thrust front where thin Mesozoic and lower Tertiary successions are thrust over the foreland of the Ebro Basin.

The descriptions of the geology along the transect are based on comprehensive 1:50 000 mapping (Teixell 1992; Teixell & García-Sansegundo 1994; Teixell *et al.* 1994; Teixell & Montes in press), combined with stratigraphic and structural observations. In this paper, the lithological framework is first summarized (Fig. 3), and then the surface structure of each of the zones, being later integrated in the complete balanced cross-section (Fig. 4).

Stratigraphy

The stratigraphy of the Ansó transect is summarized in Fig. 3. Palaeozoic rocks older than Permian crop out in the core of the Axial Zone and in the Iguntze massif (Fig. 2). These rocks were first deformed by the Hercynian orogeny and form the basement of the Pyrenees. Permian rocks post-date the Hercynian deformation and consist of terrigenous red beds, deposited in small fault-bounded basins (Bixel & Lucas 1983).

The most complete Mesozoic successions are found to the north of the Lakora thrust, the domain classically included in the North Pyrenean Zone. Above the Lakora thrust, there is a thin slice of Triassic limestones, shales and volcanic rocks (Larrau slice, Casteras 1949). This slice is in turn overthrust by the Palaeozoic rocks of the Iguntze massif, which are unconformably overlain in an onlap relationship by Albian to Upper Cretaceous conglomerates and breccias (Mendibelza and Errozaté Formations, Boirie & Souquet 1982; Durand-Wackenheim *et al.* 1981) (Fig. 3).To the north of the Iguntze massif, and separated by the Licq fault (Fig. 2), the Chainons Calcaires region displays a complete sequence of Triassic, Jurassic and Lower Cretaceous carbonates and shales (Paris 1964) (Fig. 3).

To the south of the Lakora thrust, the Palaeozoic is directly overlain by Upper Cretaceous rocks, that rest on a remarkably flat erosion surface (Ribis 1965; Souquet 1967; Teixell 1990a). The Upper Cretaceous thins southwards, and in the Axial Zone is composed at the base of shelf carbonates ('Calcaires des Cañons' of Fournier 1905) (Fig. 3). The top of these limestones contains a discontinuity marked by a palaeokarst in the south and a rapidly deepening sequence in the north, interpreted as a product of an abrupt tilting of the depositional surface. This occurred just before the end of carbonate sedimentation, giving way to terrigenous marine sedimentation during the late Santonian–Maastrichtian (Fig. 3). In the External Sierras, the Upper Cretaceous overlies Triassic limestones, shales and evaporites that form the main detachment level, but these rocks pinch out to the north somewhere beneath the Jaca Basin.

Tertiary rocks are found to the south of the Axial Zone in the Jaca and Ebro Basins (Fig. 1), and were deposited syntectonically with the main Pyrenean compressional deformation. The Jaca Basin is an E–W elongated foredeep that was incorporated in the south Pyrenean thrust belt as deformation progressed. It shows an overall regressive sedimentary infill, ranging from deep-water turbidites to fluvial–alluvial red beds (Mutti *et al.* 1972; Puigdefàbregas 1975) (Fig. 3).

The northern half of the Jaca Basin is occupied by lower to middle Eocene turbidites of the Hecho Group (Mutti

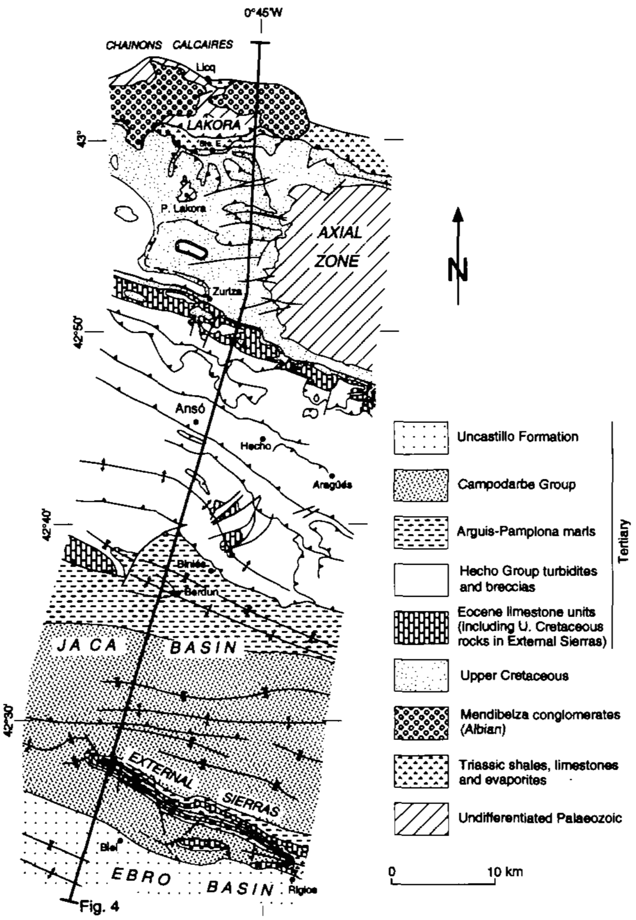

Fig. 2. Simplified geological map along the cross-section presented in this paper. Note that the map pattern shows different exhumation levels, reflecting different elevations of basemental depth.

1984). The turbidites are coeval with platform carbonates that formed the southern basin margin (Puigdefàbregas & Souquet 1986; Barnolas & Teixell 1992, 1994), and which are now exposed in thrust-related culminations and in the External Sierras. The platform carbonates become progressively younger towards the south, whereas the turbidites onlap over the carbonates (Labaume *et al.* 1985). To the east of the Ansó transect, in areas where the substratum to the turbidite group lies at greater depths, the preserved Hecho Group reaches a thickness of *c.* 4500 m (Teixell 1992). Characteristic of the Hecho Group (in the study region) are eight carbonate megabreccia and calcarenite beds, up to 200 m thick, which form excellent marker units ('megabeds' or 'megaturbidites', Rupke 1976; Johns *et al.* 1981; Labaume *et al.* 1983, 1987; Teixell 1992).

The Hecho Group is overlain by shelf and slope marls and sandstones (Pamplona marls and other formations, Puigdefàbregas 1975), of late Lutetian to mid Priabonian age. In total, these formations reach a maximum thickness of *c.* 2600 m, and thin dramatically to the south (e.g., to only 700 m in the equivalent Arguís marls of the External Sierras). These units are overlain by a thick (up to 3800 m) series of terrestrial sandstones and shales (Campodarbe Group, dated as upper Priabonian–Rupelian by Hogan 1993), whose outcrop dominates the southern half of the Jaca Basin. The upper part of the group includes alluvial fan conglomerate bodies.

The Ebro Basin is separated from the Jaca Basin by the frontal thrust complex of the External Sierras. The northern border of the Ebro Basin is characterized by terrigenous rocks of the Uncastillo Formation (Soler & Puigdefàbregas 1970). These conformably overlie the Campodarbe Group of the south side of the Sierras along the traverse, although more to the east they overlap the Mesozoic–Eocene. The Uncastillo Formation consists of massive conglomerates, which pass southwards into fluvial sandstones and shales (Puigdefàbregas 1975; Nichols 1987*a*).

Structure

The Lakora thrust sheet. In the northern part of the section, the Lakora thrust sheet (southern edge of the North Pyrenean Zone) is bounded to the south by a system of south-directed gently dipping thrusts, the lowermost of which is named after the classic locality at Pico Lakora (Lakhoura), where an isolated klippe of the thrust sheet was recognized by Founier (1905) (Fig. 2). These thrusts override the Axial Zone unit (Fig. 4). Overlying the Lakora thrust, the Iguntze thrust encloses the intervening Larrau slice as a horse and has carried the Iguntze massif (Figs 2 and 4). The frontal ramp of the Lakora thrust sheet and the hanging-wall cutoff of the Palaeozoic–Cretaceous unconfomity crops out in the Lakora klippe, where the beds define an overturned anticline (Casteras 1949) (Fig. 4).

The Lakora thrust sheet is bounded to the north by the Licq fault (Fig. 4). This fault now has a subvertical attitude, although it behaved as a south-directed thrust during part of its complex history. To the north of this fault is the Chainons Calcaires region, which, although classically included in the North Pyrenean Zone, is deformed into a south-verging thrust system. North of the cross-section, the passage to north-vergent structures of the northern Pyrenees is progressive, without a major bounding fault (see maps in Paris 1964).

The Axial Zone. The Axial Zone unit is characterized by two generations of Alpine structures: an early system of small-scale imbricate thrusts, localized within cover rocks (Larra thrust system, Teixell 1990*b*), and a second system forming the large Axial Zone antiform and associated minor folds.

The individual thrusts of the Larra system sole out into a bedding-parallel detachment located within the Upper Cretaceous (Larra thrust). This floor thrust in turn branches in the rear from the Lakora thrust (Fig. 4), and climbs up the Upper Cretaceous stratigraphy southwards across the Axial Zone. In the north, the splaying imbricates from the Larra thrust are very closely spaced (Fig. 4), and incorporate the upper part of the Calcaires de Cañons and overlying shales (Teixell 1990*b*). To the south, at the Sierras Interiores, the thrusts form a very spectacular imbricate stack of larger thrust slices, due to the greater thickness of the competent layers involved (uppermost Cretaceous sandstones and lower Tertiary limestones). These thrust slices at the Sierras Interiores have been recognized by many previous authors (Van Elsberg 1968; Soler & Puigdefàbregas 1970; Labaume *et al.* 1985, etc.), and show well developed fault-propagation folds (Alonso & Teixell

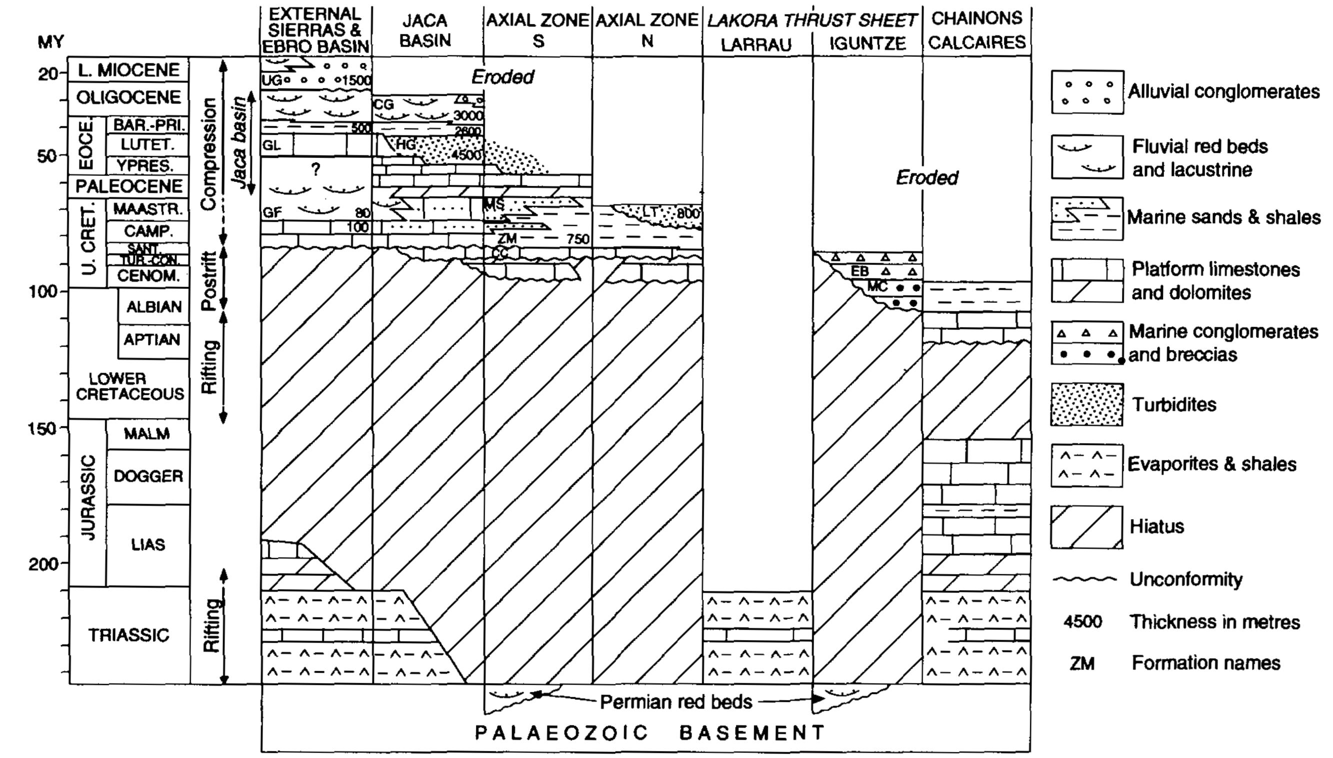

Fig. 3. Space/time diagram showing the stratigraphy of the southern Pyrenees along the line of cross-section. The time scale is after Harland *et al.* (1990). Formation names: UF, Uncastillo Formation; CG: Campodarbe Group; GL, Guara limestone; HG, Hecho Group; GF, Garumnian facies; MS, Marboré sandstone; ZM, Zuriza marls; CC, Calcaires des Cañons; LT, Longibar turbidites; EB, Errozaté breccias; MB, Mendibelza conglomerates.

1992). In each case, the imbricate thrusts may converge upward in roof thrusts forming duplexes, although this is difficult to document accurately in the north, due to the present level of erosion.

It is important to note that, although there are numerous thrusts within the Cretaceous and Tertiary strata (Fig. 4), no evidence of major detachment along the basement–cover interface has been found. The Larra thrust system is accompanied by occasional development of cleavage, especially in the northern exposures.

The second-generation antiform of the Axial Zone folds both the Lakora and Larra thrusts, and has a westerly plunge of 11°. This gentle plunge causes the termination of the Palaeozoic outcrops and no abrupt bounding structure is observed. The antiform is characterized by a flat top, affected by normal faults, a homoclinal gently-dipping northern limb, and a southern limb defined by a system of hectometric-scale overturned folds (Fig. 4). These have an associated axial planar cleavage.

The Jaca Basin. The broad surface structure of the Jaca Basin is an asymmetric synform, located between the Axial Zone culmination and the External Sierras (Figs 1 and 2). The map pattern, however, shows clearly two divisions, corresponding to different levels of exhumation: a northern part dominated by the Hecho Group, and a southern part dominated by the younger Campodarbe Group. The northern part of the Jaca Basin fill is deformed by two main generations of structures, as found in the Axial Zone. They consist of an early system of gently dipping thrusts, which were later deformed by a second system of dominant folds and thrusts (Soler & Puigdefàbregas 1970; Ten Haaf *et al.* 1971, Labaume *et al.* 1985). The first thrust system shows little associated folding and represents the southern continuation of the Larra thrust system. The second-generation thrusts are steeper, and form a large-scale imbricate fan (Fig. 4). The intervening folds vary from metric to map-scale in size, and may be accompanied by slaty cleavage. These second structures are correlated with the antiform of the Axial Zone.

In the southern part of the Jaca Basin, the second system of folds are dominant, defining the ESE-trending Guarga synclinorium (Puigdefàbregas 1975) (Fig. 4). The folds are upright, with a poorly defined vergence. In general, they show angular geometries towards the fold cores, while the outer arcs may have more rounded forms. These folds are of kilometric scale, and the anticlines can be very tight (e.g. Botaya anticline, Fig. 4).

The External Sierras and the Ebro Basin. The surface structure of the western External Sierras conforms to a narrow and complex anticline (Santo Domingo anticline, Almela & Ríos 1951; Nichols 1987b), whose core is disturbed by thrust faults (Figs 2 and 4). This fold appears as almost isoclinal: both limbs dip approximately 70° to the northeast. Immediately west of the cross-section, the core thrusts die out, and the limbs of the Santo Domingo fold are connected in a simple anticlinal closure (Fig. 2). The fold-axis plunges very steeply at the closure (Nichols 1987*b*), although it can be traced to the west, in the Oligocene strata that bury the Mesozoic–Eocene of the Sierras (Turner 1990).

To the south of the Santo Domingo anticline no major

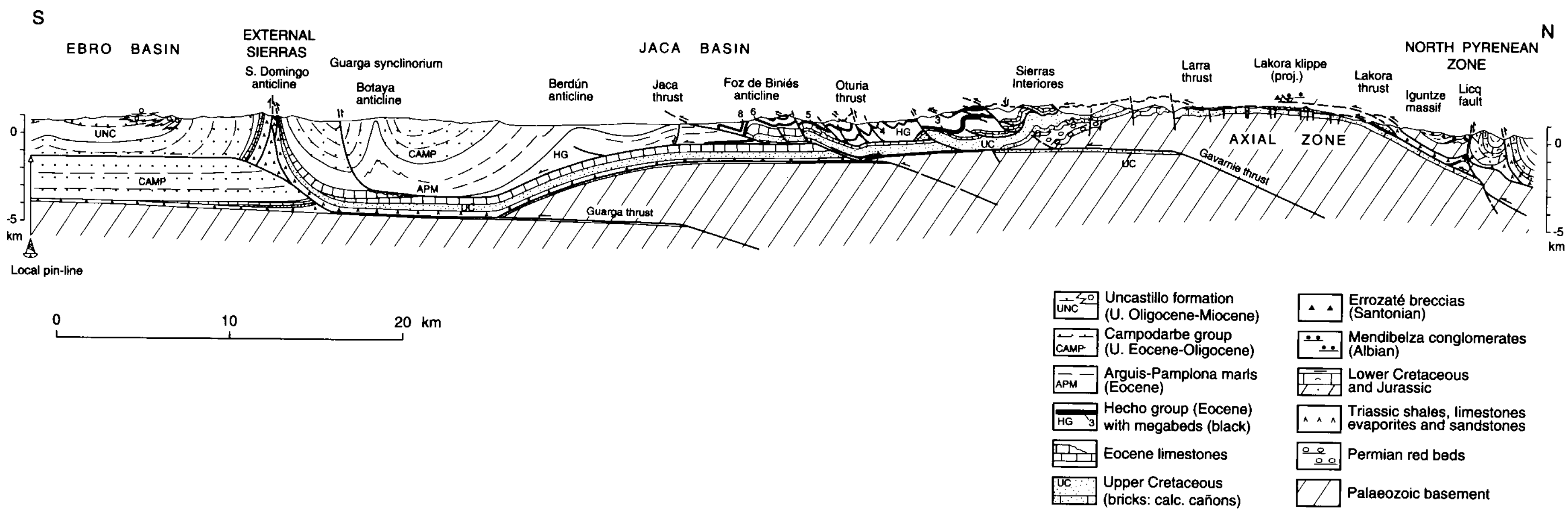

Fig. 4. Balanced cross-section through the western central Pyrenees from the southern margin of the North Pyrenean Zone to the Ebro Basin (Ansó transect). See Figs 1 and 2 for location. A restored version of the section can be found in Fig. 5.

thrust is exposed at the surface. The Campodarbe beds of the southern limb of the anticline are vertical or strongly overturned, and the dips of the Uncastillo strata decrease rapidly to the south, until they become almost flat-lying, defining a syntectonic bed fanning or progressive unconformity (Puigdefàbregas 1975; Nichols 1987*b*). Nevertheless, a pair of gentle folds can still be recognized further to the south (Figs 2 and 4).

Balanced cross-section; Ansó transect

Using the surface data, combined with seismic and well information available to the east of the study area, a balanced cross-section was constructed along the Ansó transect (Fig. 4). The section runs NNE–SSW, approximately parallel to the movement direction inferred for the southern Pyrenees (Séguret 1972). The following descriptions focus upon problems and analysis of the balanced section construction from north to south.

To the north of the Licq fault, the thrust sheets of the Chainons Calcaires are detached in the Triassic (Fig. 4). To the south of the Licq fault, in the hangingwall of the Lakora thrust, the Larrau slice is shown as flat lying and extending below the entire Iguntze massif, as suggested by a tectonic window existing between this massif and the equivalent Mendibelza massif (Teixell 1993). Below the Lakora thrust, the Calcaires des Cañons have been continued as a subsurface footwall flat to the north of the Lakora–Larra branch point (Fig. 4). This serves to balance the 5 km of shortening caused by the Larra thrust system above its basal detachment level (Teixell 1992). The gentle dip of the Larrau slice and overlying sheets supports this solution.

Further to the south, the Axial Zone antiform shows the Palaeozoic–Cretaceous unconformity at shallow depths, (this is constrained from its up-plunge outcrop a few kilometres to the east, at about 2000 m above sea level) . The Larra thrust system appears as a very thin sheet located within the cover, with an underlying sole thrust consisting of two flats connected by an intervening ramp region (Fig. 4). This ramp is largely eroded at the level of the Upper Cretaceous marls.

Beneath the Axial Zone antiform, an underlying basement thrust has been inferred (e.g., Gavarnie thrust, Choukroune *et al.* 1968). The simple geometry of the antiform may be explained by a single thrust fault, the shape of which has been approximated assuming a flat-topped fault-bend fold geometry (Suppe 1983), and neglecting the internal deformation. The slip thus inferred agrees well with shortening calculated from the frontal imbricates of the northern Jaca Basin. The termination of the Palaeozoic outcrops is caused by a gentle plunge of the antiform and no lateral ramp is required; instead the westerly plunge possibly represents a decrease in antiform amplitude related to reduced displacement on the Gavarnie thrust.

In the northern part of the Jaca Basin, the cross-section has been constructed at depth taking into account the major surface structures as defined by the carbonate megabeds, although local detachments between the Hecho turbidites and the underlying Upper Cretaceous–lower Tertiary competent rocks seem necessary. The Foz de Biniés anticline is interpreted as a ramp anticline of the Jaca thrust (Labaume *et al.* 1985; Cámara & Klimowitz 1985) (Figs 2 and 4). The subsurface location of the foot wall ramp implies that the displacement deduced at rear of this thrust is much greater than that estimated at the surface (Fig. 4). It is proposed that displacement has partly been transferred to an additional flat located on top of the Eocene limestone and below the outcropping Jaca thrust ramp (fig. 4). This detachment may be partly responsible for folds of the Guarga synclinorium further to the south. The tightness of the Botaya anticline and other folds along the synclinorium suggests they are detached in the Upper Eocene marls (APM in Fig. 4), an assertion supported by depth-to-detachment calculations.

South of the Jaca thrust and the Berdún anticline (Fig. 4), a wide zone of persistent southward dips in the marls and Campodarbe strata is interpreted as the frontal culmination wall of another major basement thrust (Fig. 4). An alternative interpretation invoking duplexes of cover rocks would be ruled out by the Roncal-1 well, located to the north of the flexure some 12 km to the west of the transect. This basement thrust is equivalent to the Guarga thrust deduced further to the east by Cámara & Klimowitz (1985) on the basis of subsurface seismic information. As in the Axial Zone, the shape of the thrust has been drawn from the limb dips using an idealized fault-bend fold geometry. Another intervening basement thrust between the Gavarnie and Guarga thrusts has been tentatively projected into the present section (Fig. 4), based upon a similar basement culmination feature deduced some 15 km to the east (Teixell 1992).

The subsurface structure of the western External Sierras has been the subject of diverse interpretations. Nichols (1987*b*) interpreted it as a triangle zone composed of forethrusts and backthrusts. Pocoví *et al.* (1990) interpreted the Santo Domingo anticline as a large detachment fold, whose southern limb would be the authochtonous Ebro Basin block. Given the enormous accumulation of Triassic rocks that this interpretation requires in the core of the fold, and the refolding of thrusts observed to the west of the traverse (i.e. Puigdefàbregas & Soler 1973), the Santo Domingo anticline is here considered as entirely allochthonous and cut by an underlying thrust ramp (Fig. 4). This ramp does not emerge to the surface, and may continue as a buried detachment. The gentle folds which affect the Uncastillo Formation south of the External Sierras, which may be growth folds, tighter at depth, may be taken as additional evidence for the detachment.

The Ansó cross-section shows the importance of basement in the overall geometry of this segment of the Pyrenees. Major thrust faults appear to have a simple shape, with gently dipping (<20°) ramps in basement that turn into flats within cover rocks. A more complex situation is deduced in the Lakora thrust, reflecting pre-thrusting structures (see below). Basement forms major thrust sheets with little degree of overlap, markedly different from the antiformal stacking reported in more eastern transects of the Pyrenees (i.e. Muñoz 1992, etc.; Fig 1b).

Timing of deformation

The timing of the deformation structures can be in some cases determined from relationships with syntectonic sediments, and in others it may be inferred from indirect criteria taking into account the regional geological setting.

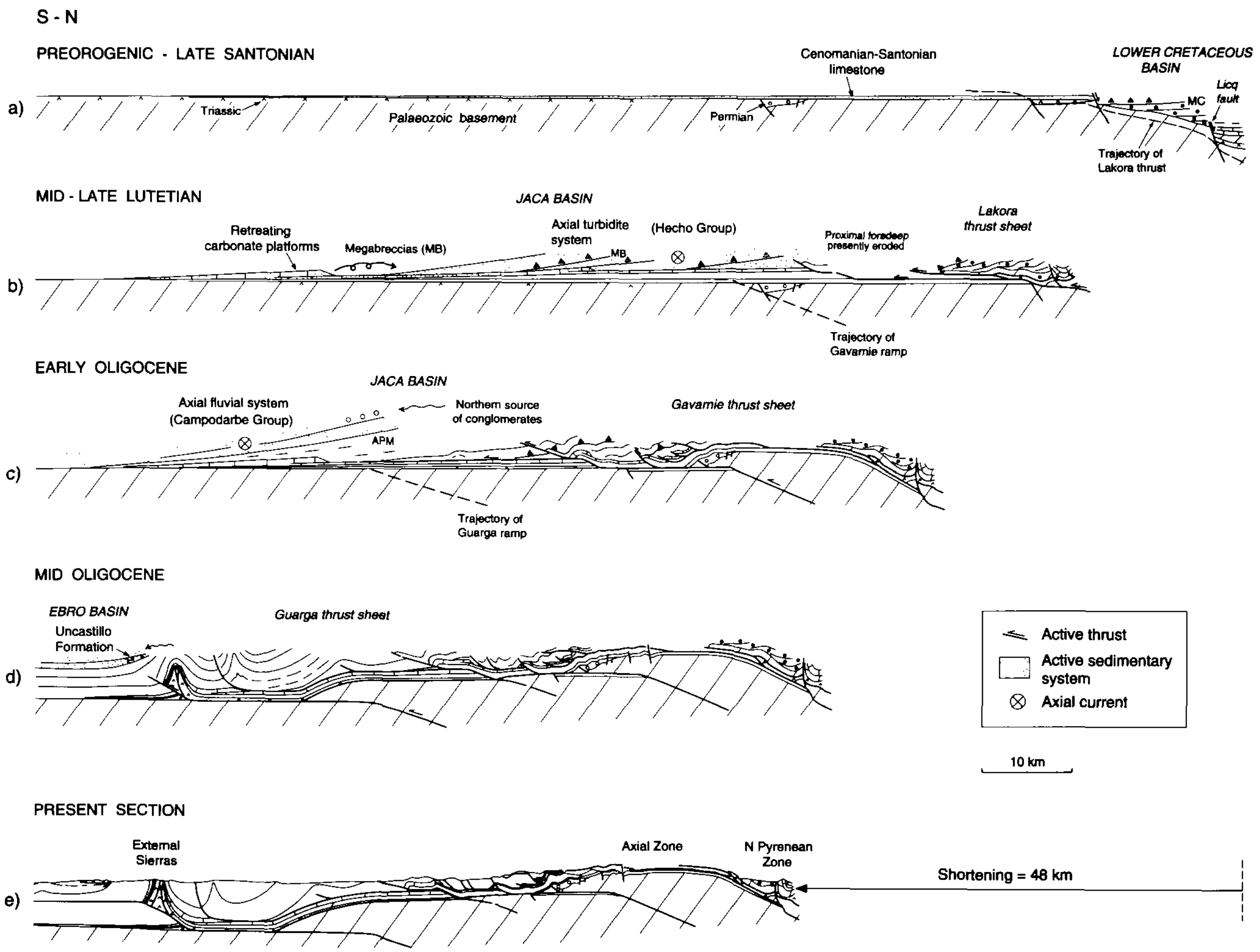

Fig. 5. Sequentially restored sections of the Ansó transect in stages to illustrate the tectonic–stratigraphic evolution. See text for explanation. Note that only the Lakora thrust inverts a pre-orogenic basin margin. MC, Mendibelza conglomerates; MB, Carbonate breccia megabeds of the Hecho Group; APM, Arguís–Pamplona marls.

Larra thrust system. The Larra thrust system can be continued to the east along the Sierras Interiores to the N–S-trending Boltaña lateral ramp anticline (Soler & Puigdefàbregas 1970). This growth fold developed during mid–late Lutetian to Bartonian times, as indicated by progressive and angular unconformities (Montes 1992), thus indicating a similar age for Larra thrust system.

Lakora thrust. Assuming that the Larra thrust splays from the Lakora thrust, as inferred from the thrust geometry in the cross-section, the age of movement on the Larra thrust can be regarded as the age of the last translation of the Lakora thrust sheet as a whole (at least for the segment behind the branch line between both thrusts). The total duration of the Lakora thrust is, however, difficult to establish. It may be speculated that the abrupt northward tilting recorded by the upper Santonian limestones of the Axial Zone (see above),was caused by load-induced flexure, in agreement with the development of the earliest south Pyrenean compressional structures recorded elsewhere at this time (Papon 1969; Simó 1989). If so, this could reflect the initial movement of the Lakora thrust sheet, although there is no direct evidence as the proximal foredeep of this and later stages has been eroded.

Gavarnie thrust. The Gavarnie thrust and the associated Axial Zone antiform deform both the Lakora and Larra thrusts. The second, dominant generation of folds and thrusts of the Jaca Basin, which are the southern continuation of this thrust, show synsedimentary growth relationships with Priabonian to Rupelian strata (Puigdefàbregas 1975; Teixell 1992).

External Sierras and Guarga thrust. In the vicinity of the cross-section, the development of the External Sierras has been dated as mid Rupelian to latest Oligocene–earliest Miocene, as suggested by angular and progressive unconformities in the upper part of the Campodarbe and in the Uncastillo beds (Puigdefàbregas & Soler 1973; Pocoví *et al.* 1990; Hogan 1993).

In the interpretation presented in this paper, displacement on the Gavarnie thrust is balanced with the structures in the interior of the Jaca Basin. Thus, the main emergence of the External Sierras can be related to the Guarga thrust (Fig. 4).

Sequential restoration and basin evolution

The Ansó cross-section has been sequentially restored in order to evaluate the magnitude of Alpine shortening and to gain insight on the pre- and syntectonic sedimentary basins (Fig. 5a–e). The method used is that based on bed-lengths, since most of the section contains competent units in which strain is negligible or concentrated only in small zones, starting from a local pin-line in the south (Fig. 4). The datum is the base of the Upper Cretaceous, which can be considered as flat-lying at the scale of the section and is sufficiently preserved from erosion. The restoration is shown by a series of steps, with three intermediate stages between the pre-orogenic and present states (Fig. 5 a–e). In each stage, the relationships between the active thrusts and the main syntectonic sedimentary units is illustrated.

The pre-orogenic stage corresponds to mid Santonian time (Fig. 5a). The Chainons Calcaires Mesozoic succession is bounded by the normal-fault precursor of the Licq fault (Ducasse *et al.* 1986; Teixell 1993). This region represents the margin of a Lower Cretaceous basin that extends to the north, in the remainder of the North Pyrenean Zone, and can be attributed to the Early Cretaceous extensional tectonics that has been postulated in other parts of the Pyrenees (i.e. Puigdefàbregas & Souquet 1986; Berastegui *et al.* 1990). The Albian Mendibelza conglomerates record a shift of the basin margin, the sedimentation covering the Licq fault and onlapping a tilted (flexured) margin (Iguntze block). The Upper Cretaceous limestones of the Axial Zone imply a new, very marked shift to the south, with expansive sedimentation over the present Axial Zone and Jaca Basin domains. The limestones form a tabular body of shelf deposits, indicating homogeneous and moderate subsidence, consistent with thermal sag following the Early Cretaceous extension. The onlap of the Albian strata may be interpreted to reflect the last stages of fault-dominated subsidence and the transition to the thermally controlled subsidence.

Figure 5b shows the architecture during Lutetian time. The Lakora thrust sheet resulted from inversion of the North Pyrenean basin margin, slicing off a thin piece of basement (Iguntze massif), and detachment begun to propagate into its foreland as the Larra thrust. To the south of these structures, the Hecho turbidites formed a typical foreland clastic wedge, that progressively onlapped southwards onto a retreating carbonate platform complex of the distal basin margin (Labaume *et al.* 1985; Puigdefàbregas & Souquet 1986; Barnolas & Teixell 1992). The resultant taper of the sedimentary basin is about 5°. The total onlap migration of the turbidites is some 45 km southwards, which is more than double of the estimated thrust displacement at the hinterland, implying that the basin widened with time. The terrigenous turbidites were sourced in the hinterland, essentially to the east of the transect, and redistributed by axial currents (Mutti 1977, 1984). The carbonate megabreccia beds interbedded with the turbidites are interpreted to be derived from shelf-edge collapses of the retreating carbonate margin (Barnolas & Teixell 1994), and thus were sourced transversely.

The third stage (Fig. 5c) shows the development of the next basement fault, the Gavarnie thrust, whose ramp anticline forms the Axial Zone culmination. At this time, the northern part of the Jaca Basin was detached and imbricated, and the uplifted Hecho group was reworked into a terrestrial foreland basin. However, the basin was still dominated by axial fluvial systems (Campodarbe Group), still sourced from the east (Puigdefàbregas 1975; Hogan 1993).

The fourth stage portrays a new basement thrust and the deformation of the entire Jaca Basin, which is separated from the sedimentary area (Ebro Basin) by the rising thrust front of the External Sierras (Fig. 5d). The Sierras had commenced as a large fault-propagation fold, during the sedimentation of the upper Campodarbe Group. This structure was then uplifted and tightened by a basal, non-emergent thrust, giving way to the development of progressive unconformities in the Uncastillo Formation. The formation originated in a large fluvial system derived from reworking of the Jaca Basin, bypassing the Sierras by a structural low caused by the abrupt increase of westerly plunge (Hirst & Nichols 1986; Friend 1989). This situation continued until approximately the Oligocene–Miocene boundary, where the structural configuration was very close to that of the present section (Fig. 5e).

Shortening and deformation rates

The Alpine contraction along the study transect can be estimated from the comparison of the present-state and the restored sections. From the southern pin-line to the Licq fault, the shortening is calculated to be a total of 48 km, which represents approximately 40% of the undeformed length. This value can be further partitioned in the different contributions by the principal structures. The Lakora thrust and related branches imply 22 km of shortening, 5 km of which can be ascribed to the Larra thrust system. In addition, 14 km of shortening can be attributed to the Axial Zone antiform and the internal thrusts of the Jaca Basin, whereas the remaining 12 km of shortening were taken up by the External Sierras and the frontal culmination wall of the related Guarga thrust.

According to these values, and to the timing discussed above, it can be calculated that the Larra thrust system evolved at a shortening rate of 1 mm a^{-1} (time scale of Harland *et al.* 1990). In contrast, the Gavarnie and related thrust system in the interior of the Jaca Basin developed at a rate of 1.3–1.4 mm a^{-1}, whereas the emergence of the External Sierras was accomplished at a rate of 1.1 mm a^{-1} from the mid-Oligocene to the earliest Miocene. It must be remembered that these values do not represent the total orogenic contraction rates of the Pyrenean chain, as the structural development of the north-vergent system of the North Pyrenean Zone has not been analysed in this paper.

Discussion and conclusions

The structural transect presented here constitutes an example of relationships between basement and cover thrusting in an orogenic belt, and shows how these influence the evolution of adjacent foreland basins. The Ansó balanced section is a new, constrained traverse which demonstrates the influence of Alpine age basement structures in controlling the geometry of this part of the southwestern Pyrenees. Basement units are at different elevations and define a series of steps separated by monoclinal flexures, which are reflected in the erosion level and corresponding map pattern of the overlying cover rocks. Flexures correspond to hanging-wall ramps of basement thrusts, which may be constructed using an idealized kink-like fault-bend fold geometry. Some of these thrust sheets generate a marked structural relief and are fairly thick-skinned.

Basement thrust sheets have slipped less distance than their length, resulting in less overlap than that documented more to the east in the Pyrenees (cf. Muñoz 1992). Thus, the Axial Zone culmination in this area does not appear as an antiformal stack, as for example in the ECORS section (Choukroune *et al.* 1989; Muñoz 1992), but can be interpreted as a large flat-topped ramp anticline with little internal disruption. The very gentle plunge of this anticline, due to reduction of displacement along its underlying Gavarnie thrust, causes the westerly termination of the Palaeozoic outcrops, without a noticeable lateral ramp. Other basement thrusts exist to the south of the Axial Zone, beneath the south Pyrenean cover rocks of the Jaca Basin. The southern margin of the North Pyrenean Zone is formed by gently dipping thrust faults with large south-directed displacement. Vertical structures such as those of the North Pyrenean Fault Zone, which occupy an analogous position in more eastern parts of the orogen, may have also had originally low-angle attitudes, but have experienced more rotation there due to the higher amplitude of the Axial Zone.

In the Ansó transect, basement thrusts can be correlated with different groups of structures within the cover units. Detachment levels along the traverse may be located in the Triassic shales and evaporites; however, flat and long detachments can also be located within the Upper Cretaceous limestones and marls (e.g. Larra thrust), or at the base of Eocene marl and turbidite successions, especially if Triassic strata are absent. In the thrust front of the External Sierras, a basal, non-emergent thrust is inferred to underlie the exposed structure.

When compared to the ECORS-Pyrenees section, the Ansó transect implies significant along strike change in structure within the central Pyrenees. Nevertheless, the geometry depicted in this transect appears valid for a large region in the Jaca–Pamplona segment of the orogen. In addition, the shortening of the southern Pyrenees along the transect is only 48 km (40%). When this is compared with the 110 km estimated by Muñoz (1992) for the equivalent south-vergent structures in the ECORS-Pyrenees section, these values imply a remarkable reduction of shortening towards the west. However, part of this large difference can be due to uncertainties in the position of the basal cutoff and the amount of Alpine shortening of the deeply eroded Axial Zone in the ECORS transect. In the remainder of the North Pyrenean Zone, to the northwest of the study area (ECORS-Arzacq profile), shortening has been estimated in 23–30 km (Daignières *et al. in* Grandjean 1992). Considering this, the total shortening of the Pyrenean orogen along the Ansó transect may only be a total of 70–80 km.

Sequential restoration of the balanced section constructed in this study links the main basement thrusts active at each moment with their continuation into the cover, and illustrates the relationships of the structures with the syntectonic sedimentation. These relationships indicate that the major thrusts developed in a forward-propagating sequence, with the Lakora thrust inverting the Cretaceous extensional basin and governing late Cretaceous (?) to mid-Eocene foreland marine sequences (including turbidites), the Gavarnie thrust causing uplift of the previous proximal foredeep, along with shallowing and transition into terrestrial sedimentation during the late Eocene to the Oligocene, and finally the Guarga thrust partitioning the foreland basin and shifting the locus of sedimentation to the authochtonous Ebro Basin in late Oligocene to earliest Miocene times.

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