Journal of Structural Geology 28 (2006) 1909–1920

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Inversion of small basins: effects on structural variations at the leading edge of the Axial Zone antiformal stack (Southern Pyrenees, Spain)

Eduard Saura*, Antonio Teixell

Departament de Geologia, Unitat de Geotectònica, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

Received 5 June 2006; accepted 9 June 2006
Available online 22 August 2006

Abstract

The southern Axial Zone of the Pyrenees consists of a foreland-dipping system of thrusts and backthrusts, forming the leading edge of a basement-involved antiformal stack. Several small Stephanian-Permian extensional basins were strongly inverted during the Pyrenean (Cainozoic) orogeny and controlled thrust geometry and kinematics, causing lateral structural variation. Palinspastic restoration reveals three main grabens (Erill Castell, Estac and Gramós basins) capped by undeformed Triassic strata, in the lower (Orri and Erta) thrust sheets. The overlying Nogueres thrust sheet, partitioned into several slices, contains smaller basins (Northern basins). The Erill Castell half-graben, with a steeply-dipping sedimentary infill, was inverted along its border fault and extruded by bedding-parallel backthrusts. The narrow, thick Estac basin, which was less deformed internally, was a heterogeneity causing major lateral variation in the system. The Gramós basin, originally wide and covered by a gentle unconformity angle, was also inverted along its border fault, but caused less lateral variation in the thrust system. The Northern basins appear only in the western part of the present-day Nogueres thrust sheet, where minor units are strongly stacked and rotated. In the east, thrust slices are large and shallow dipping. The study case is a good example of complex 3D thrust development influenced by the initial geometry of a heterogeneous basin system.

Keywords: Extensional fault; Basin inversion; Stephanian-Permian; Thrust; Antiformal stack; Pyrenees

1. Introduction

The occurrence of pre-existing extensional basins in an area undergoing orogenic shortening usually results in the inversion of basin faults that possess favourable orientation (Gillcrist et al., 1987; Hayward and Graham, 1989; Coward, 1996). Compressional structural geometries and patterns are conditioned by the basin characteristics (i.e., location and architecture of basin faults and associated lithologic changes). Such features are very well illustrated at the leading edge of the Axial Zone antiformal stack of the Southern Pyrenees, a basement-involved thrust system where complex three-dimensional relationships arose during the strong inversion of a system of small Stephanian-Permian grabens.

The Pyrenean orogen developed within the Alpine system during Late Cretaceous to earliest Miocene times, as a result of convergence between the Iberian and European plates. The structure of the orographic core of the Pyrenees (Axial Zone) is characterised by the stacking of several southward-facing thrust sheets, which involve a Variscan (Palaeozoic) basement and an upper Carboniferous to Triassic cover. These thrust sheets define a large antiformal stack (Williams, 1985; Roure et al., 1989; Muñoz, 1992) (Fig. 1) that is built up by four main complex thrust sheets: Nogueres, Erta, Orri and Rialp (from upper to lower) (Poblet, 1991; Muñoz, 1992; Saura, 2004). During progressive deformation, the location of new thrust ramps behind the overlying thrust sheet foretips resulted in forelandward rotation of previous thrust sheets. The uppermost thrust sheet (Nogueres thrust sheet) is far-travelled

* Corresponding author. Tel.: +34 9 620200454; Fax: +34 93 581 1263.
E-mail address: eduard.saura@uab.es (E. Saura).

0191-8141/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2006.06.005

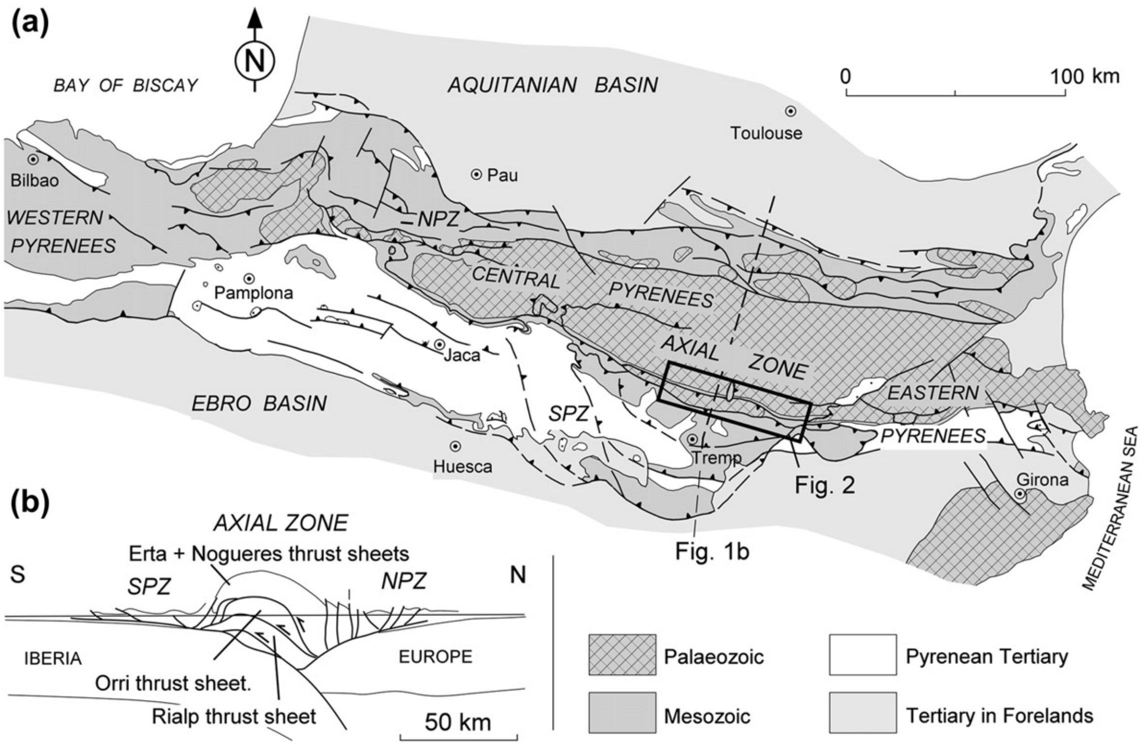

Fig. 1. a) Geologic sketch map of the Pyrenees showing the main longitudinal and transverse divisions of the chain and the location of the study area (after Teixell, 1992). b) Interpretation of the ECORS-Pyrenees deep seismic profile through the Pyrenean chain (after Muñoz, 1992), showing the main thrust sheets of the Axial Zone. SPZ: South Pyrenean Zone (cover thrust sheets); NPZ: North Pyrenean Zone.

and appears unrooted, now resting on a complex footwall flat on top of Triassic sediments. The outcrop area of this thrust sheet and the underlying Erta sheet is traditionally referred to as "Nogueres Zone" (Dalloni, 1910; Seguret, 1972), although in this work we will follow a different nomenclature referring to thrust units. Characteristic of the area is the occurrence of forelandward-rotated, synformal ramp anticlines ("têtes plongeantes", Seguret, 1972), associated with downward-facing thrusts.

Several distinct extensional basins of Stephanian-Permian age are involved and influence the geometry of the Axial Zone antiformal stack. The aim of this contribution is to show how a 3D basin system controls lateral and vertical structural variation during the building of a thrust belt, using the southern limb of the Pyrenean Axial Zone as a case study.

2. Stratigraphic setting

Rocks cropping out in the study area range from Cambrian to Oligocene in age (Figs. 1 and 2a), and can be grouped according to their deformation characteristics. The basement is formed by Cambrian to Lower Carboniferous sedimentary and low-graded metamorphic rocks, that were deformed by the Variscan orogeny around mid Carboniferous age. Stephanian-Permian sedimentary and volcanic rocks were unconformably deposited in small extensional basins, which in turn were covered by extensive, tabular Triassic beds. Jurassic to Lower Cretaceous carbonate sequences were deposited during a second extensional stage that opened the main Pyrenean rift and the Bay of Biscay, whose later closure (Pyrenean orogeny) was recorded by Upper Cretaceous – Oligocene sedimentary rocks.

Stephanian-Permian rocks occur in discontinuous outcrop areas across different thrust sheets that were defined as separate basins (Gisbert, 1983; Gisbert et al., 1985; Martí, 1986). To the west, the Erill Castell basin (Fig. 2a) has more than 1000 m of syn-rift sedimentary and volcanic rocks and extends for 15 km along strike (~E-W direction). In the central part, the Estac basin is narrow along strike (<3 km) but contains more than 800 m of syn-rift rocks. Finally, the easternmost basin (Gramós basin) is the largest, with an infill more than 1500 m thick and extending for more than 30 km along strike, beyond the study area (Fig. 2a). Some small basins, with accumulations of 200 m of sedimentary and volcanic rocks are present in the south-transported Nogueres thrust sheet. These are here called Northern basins referring to their original position.

The Stephanian-Permian successions show stratigraphic diversity, although a synthetic column can be established (Fig. 3). The lithostratigraphic framework was defined by Mey et al. (1968), while further sedimentologic and petrologic details were provided by Gisbert (1983), Gisbert et al. (1985) and Martí (1986). Basal breccias of the Upper Carboniferous Guiró Fm. (Fig. 3) appear scattered along the base of some basins, reaching thicknesses up to 350 m in the Erill Castell and Estac basins. A volcanic and vulcanoclastic formation (Erill Castell Fm.) unconformably rests on top of the breccias or the basement, and includes tuffs and ignimbrites at the lower

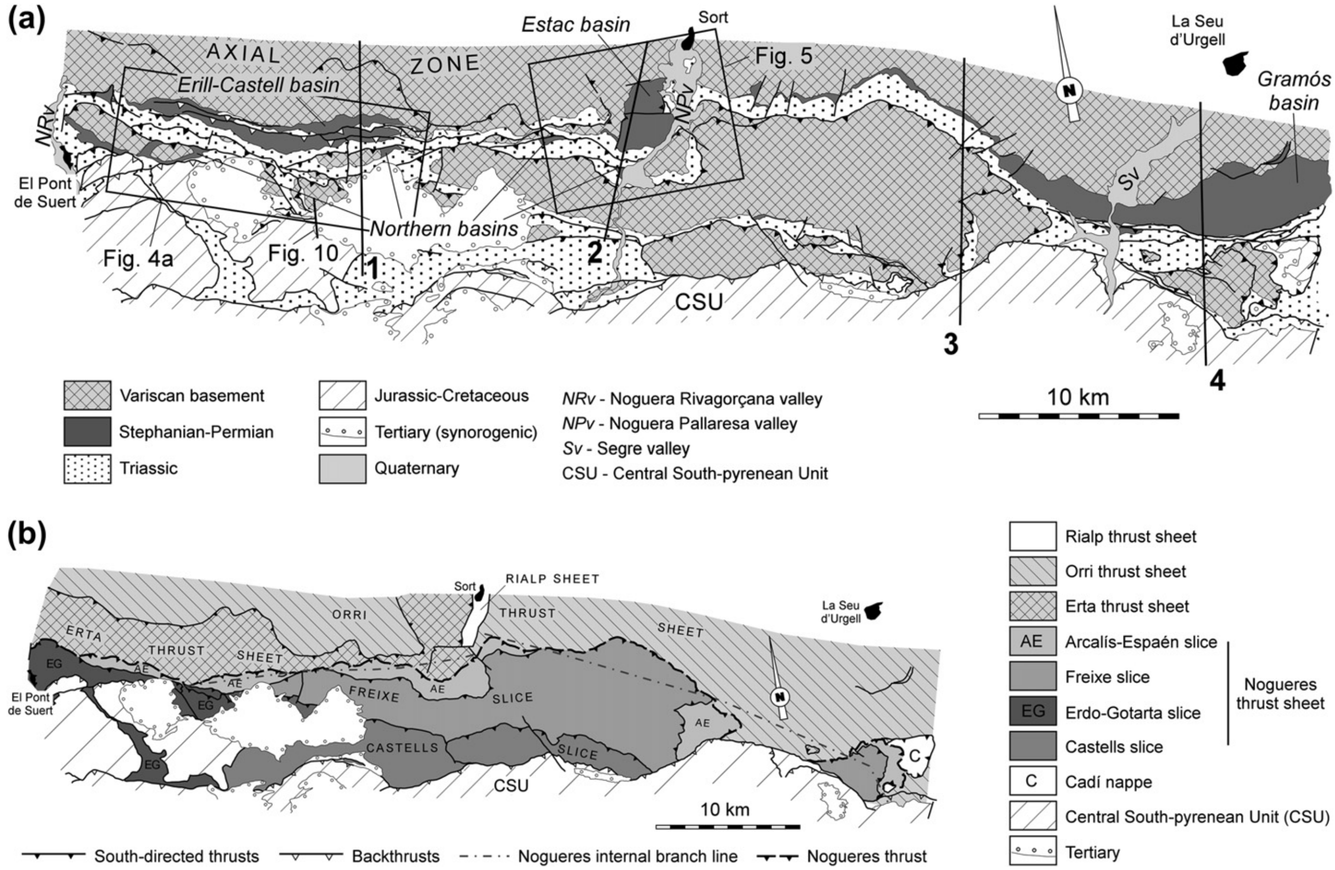

Fig. 2. a) Simplified geological map of the southern limb of the central Axial Zone antiformal stack, showing the location of the main Stephanian-Permian basins. Numbered lines (1 to 4) indicate the cross-sections of Figs. 4b, 5b, 6a and 7a. b) Tectonic sketch map showing the nomenclature of thrust sheets. The Rialp thrust sheet crops out only in the Noguera Pallaresa valley. Minor thrust slices integrating the Nogueres thrust sheet are differentiated.

part, evolving to andesitic flows in the upper part. Usually its thickness ranges from 200 to 400 m. The uppermost Carboniferous is recorded in some basins by coal beds interbedded with shales and greywackes (Malpàs Fm.), which may show marked thickness variations along a single basin (maximum thickness: 550 m in the Gramós basin). The Malpàs formation grades to the Peranera red beds of Permian age (Fig. 3). The Peranera formation reaches a thickness of 950 m in the Erill Castell basin and 1500 m in the Gramós basin, where it records the widest time window (up to the Upper Permian; Gisbert, 1981). It is made up with red shales and interbedded sandstone, conglomerate and scarce limestone layers. This formation is the last of the syn-rift succession and may itself rest unconformably upon any of the previous stratigraphic units.

A Triassic unconformable sequence, which we interpret as post-rift, shows the typical "Germanic" facies, subdivided into Buntsandstein red beds, Muschelkalk limestone and Keuper shales and evaporites (Gisbert et al., 1985; Calvet et al., 2004) (Fig. 3). The Buntsandstein starts with a basal conglomerate, followed by interbedded sandstones and shales, depicting a large-scale fining-upward trend. In the Orri and Erta thrust sheets the thickness of the Buntsandstein is constant (around 200 m); within the Nogueres thrust sheet it usually has a comparable thickness, although it may locally vary from 50 m to 500 m, suggesting that some extensional faults were still active, especially during the sedimentation of the basal conglomerates. Muschelkalk limestones crop out as discontinuous bars embedded within highly distorted Keuper, and have not been differentiated in the maps and cross-sections presented here. During Pyrenean compression, the soft Keuper layers acted as the upper detachment level for the Axial Zone antiformal stack and as the lower one for the Central South-Pyrenean Unit.

Jurassic to Lower Cretaceous carbonate sequences are detached from the Keuper layers, and separated from the Axial Zone thrust sheets by a complex backthrust zone (Morreres backhrust; Muñoz, 1992). They form a large imbricate fan in the Southern Pyrenees known as Central South-Pyrenean Unit (Seguret, 1972), whose structural evolution is beyond the scope of this paper.

Pyrenean syn-orogenic sediments in the study area are found in two different structural contexts. Upper Cretaceous to Lower Eocene foreland basin sequences are intensely deformed, forming part of the Cadí nappe of the Eastern Pyrenees (Fig. 2). This nappe overlies the Orri thrust sheet and is laterally overlapped by the Nogueres thrust sheet. Upper Eocene to Oligocene conglomerates deposited in small, isolated intermontane basins are common along the southern border of the Axial Zone (Fig. 2). These rocks are largely

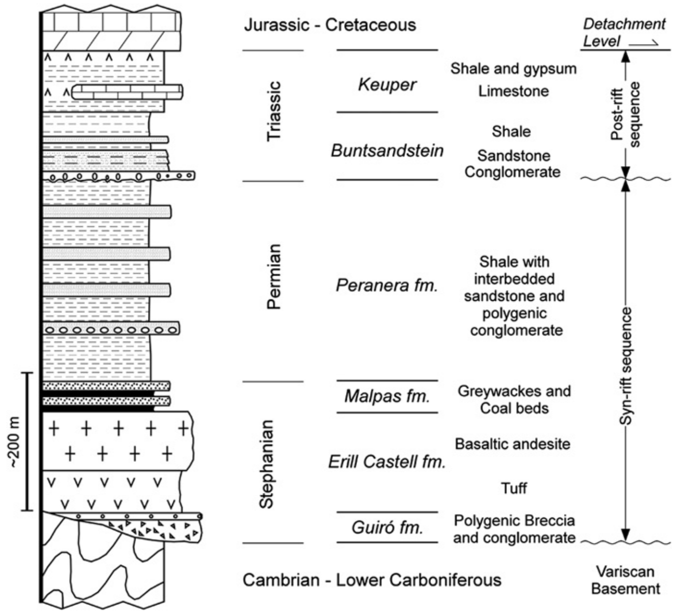

Fig. 3. Synthetic stratigraphic log of the study area (simplified after Mey et al., 1968). See text for unit thicknesses and their variations.

unconformable on any of the previous formations, and constrain timing of late deformation. Three stratigraphic units have been differentiated according to angular unconformities and changes in lithological characteristics; from older to younger they are the Sarroca, Senterada and Antist groups (Mellere and Marzo, 1992; Saura and Teixell, 2000). The Sarroca group contains pebbles derived from immediately adjacent Central South-Pyrenean and Nogueres units, and appears strongly affected by deformation. The Senterada group, which is only gently folded and contains growth-strata, contains Palaeozoic and Triassic pebbles, while the horizontally-bedded Antist group contains mainly Palaeozoic pebbles.

3. Basin inversion

The main thrust sheets recognised in the southern part of the Axial Zone antiformal stack are, from the base to the top of the pile, the Rialp, Orri, Erta and Nogueres thrust sheets (Fig. 2). The transport direction of these major units is to the SSW, parallel to the mean shortening direction of the Southern Pyrenees (Seguret, 1972; Poblet, 1991; Muñoz, 1992). However, north-directed backthrusts are locally present. The map trace and the strike of major structures is close to E-W (Fig. 2a); the folded thrusts are rotated to a foreland-dipping attitude which, combined with erosion, gives an impression of generalised northern vergence in map view. Fig. 2 also illustrates variations of the structural units along strike. The Erta thrust sheet disappears laterally to the east, while the Orri thrust sheet increases in thickness, and the Nogueres thrust sheet is heterogeneously subdivided into a number of smaller-scale thrust slices (Fig. 2b).

Tectonic inversion processes strongly determined the compressional deformation structure, as most of the structural variations are influenced by the architecture of the Stephanian-Permian basin system. In the western part of the study area, where the Erill Castell basin and the Northern basins occurred (Fig. 2a), thrust faults are steep, and bound small thrust units. On the other hand, the Estac basin, in the central part (Fig. 2a), caused a marked geometric change: to the east, thrusts dip gently, and, as the equivalent to the Northern basins did not exist, thrust units are larger in size. In this latter area, tectonic inversion was therefore less influential on the geometry of the thrust system.

In this paper, we will first describe the present-day structure of each basin and then we will discuss how differential inversion resulted in variations along and across strike. We will conclude with a 3D palinspastic reconstruction of the extensional basins system to Stephanian-Permian times and to the time previous to the emplacement of the Rialp thrust sheet, the youngest of the stack.

3.1. Structure of the Erill Castell basin

The present-day structure of the Erill Castell basin and adjoining areas and its restoration are shown in Fig. 4. The cross-section (Fig. 4b) shows a south-dipping system of foreland-directed thrusts and backthrusts. The uppermost thrusts have experienced strong rotation and overturning (Nogueres thrust sheet) whereas the lower Erta and Orri thrusts show progressively less rotation. The Erill Castell basin is incorporated in the Erta thrust sheet, and is internally deformed by an imbricate fan of backthrusts. Restoration indicates that this basin formed initially as a half-graben with its basin-bordering fault, named the Erta fault (Mey, 1968; Poblet, 1991), located to the south (Fig. 4c). Stephanian-Permian layers, with a maximum thickness of about 1000 m in the depocentre of the basin, were tilted to the south up to 30°. The basin was covered by tabular unconformable Triassic (Fig. 4c).

The Erta thrust derived from the inversion of the border extensional fault. Upsection, the thrust becomes bedding-parallel to follow an upper detachment at the Keuper level, where it branches to the Orri thrust. As a result of inversion and rotation by underlying thrust sheets, the infill of the Erill Castell basin dips very strongly to the south. We interpret that the backthrusts that internally deform the basin are rooted in the Erta thrust (Fig. 4b). They are likely associated with the early inversion of the basin due to the inclined bedding anisotropy, defining a "pop-up" style of inversion. They were later steepened along with bedding during the stacking of the underlying thrust sheets. Low-angle backthrusts accompanying tectonic inversion were predicted by Hayward and Graham (1989, their Figs. 2 and 3).

3.2. Structure and significance of the Estac basin

The Estac basin, located in the central part of the study area (Fig. 2a), is responsible for a marked along-strike change of structural style. The present-day geometry of the deformed basin is illustrated in Fig. 5. As seen in the western slopes of the Noguera Pallaresa valley (Fig. 5a), the Estac basin is incorporated in the Erta thrust sheet. Taking Triassic bedding as a

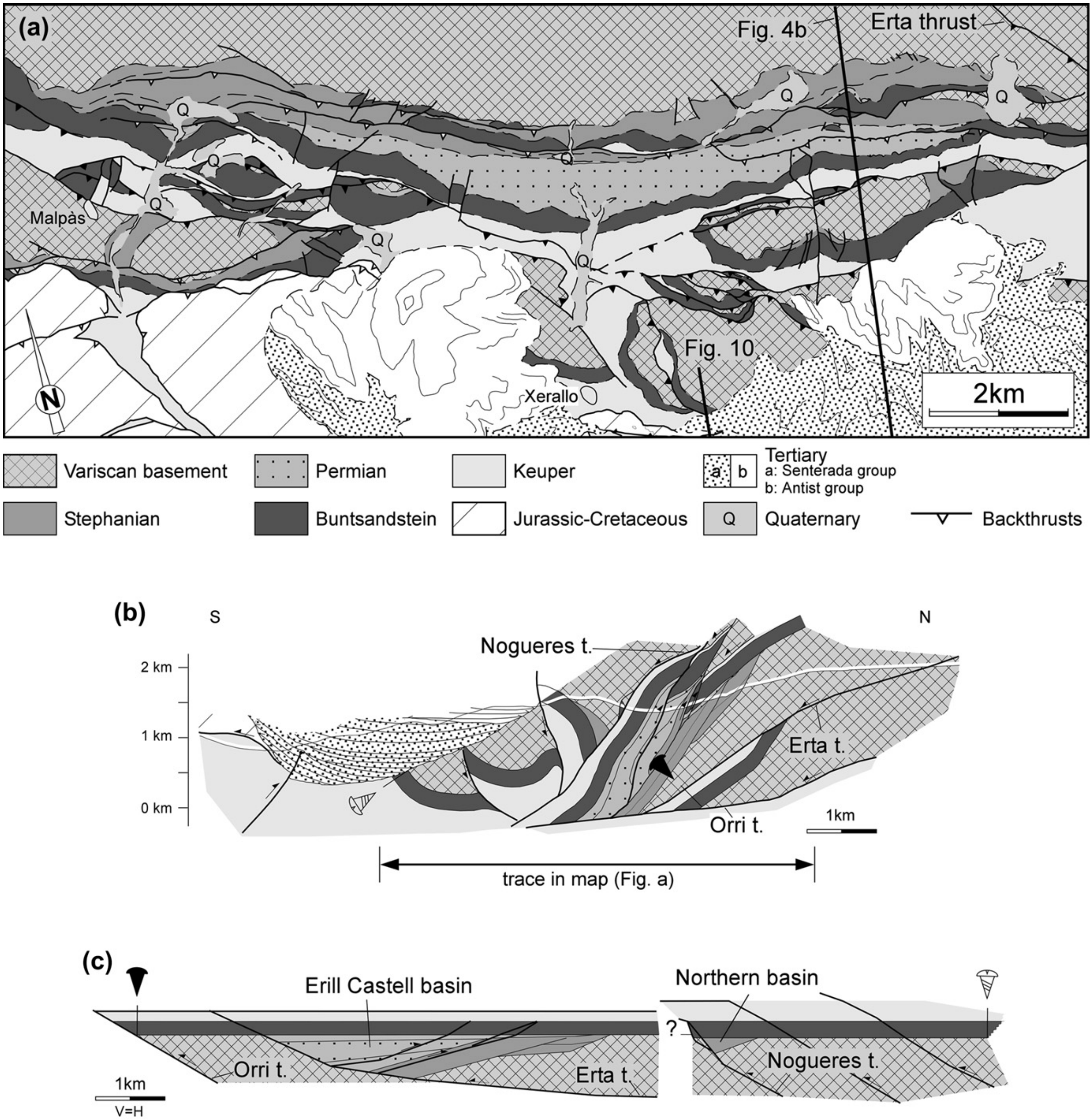

Fig. 4. a) Geological map of the Erill Castell basin and the overlying Nogueres thrust sheet. Lines within the Tertiary indicate bed traces. b) Balanced cross-section (line 1 in Fig. 2a). The northern and southern limits of the section extend beyond the actual borders of the map of Fig. a. c) Restored cross-section. Question mark indicates uncertainty about the original distance between the Erta thrust sheet and the front of the Nogueres thrust sheet. The scale of the cross-sections is double of that of the map.

pre-orogenic horizontal datum, the internal layering of the basin was originally inclined to the north, suggesting that the major extensional border fault was in this direction. However, erosion of the northern part of the basin does not allow confirmation of this hypothesis. At its leading edge, the Erta thrust directly rests on the Rialp thrust sheet (the frontal branch line of the Orri thrust lies behind) folded into a wide antiform by the emplacement of the latter.

The outcrop extent of the Estac basin is rather equidimensional (Fig. 5). The basin is narrow along strike (∼3 km) but thick (it contains more than 1500 m of Stephanian-Permian sedimentary and volcanic layers). It is bound to west and east by two high-angle cross faults (Soriano et al., 1996) (Estac and Malmercat faults, Fig. 5).

During the inversion stage, the Malmercat fault acted as a high angle lateral ramp defining the eastern boundary of

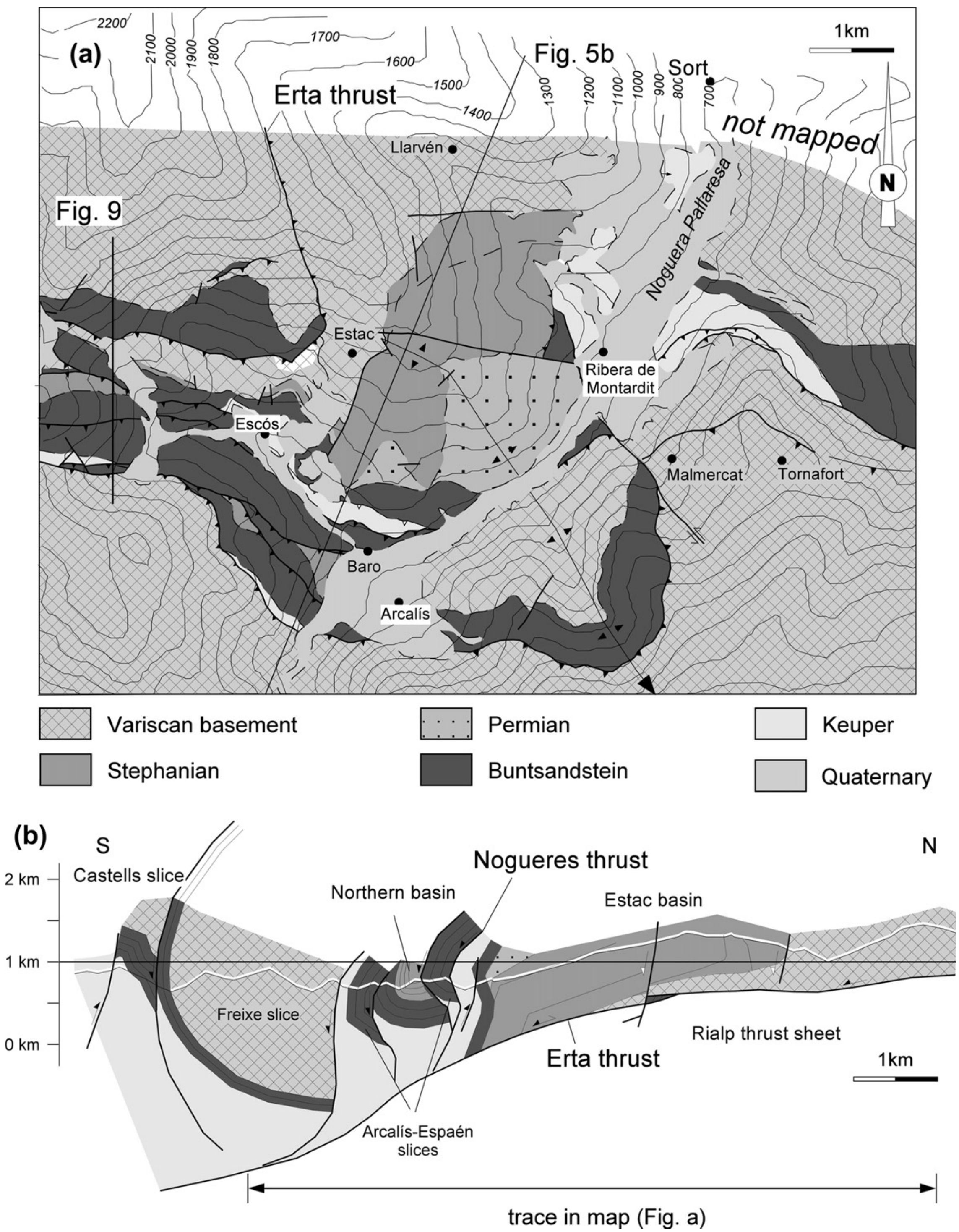

Fig. 5. a) Geological map of the Estac basin area. Topographic contour lines are indicated. The Noguera Pallaresa valley offers the most complete section of the southern limb of the Axial Zone antiformal stack, as all of the main thrust sheets (Rialp, Orri, Erta and Nogueres) are exposed. To the east of Malmercat, the Nogueres thrust directly overrides the Orri thrust sheet; to the west, the Erta thrust sheet is located between the Orri and Nogueres sheets. Triassic outcrops north of Ribera de Montardit constitute the only surface exposure of the Rialp thrust sheet. b) Cross-section parallel to Noguera Pallaresa valley (line 2 in Fig. 2a). Obliquity of structures and structural lines does not allow restoration.

the Erta thrust sheet. This caused a sharp change of structural relief, and consequently a variation in the stacking pattern of the overlying thrusts. The Estac basin marks a lateral transition from steep to shallow foreland-dipping thrust faults in the leading edge of the Axial Zone antiformal stack (e.g., compare Figs. 4 and 6).

East of the Estac basin, the Orri thrust sheet is directly overlain by the Nogueres thrust sheet (Figs. 2 and 6).

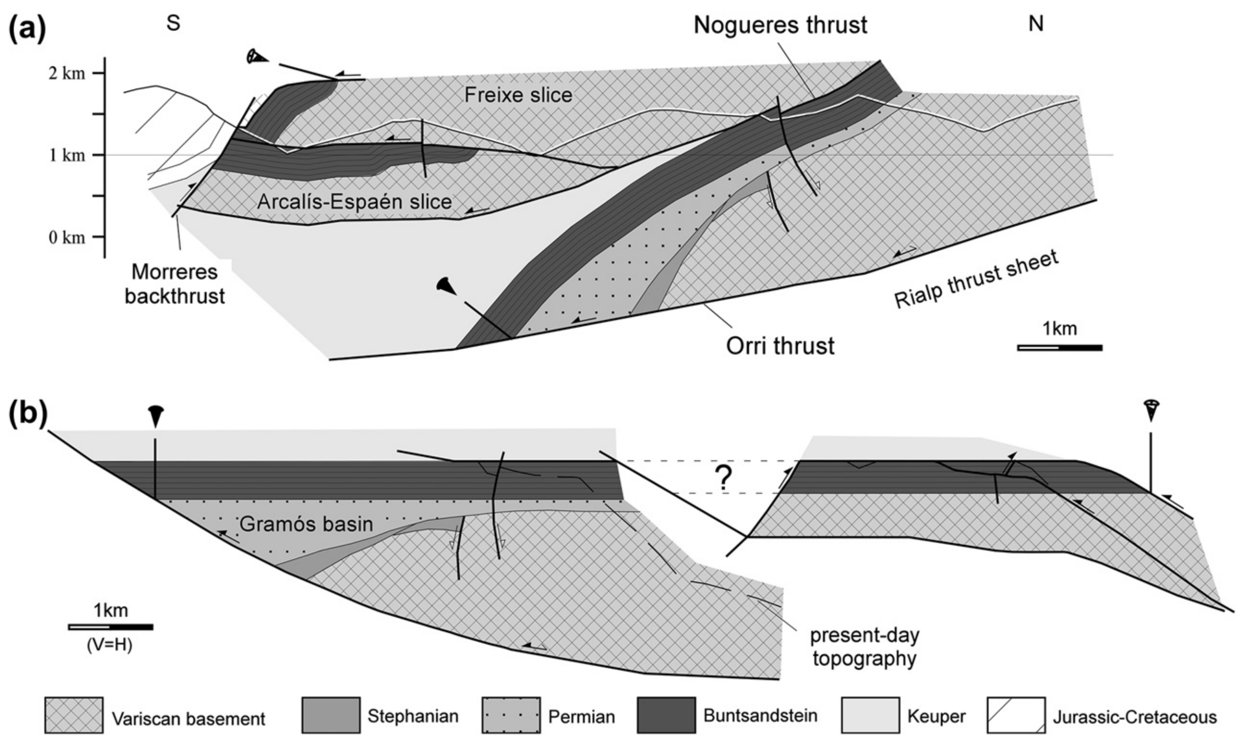

Fig. 6. a) Balanced cross-section through Orri thrust sheet and Nogueres thrust sheet (divided into the Freixe and Arcalís-Espaén slices) east of the Estac basin (line 3 in Fig. 2a). b) Restored cross-section.

Characteristic of this area is a simpler geometry with greater lateral continuity of the structures. In the eastern slopes of the Noguera Pallaresa valley, the Triassic usually rests directly on pre-Variscan rocks, and further east the Gramós basin progressively appears beneath the unconformable Triassic beds (Fig. 2a).

3.3. Structure of the Gramós basin

The Gramós basin, largely exposed in the Segre valley, is incorporated in the Orri thrust sheet (Figs. 2, 6 and 7). This area is overprinted by late extensional faults of Miocene age. The basin, extending for more than 30 km along strike, is tilted to the south defining the frontal culmination wall of the Orri thrust. The southern basin margin is never exposed, but its northern margin crops out in the downthrown side of a Miocene normal fault close to la Seu d'Urgell, where the basin is seen to be bordered by minor extensional faults (Saura, 2004). The unconformity angle between Permian and Triassic layers in this basin is lower than at Erill Castell, with the sub-unconformity beds dipping to the south ~5–10° steeper than the Triassic (this angular relation may even be reversed, by 5° at maximum).

These geometrical characteristics permit the restoration of the Gramós basin as an asymmetric graben limited by extensional faults to the north and to the south. Although synsedimentary normal faults do crop out to the north, the regional tilting of Stephanian-Permian layers with respect to the unconformable Triassic suggests that the main fault was to the south (the present-day Orri thrust; Vergés, 1993). In fact, the normal faults of the northern basin margin were active only during the sedimentation of the Guiró, Erill Castell and Malpàs formations, being fossilized by the Permian Peranera formation (Saura, 2004). Contrasting with the Erill Castell basin, the Gramós basin was less deformed internally during inversion. We interpret this as a consequence of gentler dips of Stephanian-Permian layering, which did not favour extrusion by backthrusts (Fig. 8).

3.4. The Northern basins and the structure of the Nogueres thrust sheet

The so-called Northern basins were a system of small grabens, with maximum thickness of 200 m and variable infill. Some of them have an incomplete sedimentary record, consisting of one of the Stephanian-Permian formations only (Saura, 2004). These basins were originally located north of the Erill Castell and Estac basins; Pyrenean thrusting brought them to their present position at the southern edge of the Axial Zone, as part of the far-travelled Nogueres thrust sheet. Based on the geology of the Noguera Pallaresa valley, Muñoz (1992) used a different nomenclature for the thrust units, distinguishing what he named the Lower Nogueres thrust units (including the Erta thrust sheet and the Arcalís-Espaén slice as defined here, see Fig. 2b) from the Upper Nogueres thrust units (comprising the Freixe and Castells slices). In the light of lateral equivalences of structural units, we propose a different organisation, and redefine the basal Nogueres thrust as the envelope of the minor internal thrusts, and whose diagnostic feature is

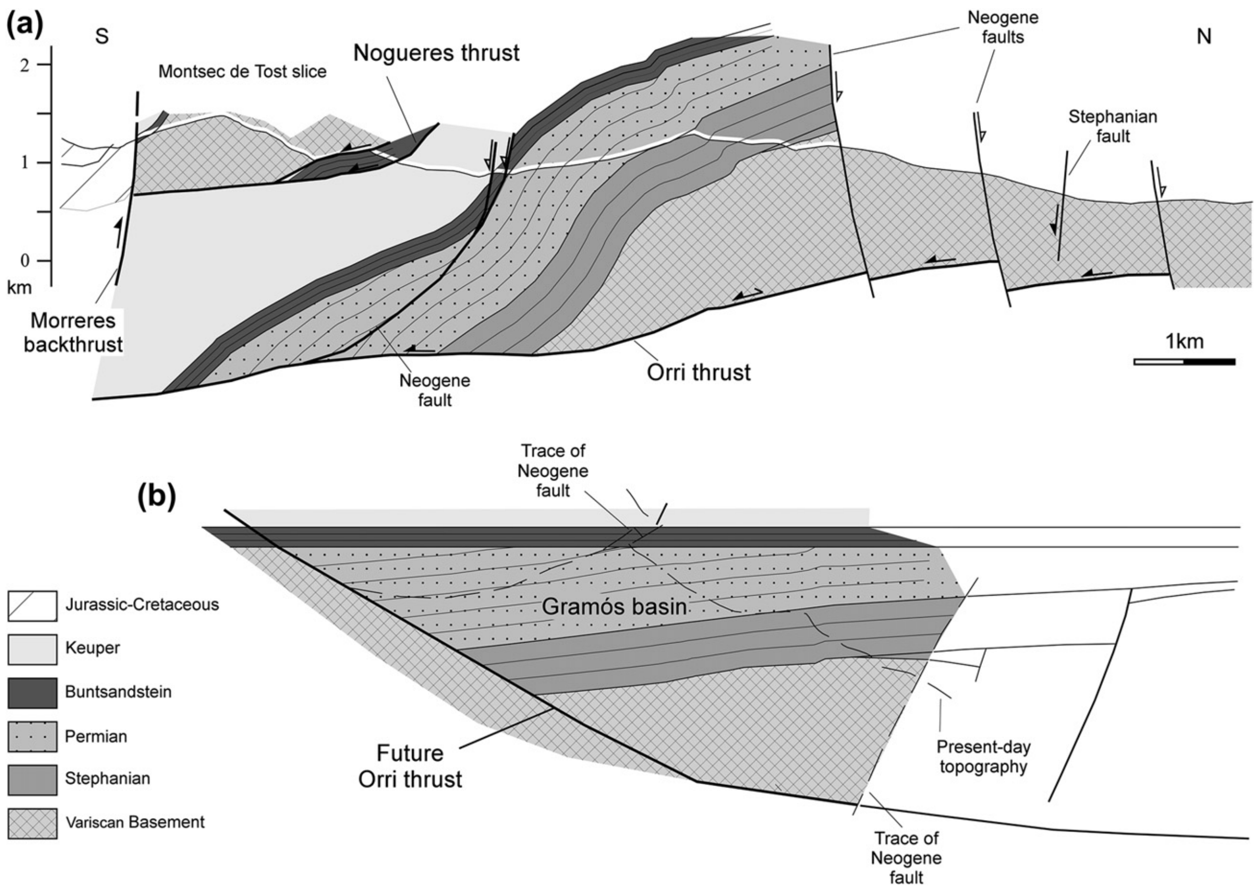

Fig. 7. a) Balanced cross-section through the Orri and Montsec de Tost thrust sheets (Nogueres thrust sheet), east of Segre river valley (line 4 in Fig. 2a). Internal deformation of Keuper rocks is not depicted. b) Restored cross-section of the Gramós basin. The Montsec de Tost unit has not been restored due to scarce preservation, although it should be brought north of the Gramós basin at an unknown distance. Dashed line indicates present day topography.

that it always conforms to a footwall flat on Triassic rocks (the footwall ramp is never observed).

West of the Noguera Pallaresa valley (Fig. 2), the Nogueres thrust, which rests on a composite footwall flat over the Triassic rocks of the Erta sheet (Fig. 4a), is strongly tilted to the foreland (more than 60°), and overlying thrust slices are numerous and small (Fig. 9). This partition into numerous slices results from the inversion of the Northern basins (Figs. 2 and 4). Footwall shortcut structures are common (formed after some slip is accommodated along basin-bordering faults). Another

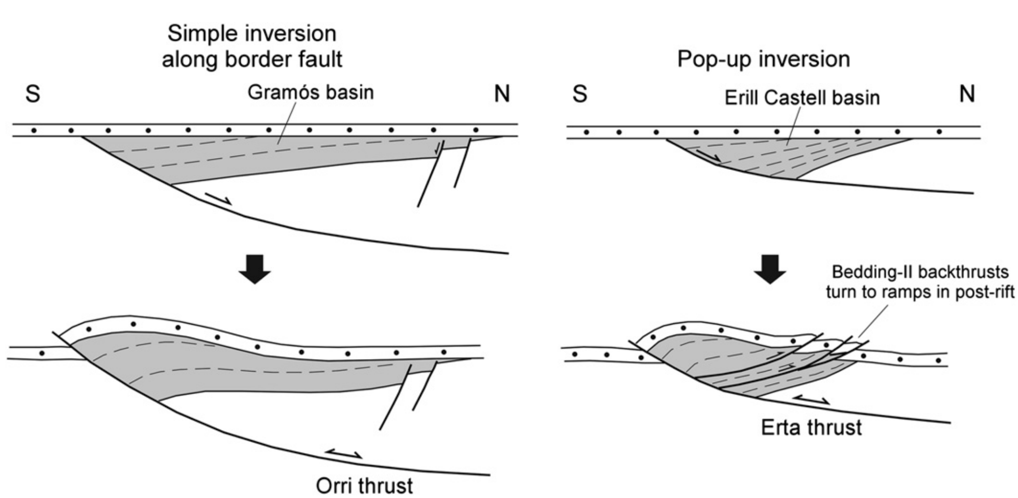

Fig. 8. Cartoon illustrating two styles of inversion of Stephanian-Permian grabens. The Gramós basin was inverted by reactivation of the border fault without intense internal deformation, whereas in the Erill Castell half-graben, the originally steeper bedding favoured backhtrusting along with the reactivation of the border fault (“pop-up inversion”).

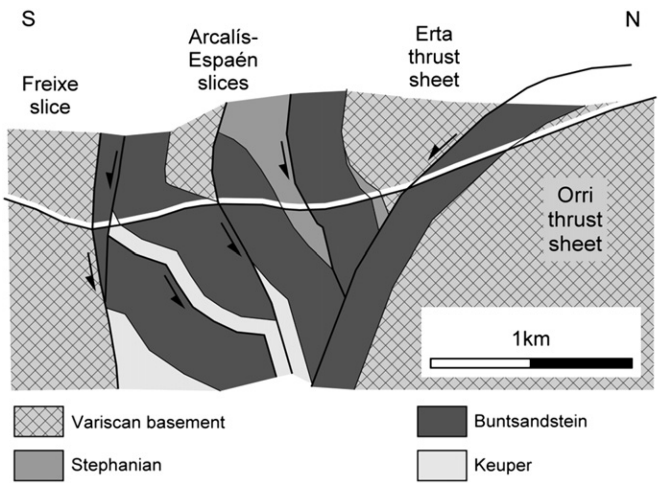

Fig. 9. Cross-section through the Erta and Nogueres thrust sheet (Arcalís – Espaén duplex and Freixe slice; location in Fig. 5) showing numerous overturned slices, characteristic of the area to the west of the Estac basin.

consequence of the inversion of the small Northern basins are frequent lateral ramps between slices and lateral changes of structural relief. This results in frequent along-strike changes within the Nogueres thrust sheet (Fig. 2b). Variation of the number of slices along different transects induced differential degree of stacking and overturning. East of the Noguera Pallaresa Valley (Fig. 2), where the Nogueres thrust sheet does not contain such basins, the partition in internal slices is minimum, the thrust slices are larger, stacking is lower, and only the uppermost thrust unit (Castells slice) is rotated to an overturned position. This feature adds to the effect of the differential structure beneath the Nogueres basal thrust. As discussed earlier, the eastern margin of the Estac basin terminates the Erta thrust sheet, and this resulted in less rotation of the Nogueres sheet. The structural variation at the Estac basin is also manifested by a change in the orientation of branch and cut-off lines of internal thrusts within the Nogueres thrust sheet. They are parallel to regional trends (E-W) west of the Malmercat fault transect, and slightly oblique (ESE-WNW) to the east of it (Fig. 2b).

At its eastern termination, in the eastern side of the Segre valley (Fig. 2), the Nogueres thrust sheet is formed by a sheet locally known as the Montsec de Tost unit (Solé Sugrañes and Santanach, 1970; Hartevelt, 1970). This unit laterally overlaps another major Pyrenean thrust unit, the Cadi nappe (see Vergés, 1993), by means of a lateral ramp. The Montsec de Tost thrust sheet is divided in two minor slices, whose main difference lies in the thickness of the Buntsandstein (200 m in the lower slice and 50 m in the upper one). This may also reflect inversion of a normal fault of Triassic age (Saura, 2004).

3.5. Age of deformation as constrained by Tertiary conglomerates

The Upper Eocene to Oligocene syn-orogenic conglomerates are best developed in the western part of the study area where stacking and structural relief are higher. Although mostly unconformable, they provide some constraints on the timing of the development of the Axial Zone antiformal stack (Fig. 4). The emplacement of the Nogueres thrust sheet was dated as Late Cretaceous to Middle Eocene by Muñoz (1992), being previous to the sedimentation of the Sarroca calcareous conglomerate group attributed to the uppermost Eocene (Saura and Teixell, 2000). The Sarroca group onlaps the southern limb of a complex, faulted synform between the tilted Nogueres slices and the Central South-Pyrenean Unit (Fig. 10), and formed ahead of the frontal culmination of the active Erta sheet during late Eocene times. On the other hand, the Senterada group, of Early Oligocene age (Mellere and Marzo, 1992), has Triassic and Palaeozoic pebbles derived from the Nogueres and Erta thrust sheets. This group progressively onlaps to the north the steepened and overturned Nogueres thrusts, whose final overturning is due to the emplacement of the Orri thrust sheet (Figs. 4 and 10), and contains growth strata that record this process. Finally, the subhorizontal Antist group, still Oligocene in age (Mellere and Marzo, 1992), probably records the emplacement of the Rialp thrust sheet, which produced uplift and erosion of the trailing edge of the Orri thrust sheet (central Axial Zone) and did not create differential structural relief in the study zone.

3.6. Palinspastic 3D-reconstruction of Stephanian-Permian basin system

The restored sections to Early Mesozoic times reveal the initial geometry of the Erill Castell, Gramós, Estac and Northern basins. In this chapter we present a three-dimensional model of the basins system that illustrates their initial position, and how they controlled the architecture of the thrust system

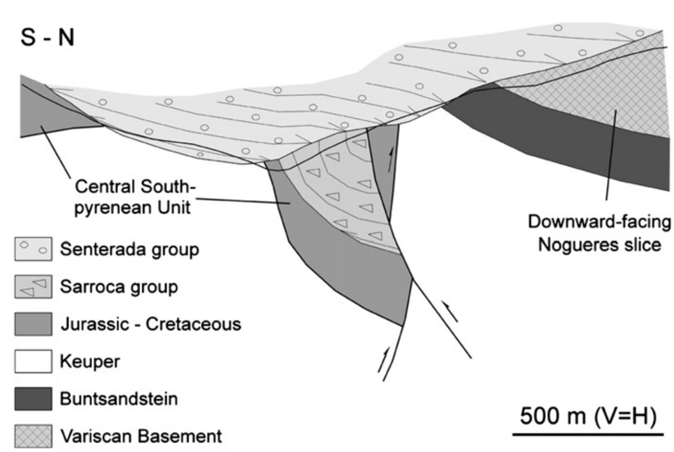

Fig. 10. Cross-section between the Nogueres thrust sheet and the Central South-Pyrenean Unit (location in Figs. 2 and 4) that illustrates the relationships between the upper Eocene – Oligocene conglomerates and the deformation structures. The upper Eocene Sarroca group is unconformable over previously deformed Mesozoic rocks and is deformed by contemporaneous high angle thrusts and backthrusts that we correlate with the major Erta thrust. The Oligocene Senterada group covers in an onlap fashion strongly overturned Nogueres rocks, and occupies a paleovalley filled late within the activity time of the Orri thrust sheet.

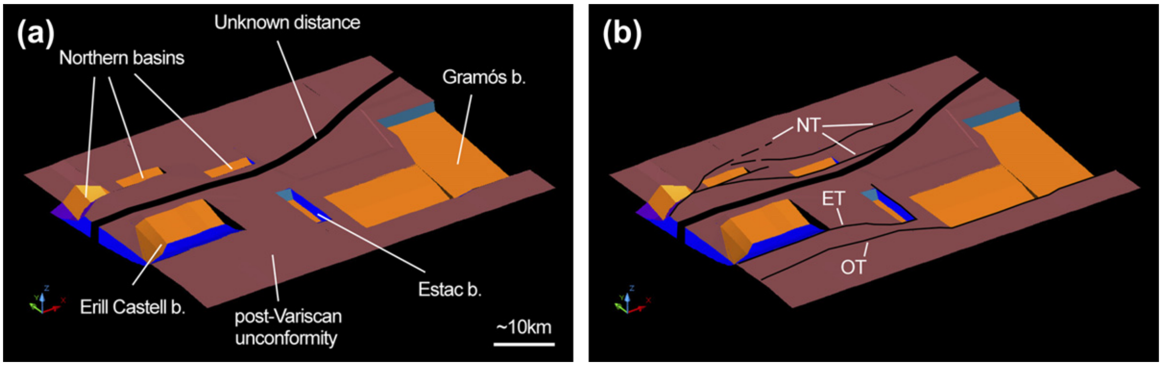

Fig. 11. Simplified palinspastic model of the Stephanian-Permian basins of the southern border of the Pyrenean Axial zone, based on several restored sections (Saura, 2004). a) Cartoon showing location of main Stephanian-Permian basins. Black gap between the Northern basins and the Erill Castell, Estac and Gramós basins indicates that the original separation is unknown due to unconstrained displacement of the Nogueres thrust sheet. b) Trace of the future Pyrenean thrusts inverting the basin system. OT: Orri thrust, ET: Erta thrust, NT: Basal and internal Nogueres thrusts.

during the inversion process. The main Stephanian-Permian basins are narrow, E-W elongated troughs, probably formed under a N-S stretching direction. E-W-trending extensional faults and normal slickensides of Stephanian-Permian age have been described in other areas of the Pyrenean Axial Zone (Poblet, 1991; Teixell, 1992). The angular relationship between syn- and post-rift sequences varies across the basins. In the SW, the Erill Castell basin (Fig. 11) was a half-graben bounded to the south by the Erta fault, active during Stephanian-Early Permian times. The analysis of the stratigraphy of the Devonian and lower Carboniferous suggests that the Erta fault reactivated a previous Variscan thrust (Poblet, 1991), and this could explain its low dip. The Gramós basin, located to the SE (Fig. 11), was an asymmetric graben where the magnitude of normal slip at its southern margin was higher than at the northern one. The stratigraphic succession indicates that fault-induced subsidence in Gramós basin lasted at least until the Late Permian, a longer period than recorded in the Erill Castell basin. The narrow Estac basin was located between two high angle faults striking N-S. Its infill indicates a high subsidence rate that contrasts with the basin dimensions. The Gramós basin was located in a southern latitude with respect to Erill Castell basin, and the Estac basin would lay in the transfer zone between the two (Fig. 11). In this position, we interpret that the Estac basin would initially have acted as a relay ramp, evolving to a pull apart-like basin with increased deformation, limited east and west by two high angle faults (Estac and Malmercat faults).

The Northern basins were originally located to the north of the three basins described above. The lack of footwall cutoffs to the Nogueres thrust does not allow an estimate to be made of the original distance between them (“unknown distance” in Fig. 11). These Northern basins were smaller than the Erill Castell, Gramós and Estac grabens, and their heterogeneous sedimentary record indicates that they were active at different times.

3.7. Evolution of inversion in time and space

We have shown that the three-dimensional architecture of the major thrust sheets and their partition into minor slices was strongly controlled by initial distribution of Stephanian-Permian extensional basins and their boundary faults. The first active thrust sheet in the study area was the Nogueres thrust sheet. To the west, where the Northern basins were present, the Nogueres thrust sheet was divided in several minor slices inverting the small grabens, often forming footwall short-cuts. Multiple slices generated complex 3D relationships, with frequent lateral ramps and branching between thrusts. To the east, the lack of Stephanian-Permian basins resulted in a much simpler structural style. This contrast is expressed in marked along-strike variations.

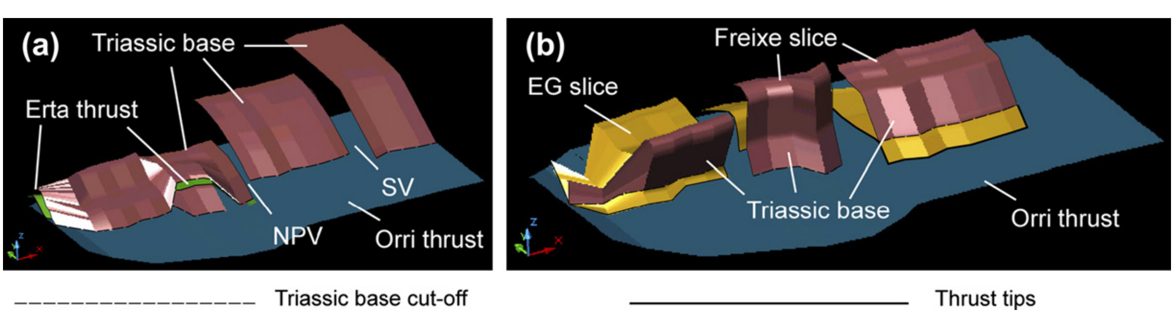

Fig. 12. Three-dimensional simplified reconstruction of the main thrusts of the southern limb of the Axial Zone antiformal stack before the emplacement of Rialp thrust sheet. The stratigraphic base of the Triassic is also indicated. a) Sketch of the Orri and Erta thrust sheets. b) Simplified sketch of the Nogueres slices. NPV: Noguera Pallaresa valley. SV: Segre valley. EG slice: Erdo – Gotarta slice.

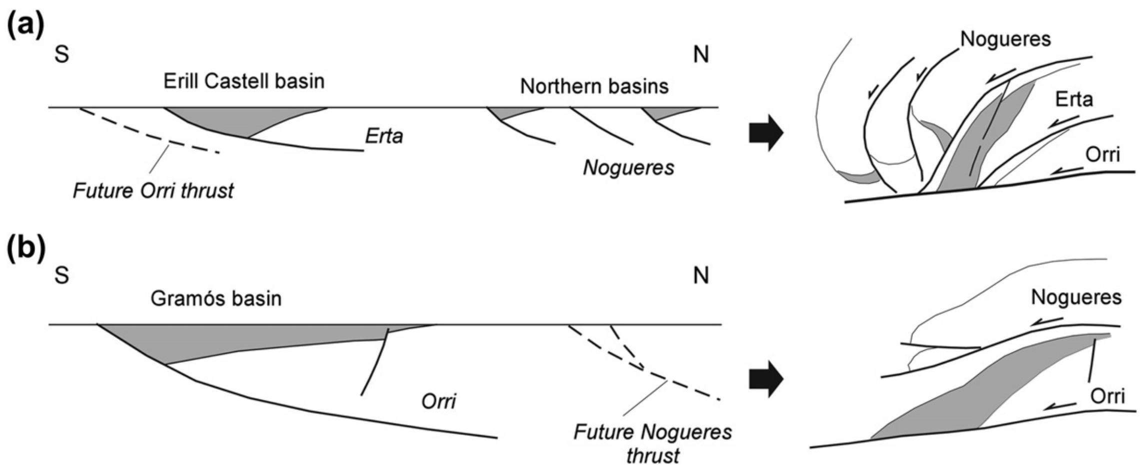

Fig. 13. Cartoon synthesising the structural variation at the leading edge of the Axial Zone antiformal stack as determined by the nature of the Stephanian-Permian grabens. a) In the east, the inversion of the Erill Castell and Northern basins induced partition into numerous thrust slices and consequently, higher degree of stacking and overturning. b) In the west, the inversion of the single Gramós basin by the Orri thrust and the absence of other basins in the future Nogueres sheet caused shallower and simpler thrust structure. The Estac basin is in between these two transects.

The inversion of the Erill Castell, Estac and Gramós basins followed the emplacement of the Nogueres thrust sheet and is diagrammatically shown in the model of Fig. 12. Deformation related to the Erta thrust sheet, to the west, inverted the Erill Castell and Estac basins. The eastern termination of Erta thrust sheet at the eastern margin of the Estac basin also determined the geometry of the Orri thrust sheet. In the east, the thick Gramós basin was incorporated into this thrust sheet, which is largest in this area. To the west, the Orri thrust sheet thins abruptly below the Erta thrust, concomitant with the increase in thickness of the latter (Fig. 12a).

West of the Estac basin, the stacking of the Orri and the Erta thrust sheets and the partition of the Nogueres thrust sheet into minor imbricates produced a stronger rotation and overturning of the upper thrust units (Fig. 13a). East of the Estac basin, where only the Orri thrust sheet exists and the Nogueres thrust slices are larger, rotation was not so strongly developed, and the leading edge of the Axial Zone antiformal stack dips shallowly (Fig. 13b). Later, the Rialp thrust sheet transported the whole system to the south, without much differential rotation of units in the study zone.

4. Conclusions

The geometry of the leading edge of the Pyrenean Axial Zone antiformal stack is controlled by the inversion of several small Stephanian-Permian grabens whose initial shape and dimensions determined the size, distribution and internal structure of the main thrust sheets. Where basins were smaller and numerous, thrust sheets are complex, divided into several imbricated slices with frequent lateral ramps and sudden changes in structural relief. Where the extensional basins were larger, the resulting thrust sheets are also larger and more continuous. The internal structure of the inverted basins was also dependent on the tilt of syn-rift layers, as bedding-parallel backthrusts may accompany basin inversion when beds were favourably oriented. Taking into account the structural relationships along and across strike we revise the subdivision in thrust units of the southern Axial Zone. Hence, the boundaries of the Orri, Erta and Nogueres thrust sheets are different from previous works (e.g., Muñoz, 1992), and within the Nogueres sheet the proposed subdivisions (Arcalís-Espaén, Freixe, Erdo-Gotarta and Castells slices) are mainly bounded by lateral structures. The described complexities provide a good example of how the inversion of an initially heterogeneous basin system controls the 3D patterns of thrusting.

Acknowledgements

Field work was financed by the Instituto Geológico y Minero de España. We thank A. Barnolas for discussion and permission to publish this work. Additional support was provided by MCYT project BTE2003-00499. The manuscript benefited from the comments by D. Brown and the reviewers G. Gutiérrez Alonso and S. Seno.

References

Calvet, F., Anglada, E., Salvany, J.M., 2004. El Triásico de los Pirineos. In: Vera, J.A. (Ed.), Geología de España. SGE-IGME, Madrid, pp. 272–274.

Coward, M.P., 1996. Balancing sections through inverted basins. In: Buchanan, P.G., Niewland, D.A. (Eds.), Modern Developments in Structural Interpretation, Validation and Modelling. Geological Society, London, Special Publication 99, pp. 51–77.

Dalloni, M., 1910. Etude géologique des Pyrenées de l'Aragon. Annales de la Faculté des Sciences de Marseille 19, 444 pp.

Gillcrist, R., Coward, M., Mugnier, J.L., 1987. Structural inversion and its controls: examples from the Alpine foreland and the French Alps. Geodinamica Acta (Paris) 1 (1), 5–34.

Gisbert, J., 1981. Estudio geológico-petrológico del Estefaniense-Pérmico de la Sierra del Cadí (Pirineos de Lérida). Diagénesis y sedimentologia. Tesis Doctoral, Universidad de Zaragoza, 313 pp.

Gisbert, J., 1983. El Pérmico de los Pirineos españoles. In: Martínez-Díaz, C. (Ed.), Carbonífero y Pérmico de España. Publicaciones del Instituto Geológico y Minero de España, Madrid, pp. 405–420.

Gisbert, J., Martí, J., Gascon, F., 1985. Guía de la excursión al Stephaniense, Pérmico y Triásico inferior del Pirineo catalán. II Congreso de Estratigrafía y Paleogeografía del Pérmico y Triásico de España, La Seu d'Urgell, 79 pp.
Hartevelt, J.J.A., 1970. Geology of the upper Segre and Valira valleys, central Pyrenees, Andorra/Spain. Leidse Geologische Mededelingen 45, 349–354.
Hayward, A.B., Graham, R.H., 1989. Some geometrical characteristics of inversion. In: Cooper, M.A., Williams, G.D. (Eds.), Inversion Tectonics. Geological Society, London, Special Publication 44, pp. 17–39.
Martí, J., 1986. El vulcanisme explosiu tardihercinià del Pirineu Català. Tesi Doctoral, Universitat de Barcelona, 303 pp.
Mellere, D., Marzo, M., 1992. Los depósitos aluviales sintectónicos de la Pobla de Segur: alogrupos y su significado tectonoestratigráfico. Acta Geológica Hispánica 27, 145–159.
Mey, P.H.W., 1968. In: de Sitter, L.U. (Ed.), Geological Map of the Central Pyrenees, Sheet 8: Ribagorzana – Tor, Spain, scale 1:50 000. Geological Institute Leiden University, Holland.
Mey, P.H.W., Nagtegaal, P.J.C., Roberti, K.J., Hartevelt, J.J.A., 1968. Lithostratigraphic subdivision of post-Variscan deposits in the South-Central Pyrenees, Spain. Leidse Geologische Mededelingen 41, 153–220.
Muñoz, J.A., 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: McClay, K.R. (Ed.), Thrust Tectonics. Chapman & Hall, New York, pp. 235–246.
Poblet, J., 1991. Estructura de les unitats del vessant sud de la zona axial del Pirineu central. Tesi Doctoral, Universitat de Barcelona, 604 pp.
Roure, F., Choukroune, P., Berastegui, X., Muñoz, J.A., Villien, A., Matheron, P., Bareyt, M., Seguret, M., Camara, P., Deramond, J., 1989. ECORS deep seismic data and balanced cross-sections: geometric constraints on the evolution of the Pyrenees. Tectonics 8, 41–50.
Saura, E., 2004. Anàlisi estructural de la zona de les Nogueres Pirineus Centrals. Tesi Doctoral, Universitat Autònoma de Barcelona, 355 pp.
Saura, E., Teixell, A., 2000. Relación entre los conglomerados oligocenos y las estructuras tectónicas en la zona de Les Nogueres, Pirineo Central. Geotemas 2, 201–203.
Seguret, M., 1972. Etude tectonique des nappes et séries décollés de la partie centrale du versant sud des Pyrenées. Caractère synsédimentaire, rôle de la compression et de la gravité. Thèse Doctorale, Université de Montpellier, Publ. USTELA. Série Géol. Struct. 2, 210 pp.
Solé Sugrañes, L., Santanach, P., 1970. Nota sobre la escama de corrimiento del Montsec de Tost en el Prepirineo español. Acta Geológica Hispánica V (5), 24–28.
Soriano, C., Martí, J., Casas, J.M., 1996. Palinspastic reconstruction of Permo-Carboniferous basins involved in Alpine deformation: the Erill Castell-Estac basin, Southern Pyrenees, Spain. Geologie en Mijnbouw 75, 43–55.
Teixell, A., 1992. Estructura Alpina de la Transversal de la Terminación Occidental de la Zona Axial Pirenaica. Tesi doctoral, Universitat de Barcelona, 252 pp.
Vergés, J., 1993. Estudi geològic del vessant sud del Pirineu oriental i central. Evolució cinemàtica en 3D. Tesi doctoral, Universitat de Barcelona, 203 pp.
Williams, G.D., 1985. Thrust tectonics in the South Central Pyrenees. Journal of Structural Geology 7 (1), 11–17.