Geologica Acta, Vol.16, Nº 4, December 2018, 439-460
DOI: 10.1344/GeologicaActa2018.16.4.7

The structure of the South-Central-Pyrenean fold and thrust belt as constrained by subsurface data

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ABSTRACT

The interpretation of the available seismic lines of the South-Central-Pyrenean fold and thrust belt, conveniently tied with the exploration wells, define the main structural features of this realm of the Pyrenees. In particular, they define the geometry and areal extension of the autochthonous foreland underneath the sole thrust. The mapping of several selected structural lines brings constraints for the structural interpretation of the South-Central Pyrenees, including the cut-off lines between selected stratigraphic horizons of the autochthonous foreland and the branch line between basement-involved thrust sheets and the sole thrust. The thrust salient which characterizes at surface the geometry of the South-Pyrenean fold and thrust belt contrasts with the linear trend of these structural lines at subsurface. This salient has been the result of a secondary progressive curvature developed since Middle Eocene times by thrust displacement gradients during overthrusting of the South-Pyrenean thrust sheets above a Paleogene autochthonous sequence. Displacement gradients resulted from the uneven distribution of weak salt layers, mostly the Triassic and the Upper Eocene ones. The minimum amount of South-directed displacement from early Middle Eocene times to Late Oligocene is 52km, which would be significantly higher if internal shortening by folding and cleavage/fracture development as well as hanging-wall erosion is added.

KEYWORDS **Pyrenees. Seismic data. Cut-off and branch lines.**

INTRODUCTION

Structural style of fold and thrust belts depends among many other factors on the mechanical properties of the deformed sedimentary pile and the existence of weak horizons such as salt layers (Chapple, 1978; Dahlen *et al.*, 1984; Beaumont *et al.*, 2000; Cooper, 2007; Lacombe and Bellhasen, 2016; among many others). These weak horizons favour decoupling of the overlying sedimentary succession and determine a thin-skinned structural style. In addition, fold and thrust belts involving salt are characterized by the existence of thrust salient, which are the result of uneven salt distribution and related thrust displacement gradients (Muñoz *et al.*, 2013). A common discussion among structural geologists when interpreting the structure of fold and thrust belts is the degree of involvement of basement into the thrust system. Thin-skinned and thick-skinned end-members can be invoked, which have strong implications on the amount of shortening to account for the observed structural relief (Lacombe and Bellahsen, 2016).

Deciphering the proper structural style can only be resolved, in most cases, by the availability and interpretation of subsurface data and their integration with surface geological data. Most of the fold and thrust belts in the Earth have been explored for geological resources and have available subsurface data. The most valuable data sets for structural interpretation are the seismic data and wells that were acquired during the hydrocarbon exploration. In the Pyrenean fold and thrust belt the exploration activity during the 60's, 70's and 80's resulted in the acquisition of a significant amount of seismic data. In addition, several deep reflection seismic profiles were acquired along the Pyrenees since the 80's that together with the wells drilled constrain significantly the structural interpretation. Increasing availability to the subsurface data sets are of great value for the understanding of the structure of the Pyrenean fold and thrust belt and have not been properly considered even in recent studies. This contribution aims to fill this gap.

The South-Central Pyrenees are characterized by a major thrust salient that has been referred historically as the South-Pyrenean Central Unit (Fig. 1; Séguret, 1972). This "structural unit" was interpreted as a primary arc inherited from a Mesozoic basin, detached from the basement along the Triassic evaporites and transported southward with only a limited amount of stratigraphic superposition in the frontal part (Séguret, 1972; Mouthereau *et al.*, 2014). However, two wells located in the South-Pyrenean thrust sheets drilled an autochthonous Paleogene succession underneath the Triassic salt at the bottom of the allochthonous Mesozoic succession (Isona and Comiols wells, Figs. 2; 3; 4; 5). These autochthonous Paleogene sediments are in continuation with the Ebro foreland basin as evidenced by the seismic data tied with the wells, emphasizing the allochthony of the South-Pyrenean thrust sheets as well as the thin-skinned style of the South-Central Pyrenees. Seismic data also allow us to rule out the existence of transverse or oblique basement-involved faults at the edges of the thrust salient as interpreted in the past (*i.e.* Segre fault along the eastern edge of the salient; Souquet *et al.*, 1977). In addition, paleomagnetic data demonstrates that the thrust salient is a progressive arc that developed by displacement gradient (Sussman *et al.*, 2004; Muñoz *et al.*, 2013). Thus, all these data demonstrate the thin-skinned structural style of the South-Central-Pyrenean fold and thrust belt and a significant amount of displacement of the South-Pyrenean thrust sheets above the foreland basin. Nevertheless, and regardless the availability of the subsurface data, there are recent structural re-interpretations that do not match with these data sets (*i.e.* Mouthereau *et al.*, 2014). The aim of this work is to present subsurface data that constrain the structural interpretation of the southern Pyrenees with the purpose to precise the geometry of this thin-skinned fold and thrust belt.

GEOLOGICAL SETTING

The Pyrenees is the orogenic system that runs along the boundary between the Iberian and European plates and formed as these plates collided from Late Cretaceous to Miocene times (Fig. 1; Roest and Srivastava, 1991; Rosenbaum *et al.*, 2002). It is an asymmetric doubly vergent orogenic wedge that formed above the subduction of the Iberian lithospheric upper mantle and lower crust under the European Plate (Fig. 1; Choukroune and ECORS Team, 1989; Muñoz, 1992; Pedreira *et al.*, 2003; Campanyà *et al.*, 2012; Chevrot *et al.*, 2015). The Pyrenean orogen resulted from the inversion of the rift system and related passive margin (northern Iberian Margin) that developed during the Late Jurassic-Early Cretaceous all along the northern Iberian plate connecting the Atlantic with the Alpine Tethys realms (Stampfli and Hochard, 2009; Tugend *et al.*, 2014).

Structural style and related tectono-sedimentary evolution changes significantly along strike. These changes are mainly expressed by differences in: width, asymmetry of the double wedge, thrust kinematics, involvement of basement and topography, among others (Fig. 1).

The main factors controlling the Pyrenean structural style are the inversion of the inherited extensional structures and the distribution of the Triassic salt (Beaumont *et al.*, 2000). Other factors, such as the weakness of the inherited Variscan crust and the lithospheric thermal state, have also contributed to the structural evolution (Jammes and Huismans, 2012; Clerc and Lagabrielle, 2014; Jammes *et al.*, 2014). The Triassic salt has resulted into decoupling of the Mezozoic cover succession and a thin-skinned style in the Pyrenean fold and thrust belt. Inversion of the Late Jurassic-Early Cretaceous extensional system and the weaker parts of the Variscan crust have promoted basement involvement and thick-skinned structural style. Areas with absence of Triassic salt and a relatively weak basement, such as the Cantabrian mountains, are characterize by a thick-skinned structural style (Alonso *et al.*, 1996), while areas with a thick Triassic salt, such as the Basque-Cantabrian Pyrenees and the central Pyrenees are characterized by thin-skinned geometries (Muñoz, 1992;

Carola *et al*., 2015). In the thin-skinned areas, basement is involved in the retro-wedge and can be involved as well in the pro-wedge underneath the detached cover, depending on the inherited rift system (Fig. 1). Thus, the Pyrenean fold and thrust belt exhibits both thin- and thick-tectonic style in different segments of the orogenic system as many other folds and thrust belts (Lacombe and Bellahsen, 2016) and cannot be assigned to a single structural style as recently proposed (Mouthereau *et al*., 2013).

THE MAIN STRUCTURAL FEATURES OF THE SOUTH-CENTRAL PYRENEES

The ECORS cross-section across the Central Pyrenees is very well constrained by geological and geophysical data (Choukroune and ECORS Team, 1989; Muñoz, 1992; Fitzgerald *et al*., 1999; Beaumont *et al*., 2000; Campanyà *et al*., 2012; Mouthereau *et al*., 2014; Chevrot *et al*., 2015). It shows the geometry of the Pyrenean asymmetric

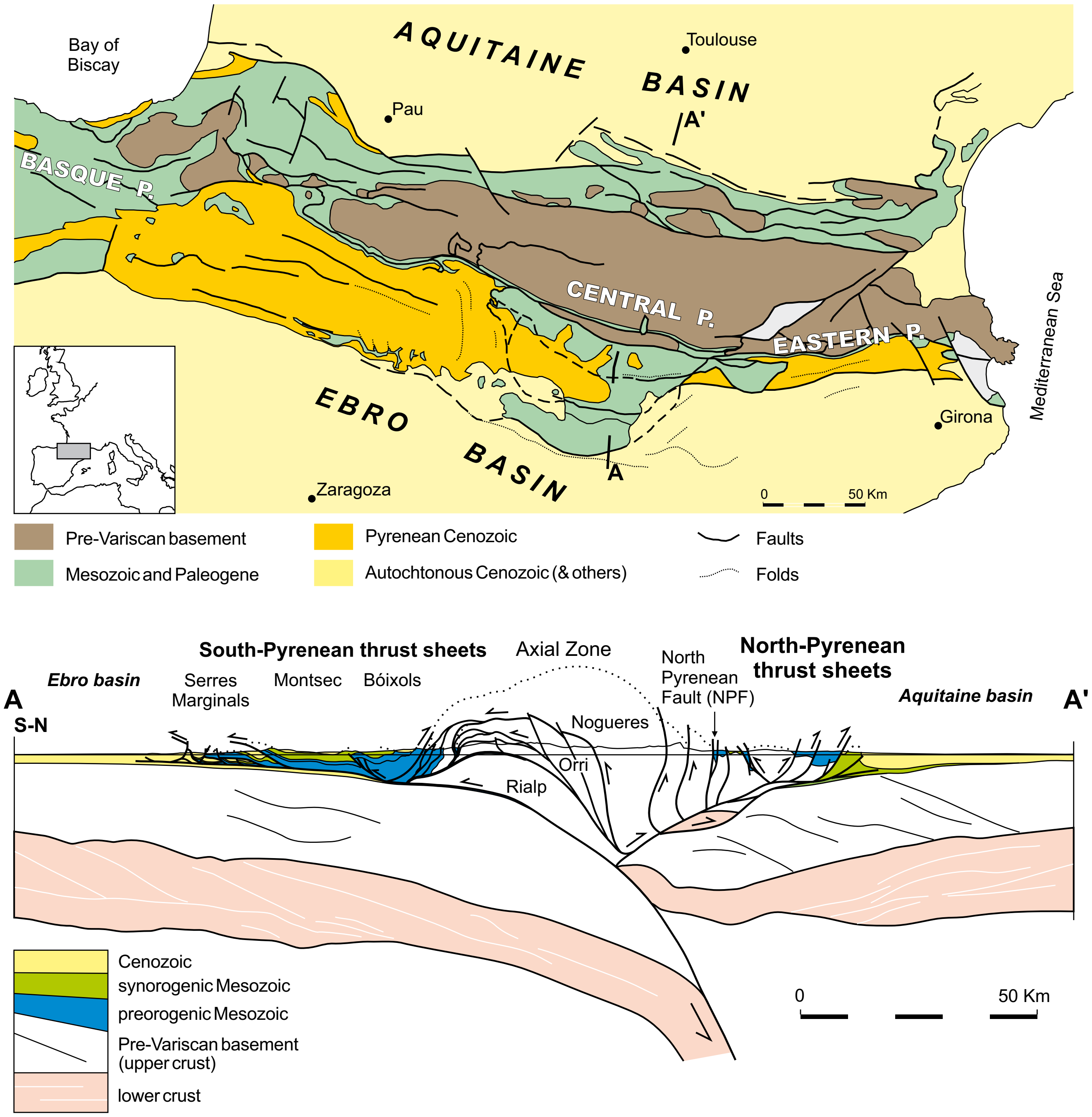

FIGURE 1. Geological sketch of the Pyrenees and the ECORS geological cross-section of the Central Pyrenees. Section modified from Muñoz, 2002.

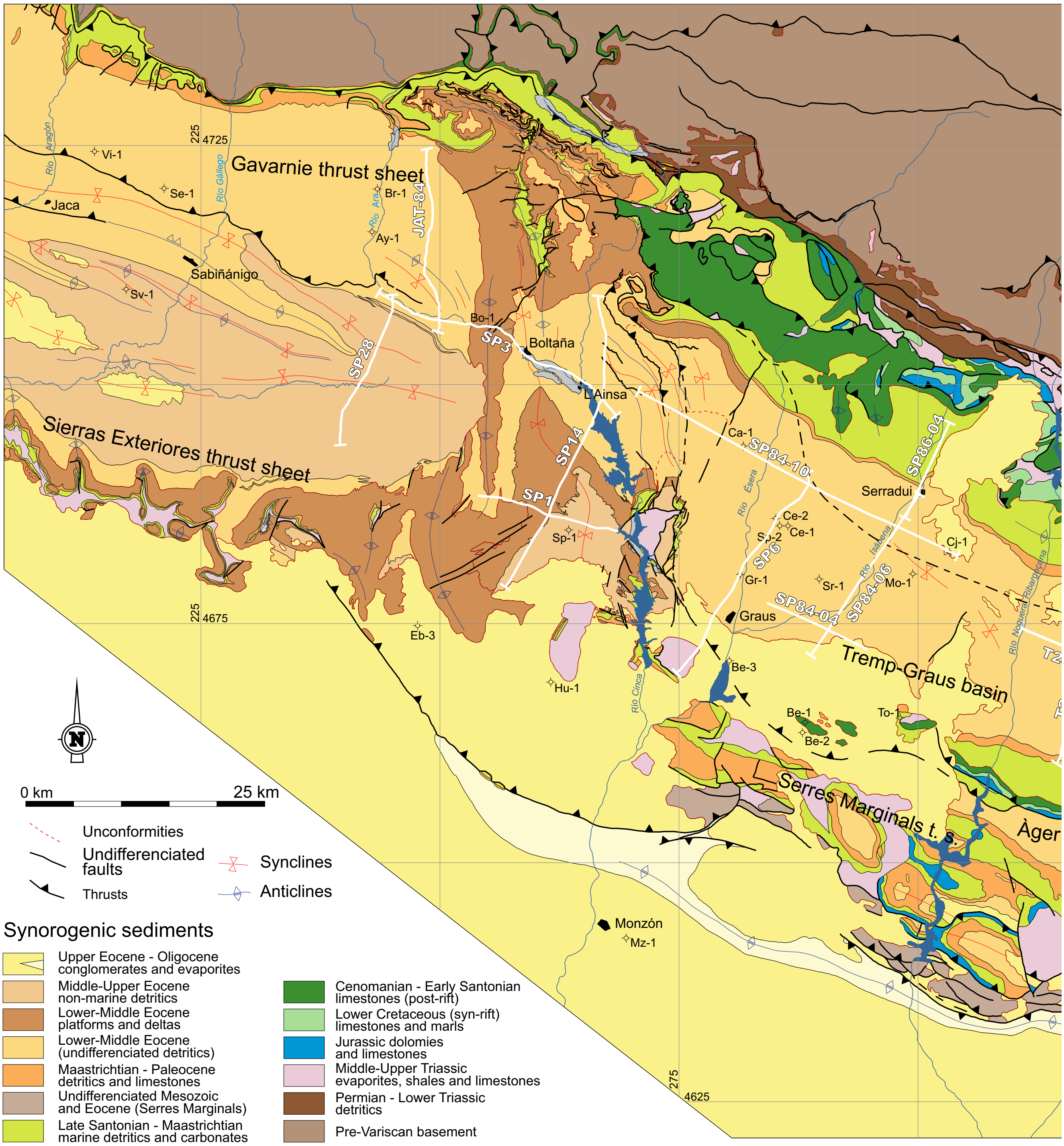

FIGURE 2. Structural map of the South-Central Pyrenees and location of the seismic and well data.

orogenic double-wedge which is dominated by a central antiformal stack of basement-involved thrust sheets, classically referred as the Axial zone (Fig. 1; Muñoz, 1992, 2002). This antiformal stack consists of three main thrust sheets, which from top to bottom are Nogueres, Orri and Rialp (Fig. 1; Muñoz, 1992). They are part of the southern orogenic wedge as they were transported to the South together with the cover thrust sheets located forwards. They were progressively deformed by underthrusting of the lower and younger units. As a result, the structures of the upper thrust sheet have been tilted in the southern limb of the antiformal stack and show downward facing folds involving upper Paleozoic rocks and Permian to Lower Triassic red beds (Nogueres zone, Fig. 6, Dalloni, 1913; Séguret, 1972).

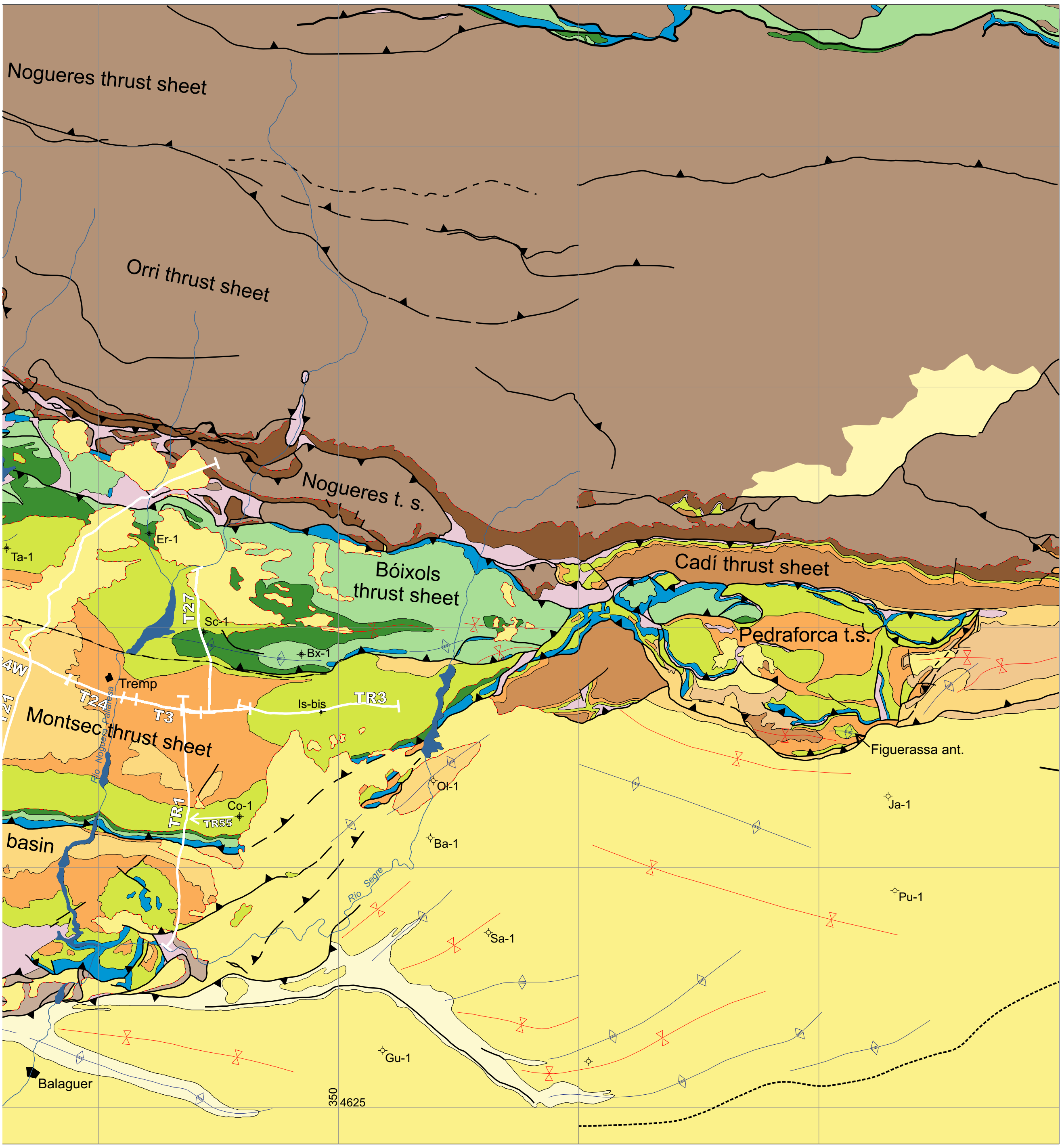

FIGURE 2. (Cont.).

South of the Axial zone antiformal stack, the Mesozoic succession has been decoupled from the basement along the Triassic evaporites and has been involved in three main thrust sheets which from North to South are: Bóixols, Montsec and Serres Marginals (Figs. 1; 2). They have involved different parts of Mesozoic and Paleogene basins with distinct significances and they have initially developed following a forward propagating thrust sequence from Late Cretaceous to Oligocene. These thrust sheets continue eastwards into the Pedraforca thrust sheet, formed by three main units: Upper, Middle and Lower Pedraforca thrust sheets, which are equivalent to the Bóixols, Montec and Serres Marginals thrust sheets, respectively (Fig. 2).

The Bóixols thrust sheet resulted from the inversion of

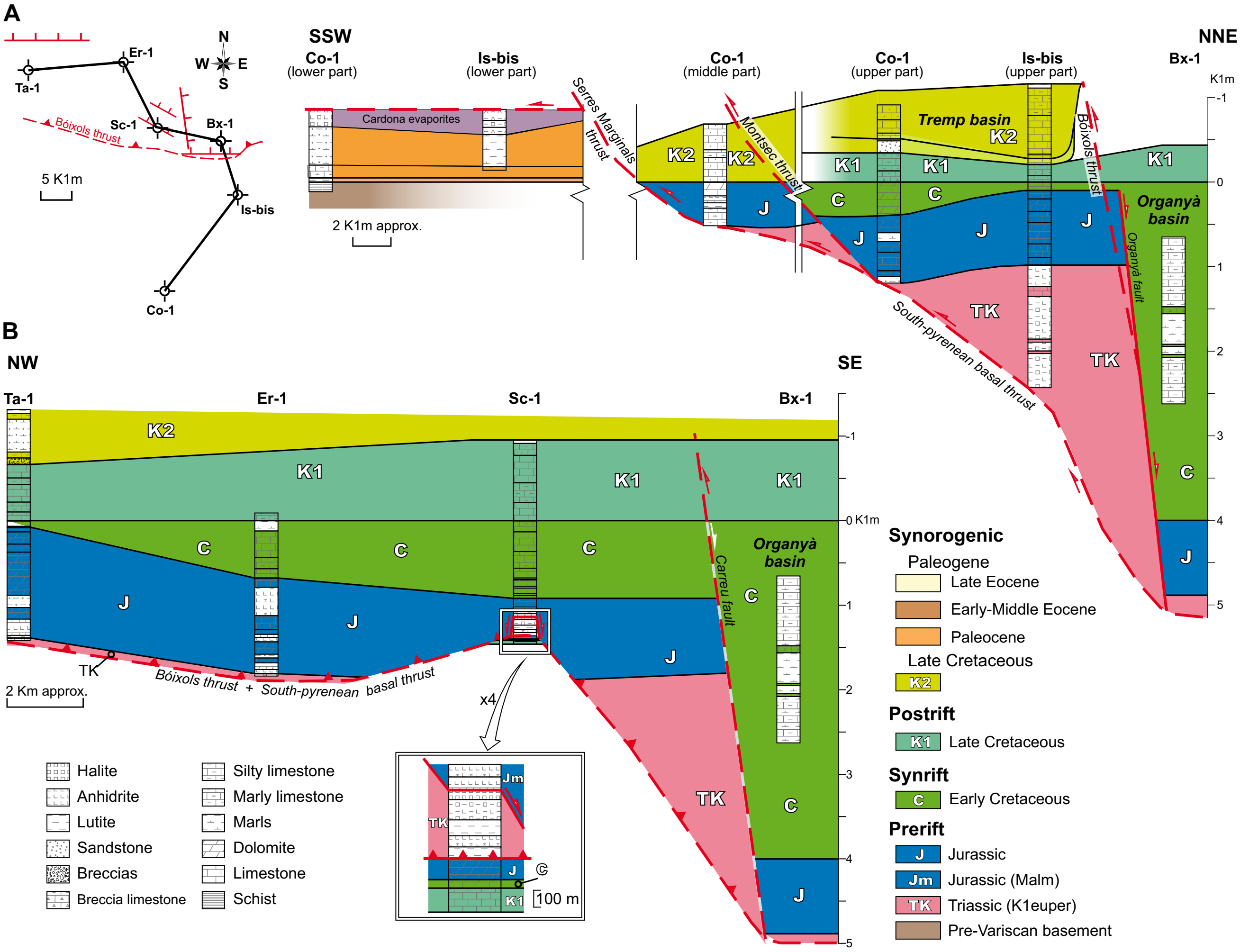

FIGURE 3. Correlation of wells in the South-Central Pyrenees which have been the basis for the identification of the main reflectors and seismic units. The stratigraphic logs of the wells have been truncated across the thrusts and restored relatively to their location before the onset of contractional deformation. The reference level for correlation is the bottom of the postrift sequence. See location of the correlation panels in the upper left corner and location of the wells in Figure 2. Modified from Mencos *et al.*, 2015.

the Lower Cretaceous basins at the southern margin of the Pyrenean rift system (Berástegui *et al.*, 1990; Mencos *et al.*, 2015). Contractional deformation started at late Santonian and continued during the Late Cretaceous (McClay *et al.*, 2004; López-Mir *et al.*, 2014). The segmented geometry of the rift system as well as the salt structures triggered by the Early Cretaceous extension, that continuously developed during the passive margin stage before the onset of contractional deformation, controlled significantly the structure we observe along the Bóixols thrust sheet and its western continuation into the Cotiella thrust sheet (López-Mir *et al.*, 2014; Saura *et al.*, 2016).

The Montsec thrust sheet involves the northern part of the Upper Cretaceous foreland basin characterised by a strong subsident turbiditic trough at the footwall of the Bóixols thrust. These turbidites grade southward into a carbonatic platform that constitutes the backbone of the Montsec Range. The Montsec thrust sheet developed from the Paleocene to the Early Eocene as recorded by continental to shallow marine sediments deposited in its footwall (Ager Basin) as well as in the Tremp-Graus piggy-back Basin (Figs. 2; 6). The lower Eocene sediments of these basins grade westward into the slope succession filling the Ainsa Basin at the footwall of the Montsec thrust. The turbidites of the Ainsa Basin and their distal equivalents in the Jaca Basin grade southward into a carbonatic platform cropping out along the Sierras Exteriores, the western equivalent of the Serres Marginals thrust sheet in the central Pyrenees (Fig. 2).

The Serres Marginals thrust sheet is characterised by an incomplete and thin Mesozoic-Paleocene succession which progressively reduces southwards. The synorogenic Upper Cretaceous carbonates are represented in all the Serres Marginals imbricates with a thickness varying from few hundred meters in the northern ones to few tens of meters in the most frontal imbricates (Fig. 6). These Upper Cretaceous sediments unconformably overlie the Jurassic carbonates that were tilted northwards and removed by erosion at the forebulge of the Upper Cretaceous foreland basin. The southern edge of the Triassic evaporites preserved by erosion at the northern limb of the forebulge controlled the location of the thrust front. Triassic evaporites also controlled the internal structure of the Serres Marginals thrust sheets. These evaporites were inflated by evacuation from the bottom of the Montsec thrust sheet and together with the thin Mesozoic succession favoured the development of detachment anticlines and diapirs (Santolaria, 2015; Santolaria *et al.*, 2015).

The South-Pyrenean thrust system was reactivated by a break back thrust sequence during the sedimentation of the Upper Eocene-Oligocene conglomerates once the Ebro Basin became endorheic and filled by a thick succession of syntectonic sediments (Vergés and Muñoz, 1990; Burbank *et al.*, 1992; Coney *et al.*, 1996; Meigs and Burbank, 1997; Muñoz *et al.*, 1997; Teixell and Muñoz, 2000; Fillon *et al.*, 2013).

The Serres Marginals and Montsec thrust sheets are at present above an autochthonous succession of Paleocene and Eocene sediments in continuation with the Ebro foreland Basin as evidenced by well and seismic data (Fig. 4). The detachment is located in the Upper Eocene salts (Cardona Formation (Fm.)). The break-back reactivation of the thrust system was coeval with both the displacement of all the cover thrust sheets above the Upper Eocene salt and the significant increase of the uplift rate and denudation of the basement thrust sheets of the Axial zone (Fitzgerald *et al.*, 1999, Beamud *et al.*, 2011). However, a problem lies on the areal extension of the autochthonous sediments, in the footwall of the sole thrust and the location and geometry of the footwall cut-off lines for the different stratigraphic units. In this work, we will discuss the available subsurface data that constrain such geometry.

SUBSURFACE DATA

Several 2-D reflection seismic surveys and wells were undertaken during the 1960's 1970's and 1980's in the studied area for hydrocarbon exploration. The oldest wells drilled in the studied area are the Oliana and Boltaña wells that were drilled in 1948 and 1952, respectively (Lanaja, 1987). The most recent ones were drilled during the early 80's (Comiols, Broto, Ayerbe de Broto).

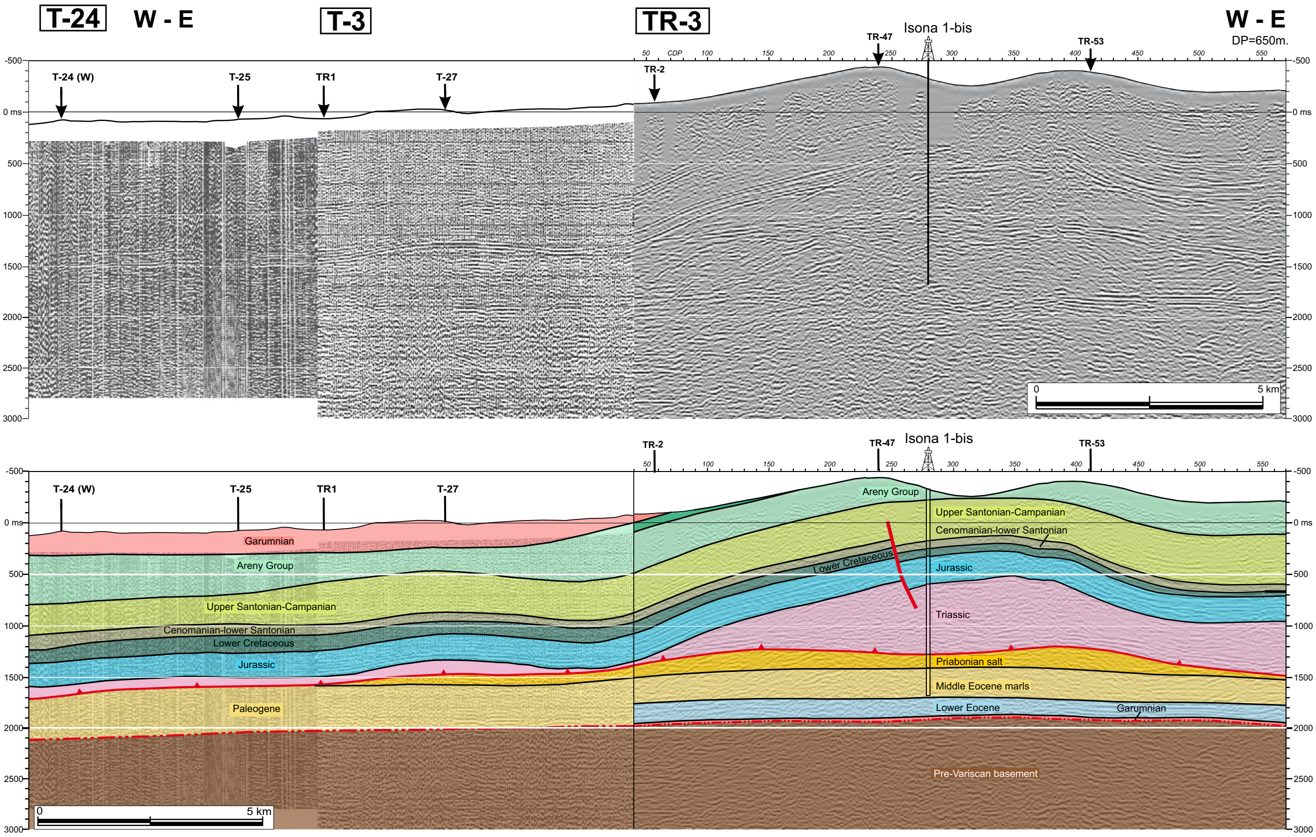

FIGURE 4. TR3-T3-T24 composite strike seismic line along the Montsec thrust sheet. Note the continuous package of autochthonous Paleogene reflectors underneath the sole thrust. See Figure 2 for location.

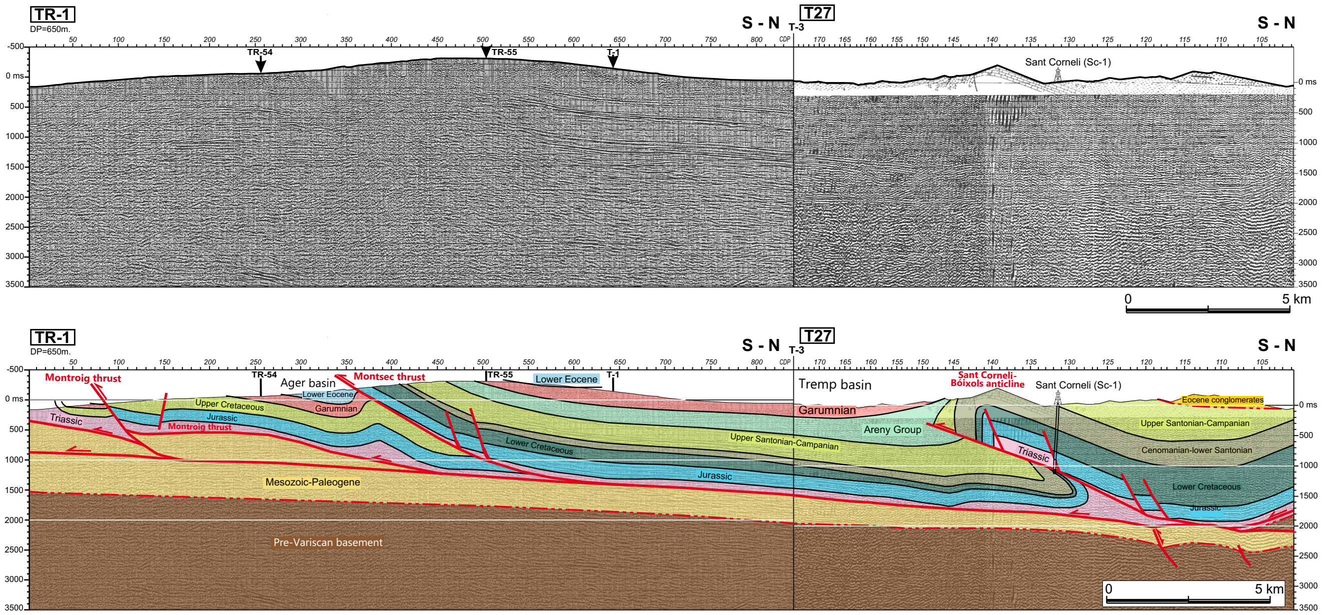

FIGURE 5. Composite seismic line (TR1-T27) parallel to the ECORS deep seismic profile. See Figure 2 for location.

Several seismic vintages are available. The oldest ones are the campaigns named ND and T acquired from the 60's to early 70's. Most of the seismic lines used in this work were acquired in the early 80's, such as the campaigns named JAT, SP and TR. More recent seismic lines were acquired in the Isábena valley by 1984 and 1986 (SP84 and SP86). The oldest lines were only available as stack versions, whereas most of the recent lines have a migrated version. Some of the lines have been available in digital format (SEGY), but most of them were only in image format (TIF or JPEG). In this case they have been converted to SEGY in order to load in the proper software for seismic interpretation (Petrel and Move).

Logs of the available wells have been used to tie the wells with the seismic lines in order to identify the main reflectors. These logs have been used to refine the identification of stratigraphic units and propose a correlation between the studied wells (Fig. 3).

About 150 seismic lines have been interpreted. Herein only some selected ones are included to illustrate and support the structural interpretation.

INTERPRETATION OF THE SEISMIC LINES

Strike seismic line along the Montsec thrust sheet (TR3-T3-T24)

A strike seismic composite line across the Isona-1 well allows to tie the different stratigraphic units drilled in the Montsec thrust sheet and its footwall. The Isona and Comiols wells cut through the South-Pyrenean sole thrust and the information they provided are of major importance for constraining the structure of the South-Pyrenean fold and thrust belt (Fig. 3). The most striking result of these wells is that they documented the existence of the Upper Eocene salt (Cardona Fm.) and an autochthonous thick Eocene to Paleocene succession underneath the Montsec thrust sheet.

The TR3 seismic line imaged the Isona anticline in the Montsec thrust sheet (Fig. 4). This is a detachment anticline cored by a 1.5km thick succession of Triassic rocks. The anticline is well depicted by a continuous package of high-amplitude reflectors characteristic of the Jurassic carbonates and marls (Fig. 4). Underneath, the Upper Triassic (Keuper) sediments are characterized by transparent seismic facies. The Isona-1bis well drilled salt, anhydrites and mudstones of this unit, but also some carbonate layers that have been interpreted as part of the Middle Triassic Muschelkak (Fig. 3). Underneath the folded Mesozoic sediments, the imaged flat lying or slightly curved reflectors in the TR3 seismic line correspond the autochthonous Paleogene succession drilled by the well. The upper reflective package is the Priabonian Cardona salt Fm. and the transparent unit corresponds to the Middle Eocene marls where the True Depth (TD) of the well is located (Figs. 3; 4). The lower continuous reflectors above the acoustic transparent basement have been interpreted as the Lower Eocene carbonates and Paleocene mudstones (continental Garumnian facies) that were drilled by the Comiols well

South of the seismic line (Figs. 2; 3; 4). These lower high-amplitude reflectors are quite continuous and can be mapped all along and across the South-Pyrenean thrust sheets. It is worth noting to emphasize the absence of Mesozoic sediments above the Paleozoic rocks of the basement.

The autochthonous Paleogene sediments can be mapped westwards along the T3 and T24 seismic lines underneath the Montsec thrust sheet westward of the Ribagorçana valley. These sediments are very slightly dipping to the West, following the westward regional plunge, but undeformed underneath the folded Mesozoic succession of the Montsec thrust sheet. Such geometric differences between the autochthonous succession and the deformed thrust sheets facilitate the mapping of the sole thrust (Fig. 4).

The autochthonous Paleogene succession can be mapped also eastwards across the eastern edge of the South-Pyrenean thrust sheets and tie with the Basella well in the deformed foreland (Fig. 2). The undeformed Paleocene to Middle Eocene sediments continue underneath the detachment anticlines of the Ebro foreland detached on the Upper Eocene salt across the oblique NE-SW trending structures of the Segre valley (Vergés, 1999), ruling out old interpretations of these structures as the expression a basement-involved fault (Segre Fault, Souquet, *et al.*, 1977).

Dip seismic line across the eastern part of the South-Central-Pyrenean thrust sheets (TR1-T27)

A composite seismic line from the frontal parts of the Serres Marginals thrust sheet to the Bóixols thrust sheet shows the main structural features of the South-Central Pyrenees (Fig. 5). The age of the reflectors is well constrained by the previous described seismic line (TR3) that allow us to project the Isona well into this line and by the Sant Corneli well in the northern part of the line. The northward tilted panels of the Montsec and Bóixols thrust sheets allow us also to project the outcropping sedimentary units at depth. Finally, the Comiols well that drilled the Montsec and Serres Marginals thrust sheets as well as the autochthonous foreland down to the basement has been projected along the TR55 seismic line (Figs. 2; 5). The internal structure of the Serres Marginals thrust sheet has not well imaged by the seismic sections acquired in the area. However, a prominent reflector in the TR1 line has been interpreted as the Montroig thrust flooring the Ager Basin and connecting with the thrust at the bottom of the Montroig range (Fig. 5). This thrust is the main one South of the Montsec thrust and shows a footwall ramp underneath the southern limb of the Ager syncline. A structural unit occurs between this thrust and the sole detachment located at the Cardona salt unit (Fig. 5). This unit was interpreted to involve a reduced Mesozoic succession and unconformably overlying Paleogene sediments to account for the map relationships between the frontal imbricates and the out-of-sequence nature of the

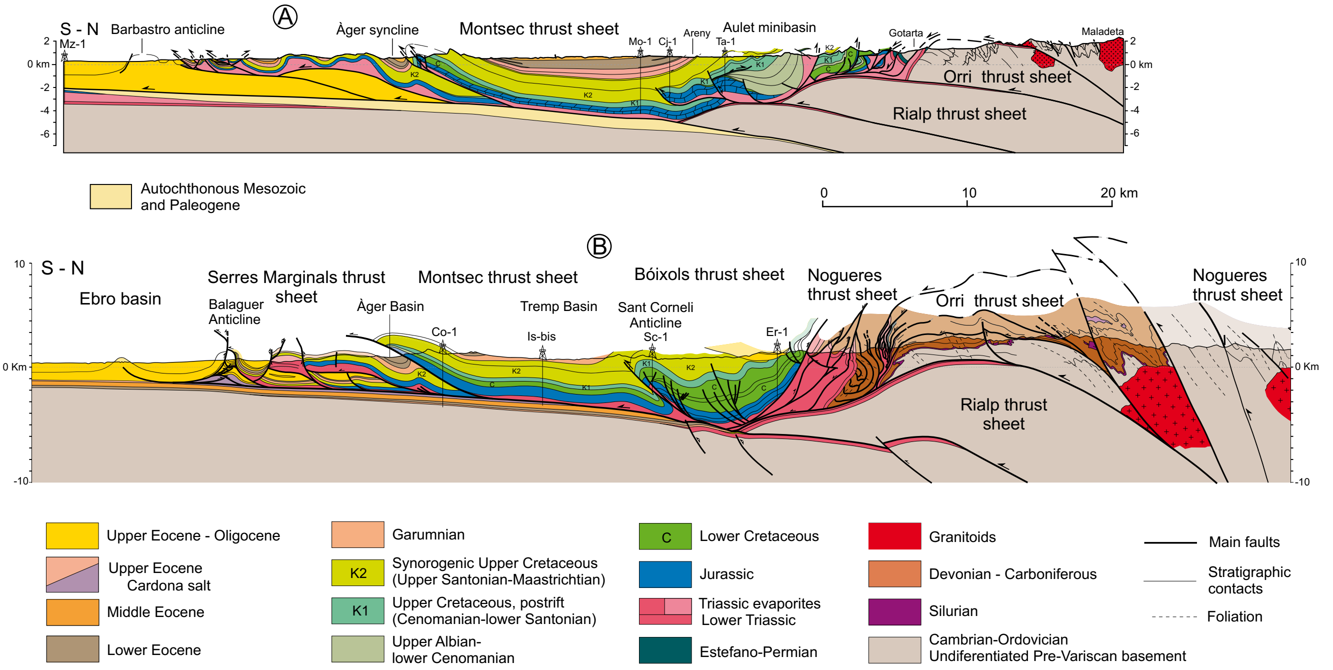

FIGURE 6. Geological cross-section along A) the Ribagorçana and B) Pallaresa valleys. The Ribagorçana cross-section has been modified from Teixell and Muñoz (2000) according to García-Senz (2002) for the northern part of the section. The bottom section corresponds to the ECORS-Pyrenees cross-section and has been updated and modified from Muñoz (1992) and Berástegui *et al.* (1993) to consider the seismic interpretation of the TR1-T27 seismic line.

Montroig thrust (Muñoz, 1992). However, it could be also formed exclusively by Paleogene rocks. But in that case, the strong stratigraphic differences between the Montroig thrust sheet, with a thick (>1.5km) Jurassic to Paleoceone succession, and the frontal most imbricates in its footwall, characterized by a reduced sequence of tens of meters of Upper Cretaceous carbonates and Paleocene continental sediments (Garumnian), overlying the Keuper rocks is difficult to explain. Such stratigraphic difference has been interpreted as the inversion of the margin of the Mesozoic extensional basin (Vergés, 1999). However, this extensional margin would involve Mesozoic-Paleocene sedimentary units that have been deposited in different tectonic settings (prerift and synorogenic, but no synrift, see Fig. 6).

The integration of the surface data across the Ager syncline and the Montsec thrust and the subsurface data permit deciphering the existence of a subthrust anticline to account for the footwall ramp interpreted in the seismic line and the information of the Comiols well. This well drilled an Upper Cretaceous succession overlying the Jurassic carbonates in the footwall of the Montsec thrust (Fig. 3). The thickness and facies of these units correspond with the ones observed in the Serres Marginals South of the Ager syncline. These units are not truncated in the northern limb of the Ager syncline as they were drilled by the Comiols well at the bottom of the footwall ramp. The simplest structure to connect the Mesozoic succession drilled by the Comiols well underneath the Montsec thrust sheet with the one folded into the Ager syncline is a subthrust anticline (Figs. 5; 6). An anticline in the same structural position is observed further East in the Pedraforca thrust sheets (la Figuerassa anticline, Fig. 2).

An axial surface North of the northward dipping panel of the Montsec range defines the bottom of the footwall ramp of the Montsec thrust and its branch line with the sole thrust. Northward, the Tremp synclinorium as well as open folds of the Montsec thrust sheet have been well imaged by the seismic lines (Figs. 4; 5).

The Sant Corneli-Bóixols anticline has not well imaged by the seismic data provided the vertical attitude of its frontal limb and the rugged topography (Fig. 5). However, the integration of the surface geology with the available subsurface data has provided a reasonably well constrained 3D geometrical model (Mencos *et al.*, 2015). The Sant Corneli-Bóixols anticline developed in the hangingwall of the Bóixols thrust as it cut through into the footwall of the main rift boundary fault (Organyà fault) during the inversion of the Organyà Basin (García-Senz, 2002). The overall 3D geometry of the Sant Corneli-Bóixols anticline, such as the western plunge of the Sant Corneli anticline, resulted from the inversion of an intricate extensional fault system that includes a breached rely ramp (Mencos *et al.*, 2015). The northward dipping back limb of the Sant Corneli-Bóixols anticline has been imaged by the seismic lines. It dips a constant angle to the North, subparallel to the Bóixols thrust at depth. The axial surface bounding the northward tilting panel suggests the position of the branch line between this thrust and the sole thrust (Fig. 5). The Sant Corneli well drilled an extensional fault in the footwall of the Organyà fault as demonstrated by the omission of lower Jurassic units. This well also drilled the Bóixols thrust and an overturned succession in its footwall characterized by very thin Lower Cretaceous sediments, unconformably overlying lower Jurassic carbonates (Figs. 3; 5). This succession has been interpreted to continue with a package of gently folded reflectors that was imaged underneath the frontal limb of the Sant Corneli-Bóixols anticline at 1.4–1.5TWTs (Two Way Travel time seconds), (Fig. 5).

The Paleogene autochthonous reflectors have been also imaged in this composite seismic line, although not so continuously as observed in the strike seismic lines across it. As a result of this uncertainty, the main question concerns the northern location of the cut-off lines of the different stratigraphic units of the foreland. In the southern part of the line T27 horizontal to slightly northward dipping reflectors have been imaged at about 2TWTs (Fig. 5). They correspond to the Paleocene red beds and Lower Eocene carbonates as identified by the TR3 seismic line and the Isona and Comiols wells. They continue to the North at least as far as the position of the Sant Corneli anticline forelimb at surface. In the southernmost part of the T27 profile (between CDP 162 and 180) these lower reflectors form an angle with the Jurassic reflectors suggesting a footwall ramp in the sole thrust that would most probably involve the Upper Eocene Cardona salt or lateral equivalent sediments northward of the salt pinch out. Southwards, the reflectors of the autochthonous foreland continue subparallel to the sole thrust, although they have not been well imaged in the TR1 line.

Underneath the Organyà Basin a prominent set of high-amplitude reflectors in continuation with the autochthonous foreland have been imaged between 2 and 2.4s TWT (Fig. 5). They are deformed by an open anticline that has been interpreted as the result of an inverted Permian-Triassic basin. The reflectors are truncated by the sole thrust suggesting the position of the cut-off lines for different stratigraphic units (between CDPs 102–120 at line T27 in Figs. 5; 6). This basement-involved subthrust fault has also been imaged by strike lines along the Bóixols thrust sheet (Mencos *et al.*, 2015).

Seismic sections between the Pallaresa and Ribagorçana valleys

Seismic data along the Ribagorçana valley as well as strike lines connecting these lines with the above described lines imaged the autochthonous Paleogene succession, particularly the high-amplitude set of reflectors above the acoustic transparent basement that has been interpreted as Paleocene to Lower Eocene sediments (Teixell and Muñoz, 2000; Mencos, 2011).

The location of the cut-off line of the bottom of the Upper Eocene succession (Cardona Fm. or lateral equivalents) has been constrained by a footwall ramp of the sole thrust. Seismic data also constrain the location of the Bóixols thrust front underneath the southern limb of the Graus-Tremp synclinorium (Fig. 6).

The structural relief shown by the Upper Albian-Cenomanian Aulet minibasin, southward the Lower Cretaceous synrift basins (García-Senz, 2002; Saura *et al.*, 2016) has been explained by basement thrusting in the footwall of the Rialp thrust sheet (Fig. 6A).

Dip seismic line along the Isabena valley SP84-06-SP86-04

A composite seismic line across the western part of the Montsec thrust sheet and its contact with the Bóixols thrust sheet shows many structural features that are not visible at surface.

The Montsec thrust sheet has been deformed by detachment folds during its emplacement at Early Eocene times as demonstrated by the growth geometries observed in the seismic line. This growth sequence mainly involves the marine marls and clastics of the Fígols Group of early Ypresian age (Fig. 7). Northward, the sedimentary geometry of the Maastrichtian Areny group, and particularly its depocenter, defines the position of the Bóixols thrust front. The hagingwall of the Bóixols thrust at its frontal part along this transect is characterized by a duplex and imbricates involving a reduced Mesozoic succession that was drilled by the Caxigar well (Lanaja, 1987). In these imbricates the Lower Cretaceous sediments are absent or extremely thin (Fig. 8). All these imbricates are located in the footwall of the reactivated extensional faults of the Lower Cretaceous extensional basins and occupy a wider area with respect other transects of the Central Pyrenees (compare Figs. 6 and 8). The Jurassic carbonates are truncated immediately in the footwall of the Early Cretaceous extensional faults, underneath the unconformity at the bottom of the upper Albian sandstones, attesting for footwall uplift and salt inflation during the extensional deformation (Fig. 8). A several kilometre-thick succession of syninversion turbidites was deposited during late Santonian and Campanian times (Van Hoorn, 1971, Ardèvol *et al.*, 2000) in the footwall of thrusts which resulted from the reactivation of the main bounding extensional faults (*i.e.* Las Aras fault, García-Senz, 2002). These turbidites show growth geometries, both in the field and in the seismic sections, with the structures of the Bóixols thrust sheet demonstrating the Late Cretaceous age of the deformation (Figs. 7; 8). The upper part of the Maastrichtian Areny group sediments seals the frontal part of the Bóixols thrust sheet (Figs. 7; 8).

Underneath de Montsec thrust sheet, flat lying to slightly North-dipping reflectors have been interpreted to correspond to the Paleogene autochthonous succession as they can be tracked along many strike seismic sections from the East, where they were drilled by the Comiols and Isona wells (Figs. 2; 4). Particularly, the high-amplitude set of reflectors at the bottom of the Paleogene sequence are visible in some portions of the line (*i.e.* Line SP84-06 at 2100–2200ms between CDPs 220–130 and Line SP84-06pr at 2200ms between CDPs 1120–1070, Fig. 7). Nonetheless, it has to be emphasized that in the dip seismic lines the autochthonous reflectors above the basement are masked by seismic noise, differently to the strike sections where they have been nicely imaged. These reflectors are truncated by a North-dipping strong set of reflectors that have been interpreted as a footwall ramp of the sole Pyrenean thrust (Line SP84-06Pr between CDPs 939–945 and Line SP86-04 line CDPs 150–240, Fig. 7). This thrust shallows northward and carries a thrust sheet underneath the Bóixols thrust sheets which does not outcrop or have been drilled. It has been named Ribagorça thrust sheet and could involve basement as well as Permian to Lower Triassic red beds (Fig. 8). The footwall ramp of the sole thrust most probably involved the Upper Eocene succession just underneath the Bóixols thrust front. However, a question arises about the northward continuation of older sediments, such as lower Paleogene or thin Mesozoic rocks, underneath the Ribagorça thrust sheets (Figs. 7; 8).

The western edge of the Montsec and Bóixols thrust sheets: the SP84-10 seismic line

The western edges of the Montsec and Bóixols thrust sheets are characterized by oblique NW-SE to N-S trending structures which define the most prominent thrust salient of the southern Pyrenees as above described (Fig. 2). This thrust salient developed by a progressive curvature with a divergent thrust transport direction from Middle Eocene to Oligocene, as deduced from the integration of paleomagnetic, stratigraphic and structural data (Sussman *et al.*, 2004; Muñoz *et al.*, 2013). The oblique structures in these thrust sheets as well as in their footwall (Gavarnie thrust sheet) experienced a clockwise vertical axis rotation of up to 70º (Mochales *et al.*, 2012; Muñoz *et al.*, 2013).

Few seismic lines were acquired across the entire oblique system of the western part of the South-Central-Pyrenean thrust salient. One of the nicest ones, which constrains

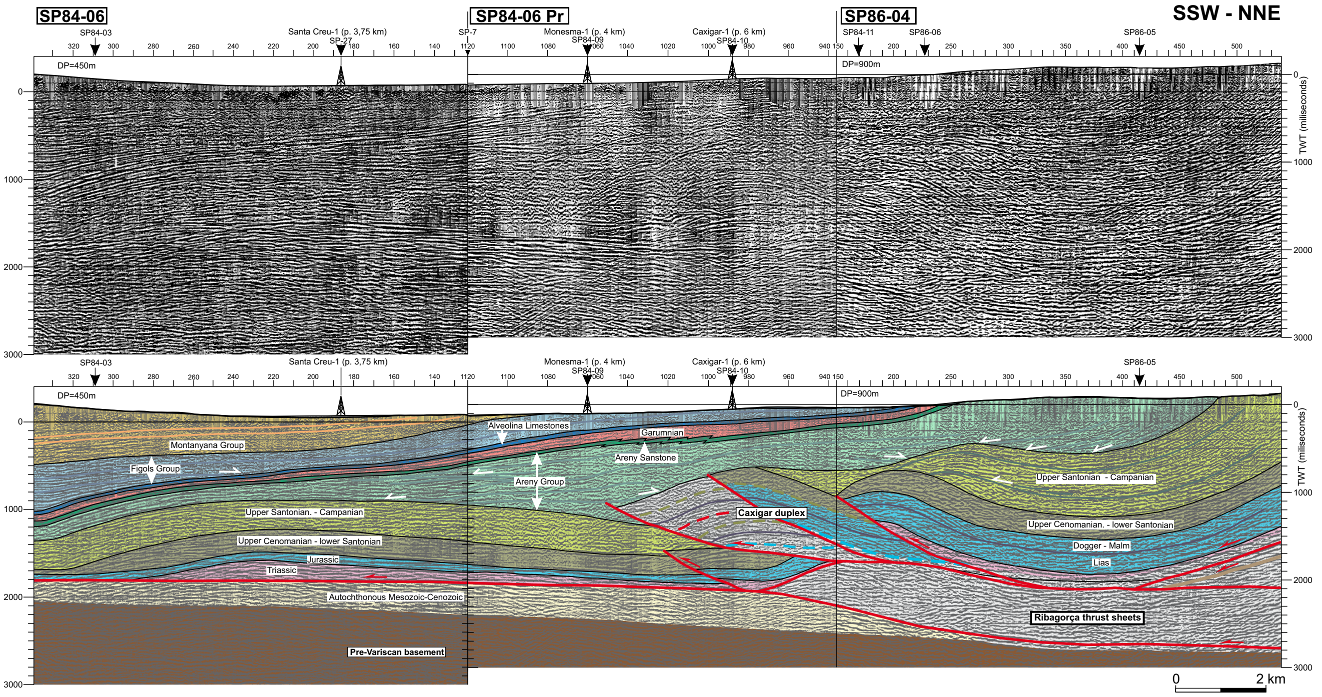

FIGURE 7. Seismic line SP84-06-SP86-04 along the Isábena valley. See Figure 2 for location.

significantly the structure of the South-Central Pyrenees, is the SP84-10 line (Fig. 9). One of the most prominent features of this line is a continuous set of horizontal to slightly West-dipping reflectors, the bottom of which was imaged at a depth ranging from 2.5TWTs in the East to 2.7TWTs in the West (Fig. 9). These reflectors are located underneath the South-Pyrenean thrust sheets and continue with the autochthonous Paleogene succession previously described in eastern lines (see intersection with the SP84-06 line, Fig. 7). The seismic facies of the lowermost continuous reflectors of this autochthonous package resemble the ones identified as Paleocene to Lower/Middle Eocene succession (transition from red beds to Alveolina limestones) in the eastern lines. However, the presence of Upper Cretaceous sediments or Triassic beds cannot be ruled out. The high-amplitude and continuous reflector at the bottom of the Upper Cretaceous succession in the Gavarnie thrust sheet, at the western part of the seismic section, diverges from the top of the autochthonous basement westward (Fig. 9). This geometry has been interpreted as a result of the existence of the leading edge of the basement involved Guarga thrust sheet underneath the Gavarnie thrust sheet (Fernández *et al*., 2012) and would correspond with the area characterized by high-amplitude short reflectors (Fig. 9).

The SP84-10 seismic line has also imaged the oblique Bóixols thrust front and the oblique thrust contact between the Montsec and the Gavarnie thrust sheets. The age of the reflectors of the Montsec and Bóixols thrust sheets have identified by tying well data and projecting the surface geology (Fig. 9). The seismic stratigraphy of the Gavarnie thrust sheet, in the western part of the seismic section, is very distinct and characterized by a more transparent unit above a continuous reflector corresponding to the Upper Cretaceous carbonates and a set of continuous high-amplitude reflectors above of Paleocene to early Ypresian age (Fig. 9). All these seismic units can be mapped all along the Ainsa Basin at the eastern edge of the Gavarnie thrust sheet and tied with well (*i.e*. Surpirenaica-1, Fig. 2) and surface data (Fernández *et al*., 2012). The floor of the Montsec thrust sheet, named in the Ainsa area as Peña Montañesa or Atiart thrust (Soler-Sampere and Garrido-Megías, 1970), truncates the reflectors of the Gavarnie thrust sheet and cannot be located precisely in the seismic line. However, this thrust lies westward of the La Foradada fault, which is a tear fault in the hanginwal of the Montsec-Atiart thrust. The triangular structural unit between the La Foradada fault and the Atiart thrust (Peña Montañesa thrust sheet) has been folded and truncated by erosional surfaces at the transition from the shelf of the Graus-Tremp piggy-back Basin to the Ainsa slope Basin (Soler-Sampere and Garrido-Megías, 1970; Muñoz *et al*., 1994; Fernández *et al*., 2012). Eastward of La Foradada fault the Mesozoic to Lower Eocene succession has been mainly tilted to the South (see block diagram in Fernández *et al*., 2012). The Montsec thrust has been sealed by the upper Ypresian sediments.

The structure of the eastern part of the Gavarnie thrust sheet at the Ainsa Basin (SP14 and SP3 lines)

The structure of the Ainsa Basin has been recently described based on the construction of a 3D geological model integrating all the available subsurface and surface data (Fernández *et al.*, 2012). In addition, paleomagnetic data and well preserved synorogenic sediments have enabled us to deduce the 4D tectono-sedimentary evolution and add additional constraints on the structure of the South-Pyrenean thrust sheets (Muñoz *et al.*, 2013). There is no other area in the Pyrenees where the tectono-sedimentary relationships and the timing of the structures are so well constrained, particularly for Eocene times. Here, enclosed are the main structural features retrieved from the interpretation of the subsurface data (Figs. 10; 11).

The structure of the Ainsa Basin is characterized by a system of kilometre-scale N-S trending folds deforming the Upper Cretaceous to Lower Eocene succession, of mainly carbonates, of the Gavarnie thrust sheet at the floor of the basin. This succession shows a very distinct set of reflections in the seismic sections (Figs. 10; 11; 12), allowing subsurface mapping and reconstruction of the 3D geometry of the Gavarnie thrust sheet (Fernández *et al.*, 2004, 2012). These folds are detachment to fault propagation folds, detached into the Triassic evaporites (Fernández *et al.*, 2012; Muñoz, 2017) and define the Ainsa Oblique zone at the western edge of the South-Central-Pyrenean thrust salient (Fig. 2; Muñoz *et al.*, 2013). The folds of the Ainsa Basin (Mediano, Añisclo, Olsón and Boltaña anticlines) grew during the sedimentation of the Middle and Upper Eocene slope to fluvial succession filling the Ainsa piggy-back Basin, dating the onset of the deformation of the Gavarnie thrust sheet at early Lutetian times (Arbués *et al.*, 2011; Fernández *et al.*, 2012; Muñoz *et al.*, 2013). Growth wedges are visible both in the field and in seismic sections (Fig. 10) and have allowed deciphering fold kinematics (Poblet *et al.*, 1998). Onset of fold growing became younger westward as the Gavarnie thrust propagated in the same direction. The oldest folds are the Mediano and Añisclo anticlines that started to growth at latest most Cuisian-early Lutetian times (Poblet *et al.*, 1998; Fernández *et al.*, 2012; Muñoz *et al.*, 2013). Deformation progressed westward synchronous with the clockwise vertical rotation along the Ainsa Oblique zone (Mochales *et al.*, 2012; Muñoz *et al.*, 2013) and continued further West in the N-S trending folds of the Sierras Exteriores (Millán *et al.*, 2000; Rodríguez-Pintó *et al.*, 2016) during Middle Eocene times. The folds of the Ainsa Basin involved the turbiditic trough but also the southward age equivalent carbonates. Thus, middle Eocene growth strata involved, from North to South: turbidites (Añisclo anticline, Fernández *et al.*, 2012), the platform to slope transition (Boltaña and Mediano anticlines, Muñoz *et al.*, 2013) and the carbonates exposed in the Sierras Exteriores (Balzes anticline, Rodríguez-Pintó *et al.*, 2016). The westward migration of the onset of deformation in the frontal part of the detached cover succession of the Gavarnie thrust sheet may account for the different ages given for the Gavarnie thrust in western transects across the Jaca Basin (Labaume *et al.*, 2016).

One of the most striking features imaged by the seismic sections in the Ainsa Basin is a thick succession (up to 1sTWT, or even more) of flat-lying reflectors underneath the fault-related folds of the Gavarnie thrust sheet in the southern part of the basin (Figs. 10; 11). These reflectors are in continuation with the autochthonous Paleogene succession observed and mapped in all the available seismic sections imaging the foreland underneath the South-Pyrenean thrust sheets (Serres Marginals, Montsec and Bóixols), some of them herein included. The upper part of these reflectors disappears to the North and that has been interpreted as a result of truncation in the footwall of the lowermost basement-involved thrust (Guarga thrust)

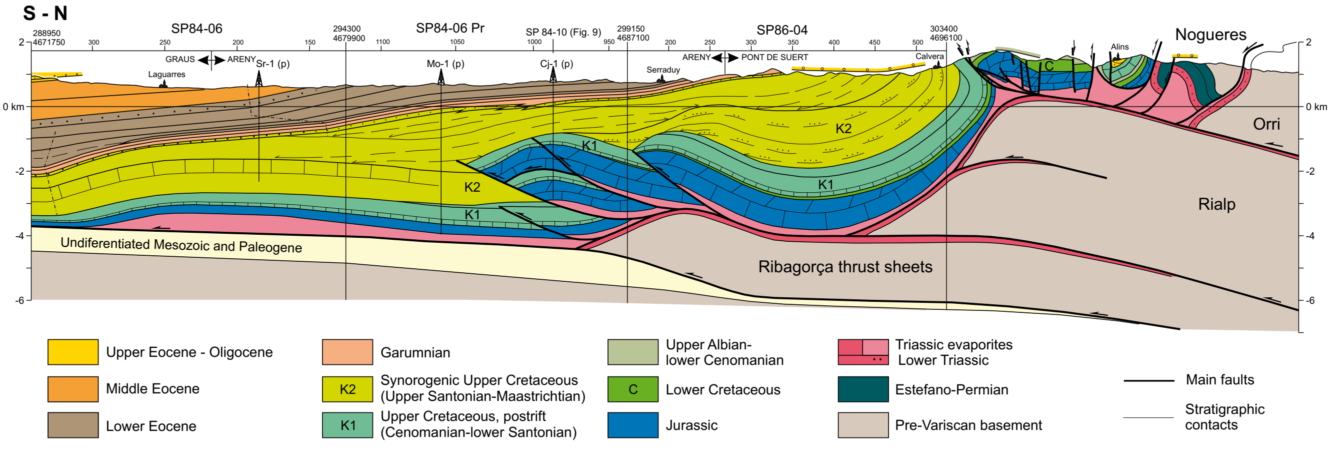

FIGURE 8. Geological cross-section along the Isabena valley following the seismic lines of Figure 7. The northern part of the section corresponds to a section by García-Senz, 2002. The boundaries between the 1:50,000 topographic and geological sheets (Areny and Pont de Suert), as well coordinates, have been added for a precise location of the section.

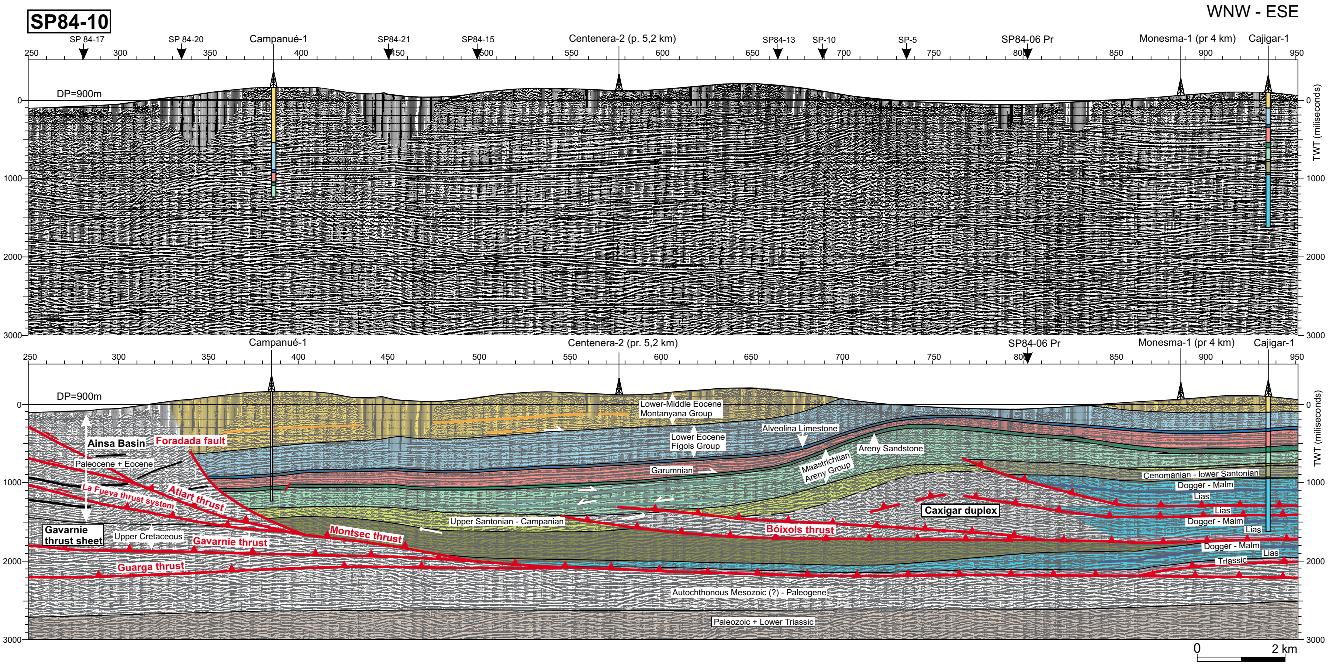

FIGURE 9. Strike seismic line SP84-10 across the eastern part of the Gavarnie thrust sheet and the western edges of the Montsec and Bóixols thrust sheets. See Figure 2 and 8 for location.

(Fig. 10). A question is the precise age of this thick package of reflectors as they have not been drilled, as well as the existence of possible repetitions of stratigraphic units, mainly in the southernmost part of the Ainsa Basin as suggested by obliquities in the upper part of the reflectors. The footwall ramp of the Guarga thrust truncating the autochthonous Paleogene has also been interpreted in the strike SP3 seismic line in order to match with the intersection with the SP28 line across the eastern Jaca Basin (Figs. 11; 12).

The structure of the eastern part of the Jaca Basin: the SP28-JAT84 composite seismic line

The most conspicuous structural feature of this seismic transect is the synformal geometry of the Jaca Basin lying on top of North-dipping to subhorizontal reflectors above the acoustic basement of the autochthonous foreland (Fig. 12). The synform is asymmetric with a significant thinner Mesozoic to Upper Eocene succession in the southern limb. In this limb the unconformity between the Lower and Middle Eocene turbidites, characteristic of the sedimentary infilling of the Jaca Basin, and their southern carbonate counterparts is very prominent (Puigdefàbregas, 1975; Labaume *et al.*, 1985, 2016). Turbidites show an onlap above the truncated carbonates (Fig. 12). The turbiditic trough developed synchronously with the carbonate platform that retreated progressively (backsteppened) as the trough advanced forward in the footwall of the Peña Montañesa thrust sheet and their westward equivalents. Tilting of the platform produced its failure and the formation of resedimented carbonates, which are interlayered with the turbidites (carbonates megaturbidites, Labaume *et al.*, 1985).

Underneath the southern limb a continuous and thick Paleogene succession has been truncated by the Pyrenean sole thrust defining a footwall ramp characteristic of the Pyrenean fold and thrust belt underneath the southern Jaca Basin and Sierras Exteriores (Cámara and Klimowitz, 1985; Teixell, 1996, 1998; Millán *et al.*, 2000; Millán-Garido *et al.*, 2006; Labaume *et al.*, 2016). Seismic data do not resolve details of the geometry of the frontal imbricates at Sierras Exteriores thrust front (Fig. 12).

In the northern limb of the Jaca synclinorium a system of thrusts and related folds involve the Lower-Middle Eocene turbidite sequences of the Jaca Basin as well as the overlying Upper Eocene-Oligocene clastics (Fig. 12). This system has been detached into the Lower-Middle Eocene marls on top of the carbonatic succession that has provided a good detachment horizon. This is confirmed by a continuous and undeformed set of South-dipping reflectors corresponding to the Upper Cretaceous to Lower Eocene carbonates, according to the seismic facies observed and mapped in the Gavarnie thrust sheet and wells drilled close to the seismic section, underneath the Yebra de Basa anticline and the Oturia-Fiscal thrust front (Fig. 12). In agreement with Millán-Garrido *et al.* (2006) there is no evidence from the seismic data to argue that

Upper Cretaceous rocks are involved in the Yebra de Basa anticline, as suggested by Labaume and Teixell (2018). The South-dipping panel of Upper Cretaceous-Lower Eocene carbonates is disrupted in its upper part by thrusts, but mainly by the structure that was drilled by the Ayerbe de Broto well, which has been interpreted as a hanginwall structure of the Oturia-Fiscal thrust (Fig. 12). Seismic data do not constrain details of the geometry of the Ayerbe de Broto structure, most probably because the presence of steep fold limbs. Another uncertainty in the seismic data is the downward continuation of the Oturia-Fiscal thrust and the geometry of thrusts that may involve the basement and the unconformably overlying Triassic rocks. Reflectors that have been interpreted as the Oturia-Fiscal thrust could continue with a basement-involved thrust, thus truncating the main detachment at the bottom of the Upper Cretaceous rocks that branches northwards with the Gavarnie thrust (Fig. 12). Another possibility is that the Oturia-Fiscal thrust branches into this detachment in the footwall of the Gavarnie thrust, defining a duplex together with the other minor thrusts involving the Upper Cretaceous-Lower Eocene carbonates. This duplex would be breached by the lower basement-involved thrusts. This interpretation would be in agreement with the similar structural elevation of both the footwall and the hanginwall of the Oturia-Fiscal thrust, once the younger southward tilting is removed. (Fig. 12). All these geometric relationships are relevant for the age of the different structures. The Ayerbe de Broto well has projected above the topography to preserve the eastern plunge of the structure according to the dip data provided by the well logs.

Basement-involved thrusts merge upwards into a detachment underneath the continuous Upper Cretaceous rocks, suggesting the presence on a weak horizon on top the Triassic succession, most probably evaporites of the Keuper facies. However, the northern edge of the evaporites is not well constrained. It should be located southward the Broto well, where Keuper rocks were not drilled, and most probably southward the Ayerbe de Broto structure. In the

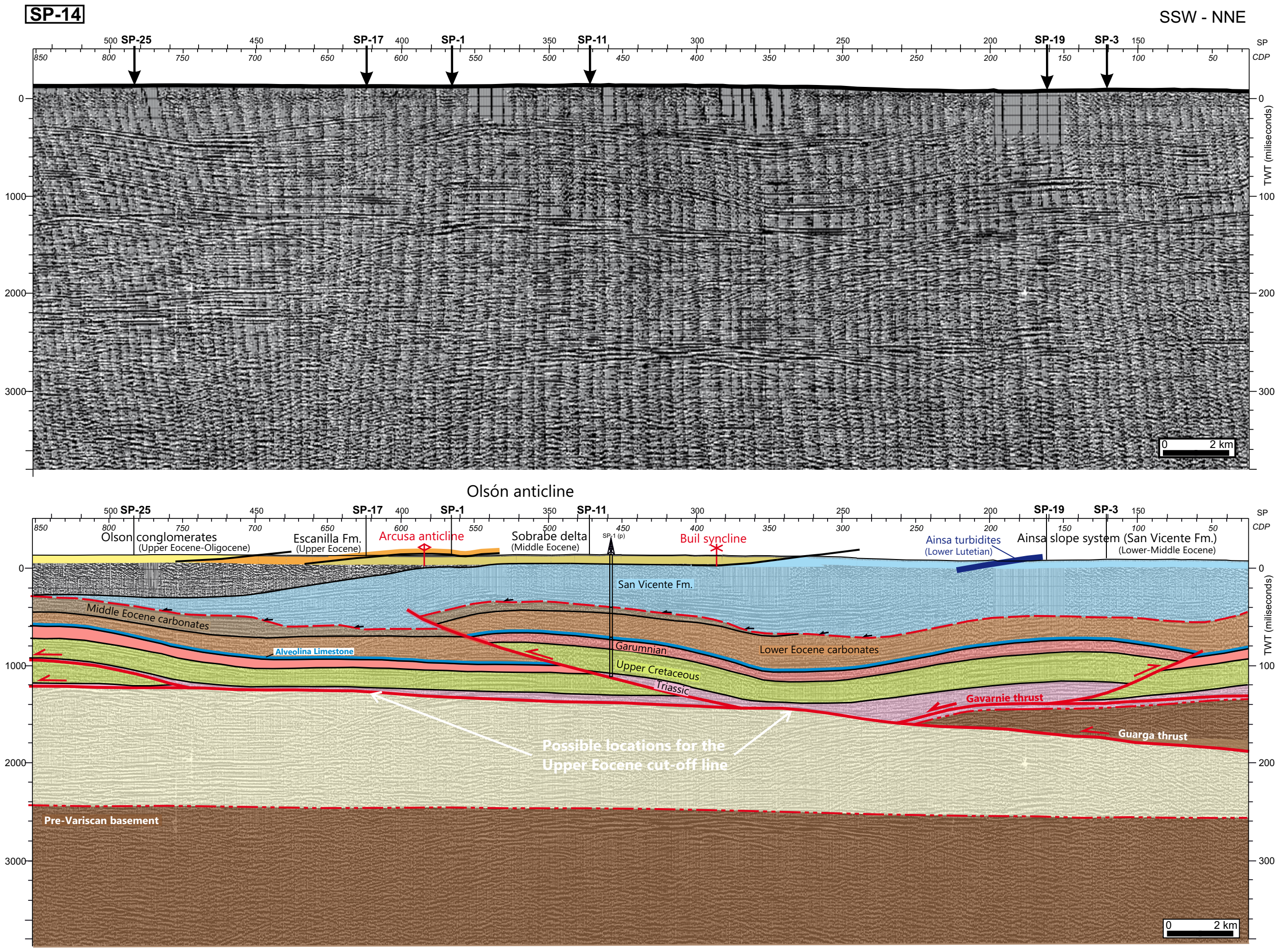

FIGURE 10. Seismic line SP14 in the Ainsa Basin. The two options for the location of the cut-off line of the Upper Eocene sediments have been depicted. See Figure 2 for location.

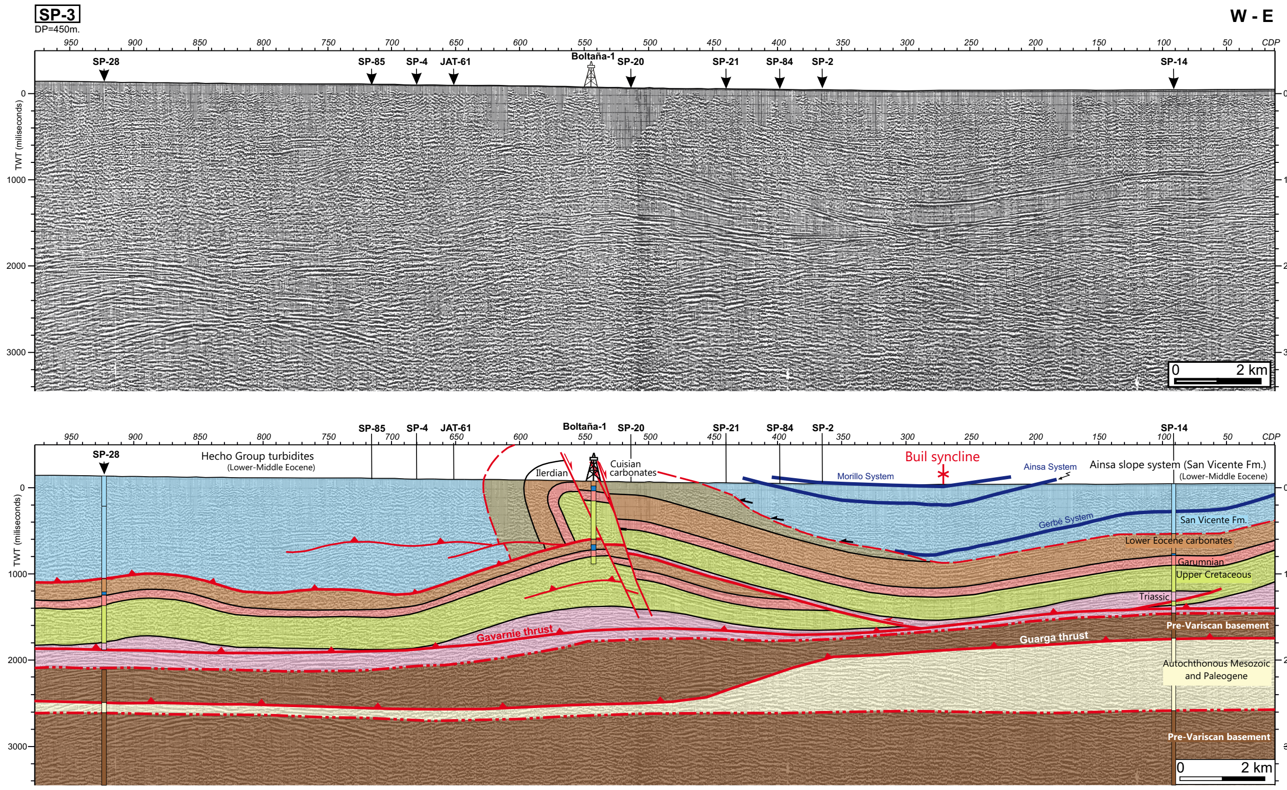

FIGURE 11. SP3 seismic line across the N-S trending structures of the Ainsa Basin and the eastern part of the Jaca Basin, westward the Boltaña anticline. See Figure 2 for location.

interpreted seismic line (JAT84) the amount and location of basement-involved thrusts are not well constrained (Fig. 12).

DISCUSSION: STRUCTURAL INTERPRETATION

The structure of the South-Pyrenean fold and thrust belt in the Central Pyrenees is characterized by a synformal geometry, South of the basement rocks of the Axial zone. In the southern limb, thrusts constitute a North-dipping imbricate stack, whereas in the northern limb thrusts and related folds have been tilted and dip to the South. The core of this syncline has constituted the main sedimentological path for the synorogenic deposits, particularly for the younger Paleogene successions, as the basement units of the Axial zone were progressively exhumed (Beamud *et al.*, 2011).

Tilting of the northern limb resulted from underthrusting of the lower basement thrust sheets (Figs. 6; 12; among many others). The axial trace of the synform runs close and subparallel to the leading edge of the southernmost and lowermost basement-involved thrust sheet, as defined by the branch line between the floor thrust of this thrust sheet and upper thrusts (Fig. 13). This branch line does not correspond to a single thrust sheet. In the eastern part of the Jaca Basin and Ainsa Basin it coincides with the leading branch line of the Guarga thrust sheet (Teixell, 1998; Fernández *et al*., 2012). Eastward, the mapped branch line corresponds to the leading edge of the Ribagorça thrust sheet, a basement-involved structural unit in the footwall of the Rialp thrust sheet (Figs. 8; 13). And further East that branch line is the leading edge of the Rialp thrust sheet (Fig. 6). The relationship between the Guarga and Ribagorça thrust sheets has not been retrieved from the interpretation of seismic data, but most probably they are independent structural units (Fig. 9). East of Noguera Ribagorçana valley basement thrust sheets are piled one of top of the other defining the characteristic antiformal stack geometry of the ECORS-Pyrenees cross-section (Fig. 6). The transition between the two cross-sections is defined by a re-entrant of the branch line which coincides with the outcrop of late synorogenic conglomerates (Fig. 13). The inverted Permian-Triassic extensional basin that has been interpreted underneath the Bóixols thrust sheet in the ECORS section developed during the latestmost stages of deformation and shows a structural position equivalent to the Ribagorça thrust sheets (Fig. 6).

The synformal geometry of the South-Pyrenean thrust system is more obvious in transects where the Pyrenees are narrower, such as in the eastern Pyrenees or in the Jaca Basin. There the synformal geometry controlled by the leading edge of the lower basement-involved thrust sheet in the North and the footwall ramp of the sole thrust in the South resulted into the development of the Ripoll-Vallcebre and Guarga synclines, respectively (Fig. 13). These synclines hosted piggy-back basins since Middle Eocene times characterized by a shallowing upward sedimentary infilling from Middle Eocene turbidites to Oligocene conglomerates (Puigdefàbregas, 1975; Labaume *et al*., 1985, 2016; Muñoz *et al*., 1986; Puigdefàbregas *et al*., 1986; Vergés, 1999).

Interpretation of the seismic lines has allowed us to map the approximate location of the cut-off lines of some distinct stratigraphic horizons of the autochthonous foreland. We have selected the Upper Eocene salt horizon (Cardona Fm.) that was drilled by the Comiols and Isona wells underneath the Montsec thrust sheet (Fig. 3) and the Lower-Middle Eocene carbonates which are characterized by a continuous and high amplitude set of reflectors drilled by the Comiols well.

South and West of these wells the Pyrenean sole thrust shows a footwall flat on top of the Cardona salt (Figs. 4; 5). The location of the cut-off line of this horizon has been approximately deduced by the footwall ramp observed northwards of this flat (*i.e*. Figs. 5; 10; Teixell and Muñoz, 2000). In the eastern Pyrenees, the Cardona salt horizon grades laterally into continental clastics that crop out immediately in the footwall of the thrust front (Vergés *et al*., 1992). The cut-off line crops out in several points and consequently is relatively well constrained (Fig. 13). In the Sierras Exteriores, the sole thrust underneath the southern limb of the Guarga syncline truncates the entire foreland Paleogene succession along a high angle footwall ramp (Fig. 12). As a consequence, the stratigraphic horizon time equivalent to the Cardona Fm., near the top of the marine Eocene succession, is truncated at the lower part of the footwall ramp. Regardless the uncertainty on the age of the reflectors in the seismic sections, the error on the position of the cut-off line is minor because the high angle of the footwall ramp. Between the eastern part of the Gavarnie thrust sheet in the Ainsa Basin and the Noguera Pallaresa valley, near Tremp, the uncertainty on the position of this cut-off line is greater. Thus, in the seismic line SP14 (Figs. 2; 10) there are two options for the position of this line. The northern one would be located at the top of the most prominent footwall ramp of the Guarga thrust (CDP 330, Fig. 10). Alternatively, the position of the Upper Eocene cut-off line could be located further South on top of a lower footwall ramp (CDP 620, Fig. 10). The two options have been depicted in the map of Figure 13.

The cut-off line of the Lower Eocene carbonates is less well constrained. It has been traced according to the northernmost position of the lower Paleogene succession imaged by the seismic lines. These reflectors are mainly visible and continuous along the strike lines. However, in the dip lines they are not so continuous and, in some areas, such as parts of the Bóixols thrust sheet deformed by tight folds with vertical to overturned limbs or by salt structures, they have been masked by the structures above. Two possible end-members for the cut-off line have

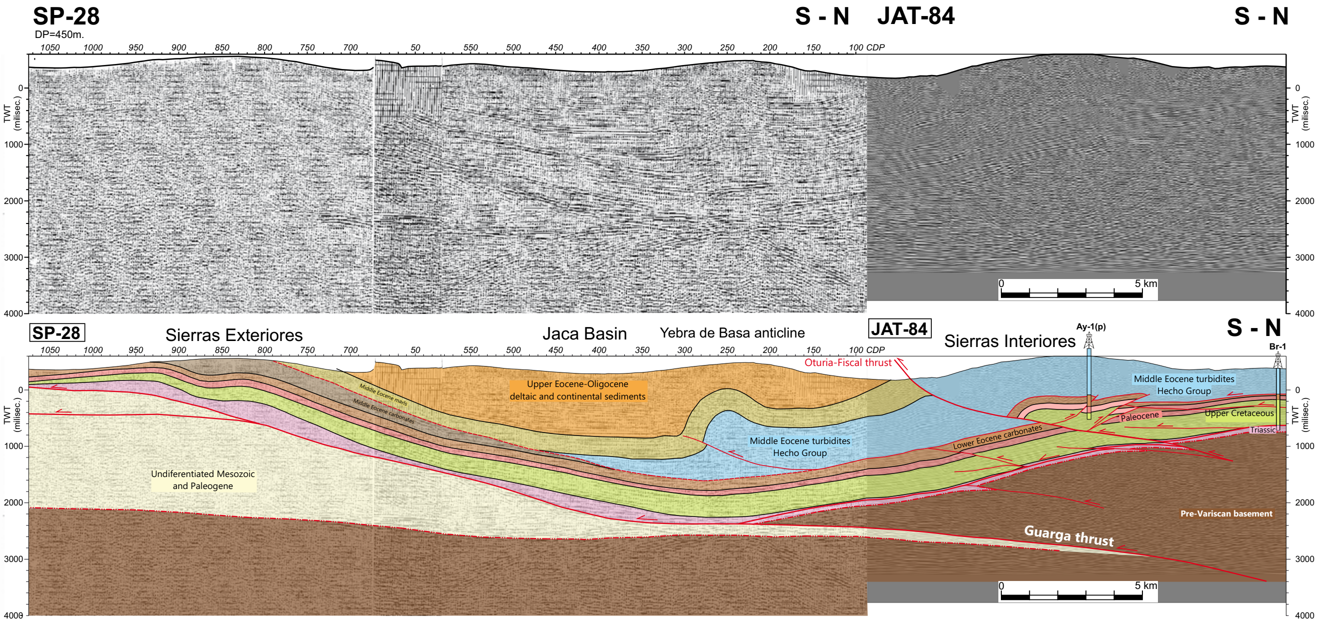

FIGURE 12. Eastern composite line SP28-JAT84 across the eastern part of the Jaca Basin. See Figure 2 for location.

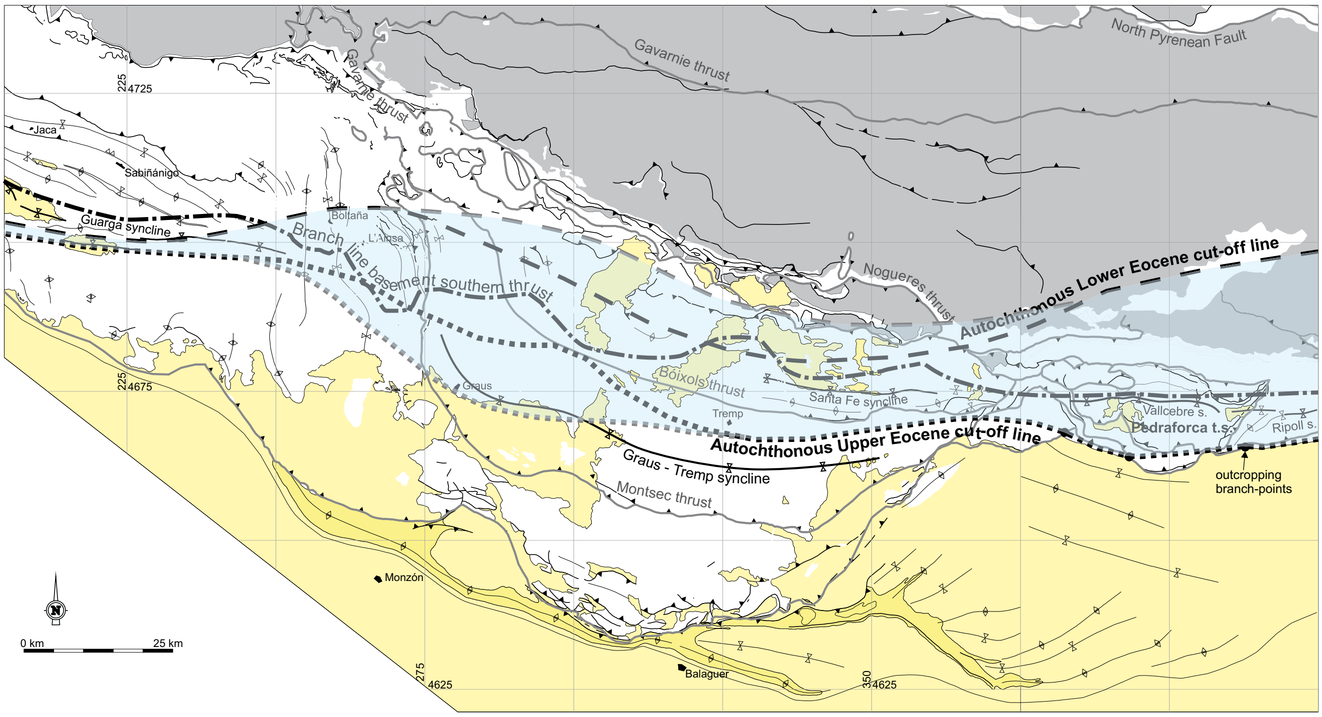

FIGURE 13. Structural map with the structural lines resulted from the interpretation of the available seismic data in the South-Central-Pyrenees. The mapped lines are the branch line between the lowermost basement-involved thrust sheet and the Pyrenean sole thrust (leading edge of the basement thrust sheets), and the cut-off lines between this thrust and the Upper Eocene Cardona Fm. (or stratigraphic equivalents) and the lower Eocene carbonates. Two possible end-members have been depicted for each cut-off line and the area between them outlined in transparent blue.

been represented in the map in Figure 13. In the eastern Pyrenees, the lower Eocene carbonates were nicely imaged underneath the allochthonous basement thrust sheets (Vergés, 1999; Martínez *et al*., 1997). In the West-Central Pyrenees, the cut-off line of the Lower-Middle Eocene carbonates is well constrained at the bottom of the footwall ramp of the frontal thrust, not far from the trace of the Guarga syncline (Fig. 13).

The structural lines described above follow an approximate N100 trend all along the central Pyrenees, independently of the structural trend and the thrust salient geometry of the structures on the surface (Fig. 13). This geometry agrees with the idea that the South-Central-Pyrenean thrust salient (South-Pyrenean Central Unit by Séguret, 1972) is not a primary arc inherited from the Mesozoic basins and later on transported. It is consistent with a thrust salient developed progressively during thrusting as deduced from the integration of structural and paleomagnetic data in the Ainsa Oblique zone (Muñoz *et al*., 2013) and paleomagnetic data in the eastern oblique structures, along the Segre valley (Sussman *et al*., 2004).

The location of the cut-off lines also yields the superposition of the South-Pyrenean thrust sheets above the undeformed Mesozoic to Paleogene succession in continuation with the foreland. Accordingly, the minimum thrust displacement for the central parts of the thrust salient since Late Eocene times is about 35km. The minimum displacement since early Middle Eocene times is 52km. These values do not consider the erosion of the frontal imbricates or the internal shortening of the Serres Marginales thrust sheet, which would increase significantly these minimum values. The maximum estimated distance between the cut-off-lines East of the Ainsa Basin is of 32km (Fig. 13). This value differs from the 49km displacement that was deduced to occur between early Lutetian and Priabonian times to account for the development of the South-Central-Pyrenean thrust salient and the paleomagnetic data (Muñoz *et al*., 2013). Such difference could be the result of the internal deformation of the South-Pyrenean thrust sheets and erosion as well as the uncertainties in the age of the reflectors and position of the cut-off lines. The estimated minimum thrust displacements since early Lutetian times are in agreement with the structural interpretation and restoration of the N-S trending structures of the Ainsa Oblique zone based on paleomagnetic and structural data that yield a total differential thrust displacement between the adjacent unrotated parts of the thrust system of about 66km during the salient development (Muñoz *et al*., 2013).

Thus, the available subsurface data rule out a recent structural reinterpretation of the ECORS cross-section that, with no data constraints, is aiming to reduce the amount of shortening and thrust displacement of the South-Pyrenean thrust sheets (Mouthereau *et al*., 2014).

The cut-off lines for the Cardona Fm. or stratigraphic time-equivalent and the top of the Lower Eocene carbonates diverge from West to East. This is the result of the mechanical stratigraphy of the involved synorogenic Eocene succession. In the western part of the studied area it is characterized by a continuous succession from carbonates to clastics with no any significant weak horizon. As a result, the entire Paleogene foreland sequence is involved in a continuous footwall ramp. On the contrary, in the eastern Pyrenees there is a salt layer on top of the Lower Eocene carbonates (Beuda Fm.), which has supplied a detachment horizon for the thrust system. The distance between the Lower Eocene and Upper Eocene cut-off lines corresponds to the flat of the sole thrust along this salt horizon (Muñoz *et al*., 1986; Vergés, 1999; Martínez *et al*., 1997). In the Central Pyrenees, northward the wide flat above the Cardona salt, the footwall ramp of the sole thrust shows a lower angle than the one in the western part, underneath the Jaca Basin. This could be the result of the existence of a thick Middle Eocene marly succession that has also supplied a good detachment horizon at the bottom, as demonstrated by the frontal structures at the transition area from the central to the eastern Pyrenees (Burbank *et al*., 1992; Vergés, 1999).

The South-Pyrenean fold and thrust belt show significant structural changes along strike. These changes have mainly been the result of the inherited extensional basins that occurred in the Pyrenean domain before the contractional deformation and the distribution of the weak horizons on both the preorogenic and synorogenic successions. Inversion of the Lower Cretaceous basins played a fundamental role at the early stages of deformation from late Santonian to Early Eocene times (Beaumont *et al*., 2000; Bond and McClay, 1995; López-Mir *et al*., 2014; Mencos *et al*., 2015). Subsequent fold and thrust development, mainly after the emplacement of the Montsec and middle Pedraforca thrust sheet (Figs. 2; 13), was controlled by the weak horizons that were deposited in the foreland ahead of the thrust front, which in turn resulted from the paleogeographic configuration of the South-Pyrenean foreland Basin. This basin formed a marine embayment opening to the Bay of Biscay until Late Eocene times. Basin restriction during Early and Late Eocene times resulted in the deposition of a salt layer in the eastern Pyrenees (Beuda Fm.) and in the eastern and central Pyrenees (Cardona Fm.), respectively (Vergés *et al*., 1992). During the late stages of deformation, the fold and thrust belt detached into this foreland salt horizons adding more than 40km of displacement and increasing the salient geometry previously developed. The mapped cut-off lines not only illustrate such displacement but also the distribution of the weak horizon successions by the width of the separation between the cut-off lines and between each of these lines and the thrust front (Fig. 13).

CONCLUSIONS

The map pattern of the cut-off lines of the two main detachment horizons of the Eocene succession of the South-Pyrenean foreland, deduced from seismic interpretation and mapping, demonstrates a minimum displacement of the fold and thrust belt of 52km since late Early Eocene times, once the Bóixols and Montsec thrust sheets were emplaced. During this time the South-Central-Pyrenean thrust salient was formed, initially by progressive curvature controlled by distribution of the Triassic salt and subsequently (since Late Eocene times) by further displacement above the Upper Eocene salt horizon. The latest displacement was coeval with basement underthrusting hindwards the thrust front. The lower basement-involved thrusts branching upwards with the sole thrust defining a composite branch line which runs subparallel to the cut-off lines of the autochthonous Eocene horizons (Fig. 13). The distance between this branch line and the thrust front defines the amount of decoupling, which is at its biggest in the South-Central-Pyrenean thrust salient. This happens because in this area the two main detachment horizons (Triassic salt and Upper Eocene salt) are superimposed. All these relationships demonstrate the secondary and progressive nature of the thrust salient and they also emphasize the thin-skinned structural type of this part of the Pyrenean orogenic system.

ACKNOWLEDGMENTS

This work has been supported by the project CGL2017-85532-P, funded by Agencia Estatal de Investigación (AEI) and Fondo Europeo de Desarrollo Regional (FEDER). Part of this work has been supported by training project funded by Shell and by the Grup de Recerca de Geodinàmica i Anàlisi de Conques (2014SRG467).

We thank Antoni Teixell, Francesc Sàbat and Josep Maria Casas for the fruitful and constructive revisions which have significantly improved the original submitted manuscript. Midland Valley is thanked for providing the Move software as well as Paradigm^{MT} for providing GoCad and HIS for the Kingdom Suite software.

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Manuscript received February 2018;
revision accepted September 2018;
published Online December 2018.