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THIRTY YEARS (1988-2018) OF ADVANCES IN THE KNOWLEDGE OF THE STRUCTURAL EVOLUTION OF THE SOUTH-CENTRAL PYRENEES DURING THE CENOZOIC COLLISION, A SUMMARY

Treinta años (1988-2018) de avances en el conocimiento de la evolución estructural de los Pirineos centrales durante la colisión cenozoica, un resumen

Belén Oliva-Urcia[1,2]

[1] *Departamento de Geología y Geoquímica, Facultad de Ciencias. Universidad Autónoma de Madrid. C/ Francisco Tomás y Valiente 7, 28049 Madrid, Spain. belen.oliva@uam.es*
[2] *Geotransfer-Geodinámica Interna, Departamento de Ciencias de la Tierra. Universidad de Zaragoza*

Abstract: *The Pyrenean Chain has drawn an extensive attention which has produced a plethora of research papers and doctoral theses about the structure-sedimentation relationships, and in recent years, geophysical and geochemical techniques have allowed quantifying the processes active during the convergence of Iberian-Eurasian plates from late Santonian to Miocene times. This convergence produced a WNW-ESE striking, narrow asymmetric chain of ~1000 km in length from the Gulf of Lion to the Galicia margin. The west-central part of the Pyrenean isthmus is the focus of this work, where a summary of some of the last 30 years' publications are grouped by technique(s): geological balanced cross-sections and geophysical constraints from oceanic magnetic anomalies, gravimetry…, which contribute to calculate shortening; geochemical data that provide information about paleotemperatures and ages of uplift; paleomagnetism and magnetic fabrics which allow calculating vertical axis rotations, dating syntectonic sediments and getting information about the strain in rocks; and analog models and their input in the understanding of the Pyrenean deformation. Short comments about the pre-convergence stages and post-orogenic evolution of the Ebro foreland basin are also included. Finally, a chronostratigraphic chart with a summary of the main events (activity of thrust sheets and uplifted areas) is shown. Despite many data have been collected, some inconsistencies are not yet resolved.*

Keywords: *Pyrenees, kinematics, deformation, geophysical survey, geochemical techniques.*

Resumen: *La cadena Pirenaica ha atraído una gran atención, lo que ha producido una gran cantidad de artículos científicos y tesis doctorales sobre las relaciones de la estructura-sedimentación durante la colisión. En años recientes, la aplicación de técnicas geofísicas y geoquímicas han permitido cuantificar (en ocasiones de manera cualitativa) los procesos que han estado activos durante la convergencia de las placas Ibérica-Euroasiática desde el Santoniense tardío hasta el Mioceno. Esta convergencia produjo una cadena de dirección ONO-ESE estrecha, de ~ 1000 km de longitud que se extiende desde el Golfo de León hasta el margen de Galicia. La parte centro-occidental del Pirineo ístmico es donde se centra este trabajo, donde se agrupa un resumen de los trabajos realizados en las últimas tres décadas (1988-2018). El agrupamiento se centra en las técnicas utilizadas a lo largo de estos años: cortes geológicos compensados, limitaciones a partir de anomalías magnéticas del fondo oceánico, gravimetría…, que contribuyen a calcular el acortamiento que se ha producido durante la convergencia; datos geoquímicos que proporcionan información sobre paleotemperaturas y edades de levantamiento/exhumación, paleomagnetismo y fábricas magnéticas que permiten calcular rotaciones de eje vertical, edades de sedimentos sintectónicos y la deformación de las rocas; y modelos analógicos que apuntan factores que influyen en el desarrollo de la deformación. Se han añadido unos comentarios breves sobre los estadios pre-convergencia y sobre la evolución post-orogénica de la cuenca de an-*

tepaís del Ebro. Finalmente se muestra un resumen con la cronología más relevante sobre la actividad de los distintos cabalgamientos y la exhumación de la parte interna de la cadena. A pesar de la gran cantidad de datos, aún queda por resolver la aparente inconsistencia entre algunos de ellos.

Palabras clave: *Pirineos, cinemática, deformación, geofísica, geoquímica.*

Oliva-Urcia, B., 2018. Thirty years (1988-2018) of advances in the knowledge of the structural evolution of the south-central Pyrenees during the Cenozoic collision, a summary. *Revista de la Sociedad Geológica de España*, 31 (2): 51-68.

Introduction

The Pyrenean Chain has claimed the attention of naturalists and geologists from all over the world since at least the end of the 19th century. It represents a "playground" for geologists due to the geological characteristics and dimension of the chain with good exposures particularly in its drier southern side. The Pyrenean Orogen is nowadays described as a double vergent chain originated by the convergence between Iberian and European plates from Late Cretaceous to Miocene times. This convergence led to the tectonic indentation of the Eurasian plate with the subduction (underthrusting) of the Iberian plate, a thickening of the Iberian crust showing a general fan-like structure and in the external domains, major thrusts and structures, confirmed by seismic reflectors, that are related to the tectonic inversion affecting the Mesozoic and Cenozoic cover. This description is accepted after deep reflection seismic interpretations were published in the late 80's and 90's, which represent an inflection point in the advance of the knowledge of the geological structure of the Pyrenees. Two ECORS (*Étude Continentale et Océanique par Reflexion et Refraction Sismique*) lines were acquired. The first ECORS line of ~250 km long was performed in the center of the Pyrenean isthmus in 1985-86 (ECORS Pyrenees Team, 1988; Choukroune, 1989; Daignières *et al.*, 1989; Roure *et al.*, 1989; Muñoz, 1992) and the second ECORS-Arzacq line, 100 km long, was performed in 1989 in the west-central Pyrenees, in the French side of the chain (Daignières *et al.*, 1994; Teixell, 1998) (Fig. 1). Prior to that time, structural and stratigraphical observations determined the foundations for building on the portrayal of the structure of the Pyrenees. The first ECORS seismic line interpretation put an end to the controversy between two previous extreme interpretations of the structure of the Pyrenees: prevalence of vertical structures linked to strong ductile crustal deformation *versus* thrust imbricates at depth, favoring the V or fan shape of the reflectors at crustal scale (Choukroune *et al.*, 1989 and references therein). The results of the second ECORS profile (ECORS-Arzacq line) were ambiguous, with only few reflectors detected beneath the Aquitaine basin, also interpreted as Iberian plate underthrusting beneath the European plate (Daignières *et al.*, 1994; Teixell, 1998; Wehr *et al.*, 2018). Recent studies compiled the results of deep seismic sounding experiments to obtain a map of Moho depth for the entire Iberian peninsula (Díaz and Gallart, 2009; Chevrot *et al.*, 2014 -PYROPE experiment, seismic reflection and refraction-; Díaz *et al.*, 2016 -TopoIberia-IberArray experiment-; Chevrot *et al.*, 2018 -OROGEN experiment-; Wher *et al.*, 2018).

Prior to the ECORS deep seismic lines, surface observations allowed describing the general structure of the Pyrenees according to five structural units, which from north to south are: the Aquitanian foreland basin, the North Pyrenenan Zone (NPZ), the Axial Zone (AZ), the South Pyrenean Zone (SPZ) and the Ebro foreland basin. The five structural units plus the North Pyrenean Fault Zone, situated between the AZ and the NPZ, can be briefly described as follows: the foreland basins collect the sediments of the uplifting orogen, the NPZ represents the Mesozoic-Cenozoic cover deformed by thrust and folds with northern vergence, whereas the SPZ represents the Mesozoic-Cenzoic cover deformed by thrust and folds with southern vergence. The SPZ represents a larger part of the orogen accumulating most of the shortening. The AZ is where the Paleozoic rocks crop out, conforming the backbone of the orogen. The main detachment level for cover thrust sheets is the Keuper facies (Upper Triassic) when present (Carez, 1881, 1909; Fournier, 1905; Souquet, 1967; Mirouse *et al.,* 1964; van de Velde, 1967; Soler, 1970; Mattauer and Séguret, 1971; Mutti *et al.*, 1972; Séguret, 1972; Puigdefàbregas, 1975; Pocoví-Juan, 1978; Mutti, 1984; Nichols, 1984; Williams and Fischer, 1984; Labaume *et al.,* 1985, Muñoz *et al.*, 1986; Bodinier *et al.*, 1987; Meléndez and Pocoví-Juan, 1987) (Fig. 1). The regional cleavage development in the west-central Pyrenees was also defined prior to the ECORS-profiles (Choukroune and Séguret, 1973) but their boundaries have been recently re-stablished by paleotermometers and further structural -microstructural- observations (Izquierdo-Llavall *et al.*, 2013).

After the balanced cross-sections based on the deep seismic lines were published, a summary of the variation along strike of the general structure of the Pyrenees is clear:

1) The antiformal stack in the AZ in the eastern section is not present in the western section (Fig. 1: cross-sections 1b and 3). The AZ in the western ECORS-Arzacq section corresponds to the hanging wall anticline of the Gavarnie basement thrust (Daignières *et al.*, 1994; Teixell 1998; Teixell *et al.*, 2016). The differences in the thickness of the antiformal stack of the AZ can be observed in a contour map of the top of the Paleozoic basement reconstructed from geological maps, cross-sections and borehole data in Figure 4 of Soto *et al.* (2006) with data from Choukroune and Séguret (1973), Autran *et al.* (1980), and Lanaja (1990). The elevation (without considering erosion) of the top of the basement would be 15 km in the central section and 1 km in the western section.

2) The NPZ in the west has a dominant southern vergence, contrary to the northern vergence observed in the central ECORS-Pyrenees section.

3) The North Pyrenean Fault Zone, the boundary between the Iberian and European plates, is clearly located between the NPZ and the AZ. Its outcrop is accompanied by evidence of Cretaceous High Temperature-Low Pressure (HT-LP) metamorphism with fragments of subcontinental mantle (Lacroix, 1900; Azambre and Ravier, 1978), related to crustal thinning under high thermal regime (Clerc and Lagabrielle, 2014). This boundary becomes far more complex than a single fault west of the outcrop of the AZ (Canérot *et al.*, 2004; Dumont *et al.*, 2015). The origin and exhumation of this HT-LP rocks is still under debate (Olivier, 2015).

The combination of surface and subsurface data results in the construction of balanced cross-sections and hence, the calculation of minimum shortening across the Pyrenean isthmus. In addition, the incorporation of a wide variety of data from geophysical techniques (gravimetry, oceanic magnetic anomalies, paleomagnetism, magnetic fabric), geochemistry (thermochonology, fluid inclusions, vitritinite reflectance, Raman Spectroscopy of Carbonaceous Materials -RSCM- …) analog and numerical models in local to regional areas, help constraining and quantifying the tectonic evolution of the orogen and the Ebro foreland basin. However, despite the piling up of geological and geophysical data in the last three decades, the first order structure of the Pyrenees is only partially understood, key points as the general evolution of the Pyrenean deformation, the total amount of shortening, the rates of convergence, the correspondence between geological and kinematic studies, the non-cylindrical structure of the Pyrenees, the nature of the subduced Iberian material and the lateral distribution and depth extent of the subduction are still matter of debate (Mouthereau *et al.*, 2014, Macchiavelli *et al.*, 2017; Teixell *et al.*, 2018; Wehr *et al.*, 2018).

This work briefly summarizes 30 years of research (1988-2018) dedicated to the structural geology and tectonics of the west-central isthmian Pyrenees in its southern part. The next sections group the advances in the knowledge of the Pyrenean evolution during convergence of Iberia-European plates based on different methodologies. Comments about the kinematic evolution prior to the collision and the post-orogenic evolution of the Ebro foreland basin (when did it become exhoreic?) are also included.

Deep structure: balanced cross-sections and geophysical constraints (shortening)

The surficial, well and seismic lines data have allowed constructing four balanced cross-sections in the area, two of them along the deep reflection seismic lines and two in the southern part of the chain between them (Fig. 1, for detailed geological location, basement thrust cutoffs and location of structures see Figs. 2, 3 and 4, respectively). Construction of a balanced cross-section comprises a geological model and deformation evolution, which is present in the final picture. When considering the pre-shortening stage, it is possible to calculate the minimum shortening undertook by the depicted structures (folds and thrusts) in the upper crust.

The first calculation of the minimum shortening in the central part using cross-sections (ECORS-Pyrenees section) resulted in 100 km (Roure *et al.*, 1989), which increased to 147 km (Muñoz, 1992) when interpreting larger shortenings for the antiformal stack of the south vergent Paleozoic basement thrusts particularly the rooting of the Nogueres basement thrust. The shortening calculation finally increases to 165 km shortening (Beaumont *et al.*, 2000) when considering deformation in the crust underneath the lowest detachment level using numerical models. The shortening in the southern vergent structures will be 112 km (Muñoz, 1992) or 128 km (Beaumont *et al.*, 2000). To the west, the shortening calculations are lower: 114 km in the western revisited Ansó-Arzacq section (Teixell *et al.*, 2016), which is located ~170 km to the west of the ECORS-Pyrenees cross-section (and 10 km to the east of the Ansó Arzacq section from Teixell, 1996, 1998). In this previous cross-section, the total shortening for the southern vergent structures was calculated in 48 km (Teixell, 1996, 1998).

Other balanced cross-sections constructed in the SPZ are the Cotiella section (~70 km west of the ECORS-Pyrenees section) where the shortening is calculated in ~110 km (Martínez-Peña and Casas-Sainz, 2003), 88 km considering the shortening related to basement thrusts (Gavarnie, Millares, Bielsa, Guarga thrusts) (Oliva-Urcia and Pueyo, 2007). The Gavarnie-Guara cross-section involves 51 km of shortening for the southern basement thrusts (Millán Garrido *et al.*, 2006). This section is located ~20 km west of the Cotiella section. Less than 10 km more to the west, in the eastern Jaca-Pamplona basin, a recent balanced cross-section portrays 41 km of shortening related to the southern vergent basement thrusts (Labaume *et al.*, 2016). The deeper structure of the Labaume *et al.*'s (2016) section is based on seismic lines. Surficial structure of sections 5 and 5' from Figure 1 are similar.

In addition to these balanced cross-sections, there are multiple geological cross-sections constructed in the SPZ interpreting the sub-surficial structure and evolution of the shortening (Millán Garrido *et al.*, 1995; Muñoz *et al.*, 2013; Izquierdo-Llavall *et al.*, 2013; Oliva-Urcia *et al.*, 2012 among others), some of them supported by seismic lines (*i.e.*, Muñoz *et al.*, 2013 and references therein), some of them balanced (*i.e.*, Oliva-Urcia *et al.*, 2012).

The shortening produced during the collision of Iberian and European plates from Late Cretaceous to late Oligocene inferred from balanced cross-sections (Choukroune *et al.*, 1989; Roure *et al.*, 1989; Roure and Choukroune, 1998; Beaumont *et al.*, 2000; Fig. 1), is accounted also from the ocean magnetic anomalies (Bay of Biscay, Atlantic Ocean) and the associated plate kinematics. The debate about the kinematic model for Iberia respect to European and African plates prior to convergence is not solved. Prior to collision, oceanic magnetic anomaly models still debate the kinematics of the plates, particularly due to discrepancies between geological and geophysical data (Barnett-Moore *et al.*, 2016 and references therein). Three different kinematic models related to the opening at the Central Atlantic Ocean (154 to 83 Ma; Macchiavelli *et al.*, 2017 and references therein) and the Bay of Biscay (120-83 Ma; Rosenbaum *et al.*, 2002) have been interpreted to influence the Iberian plate movement and the role of the

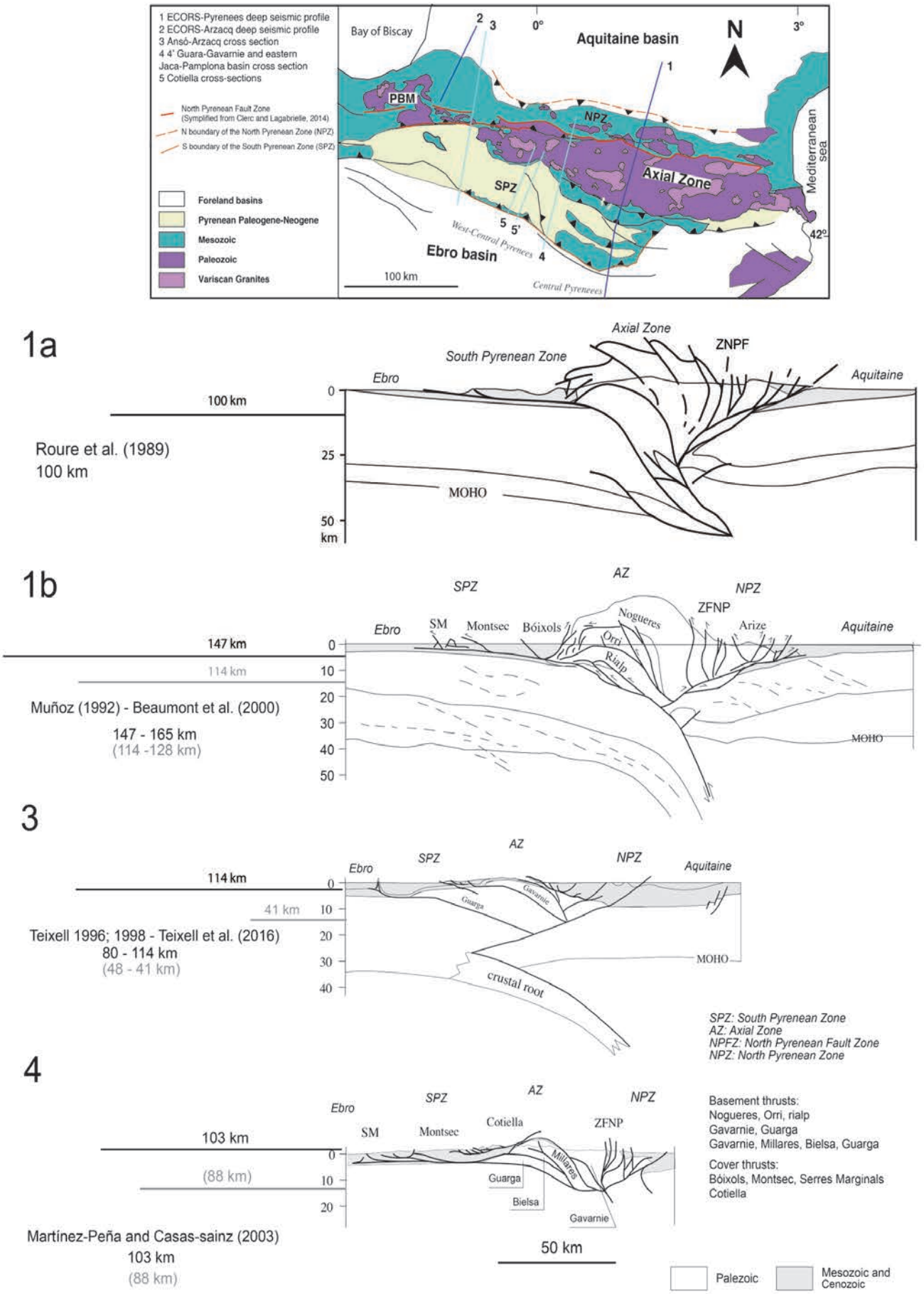

Fig. 1.- General geological map of the Pyrenees with cross-sections. Shortening after balancing is shown on the left, black (grey) is for the whole (South Pyrenean Zone) section. Sections 1 to 3 are based on deep seismic lines and gravity data.

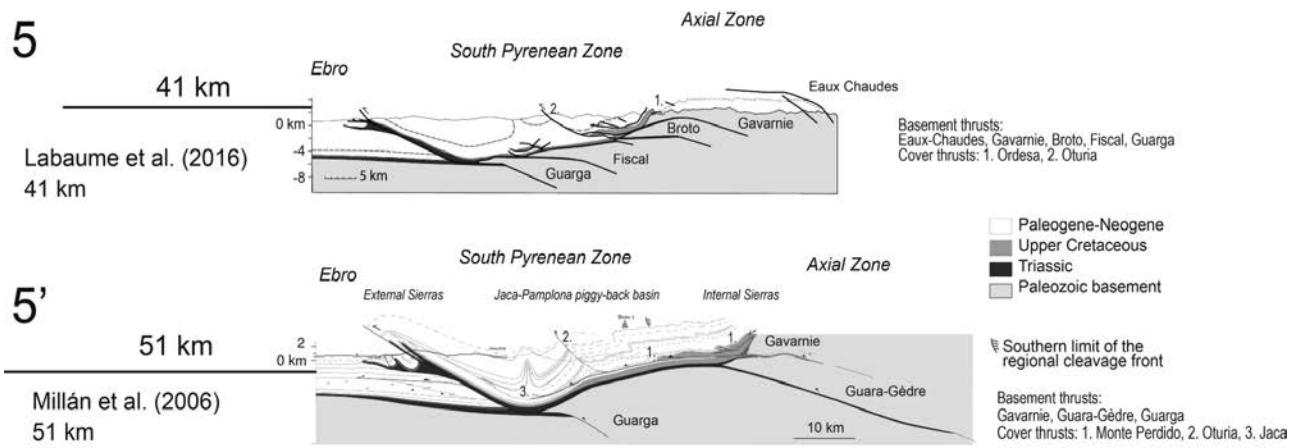

Fig. 1 cont.- Section 5 is based on reflection seismic lines. Sections 5 and 5' do not keep the same scale as previous ones.

NPZ as follows: model 1) transtensional rift between Iberian/European plate boundary where there is an important dextral transform fault during Aptian-Albian times; model 2) scissors opening of the Bay of Biscay with the North Pyrenean Fault acting as strike slip fault but only active during the collision from 83 Ma on, with synchronous significant subduction during Albian times; and model 3) transcurrent motion of Iberia during the Late Jurassic, followed by orthogonal stretching in the Early-Late Cretaceous, and subsequent frontal convergence of Iberia with the North Pyrenean Fault accommodating 400 km of eastward displacement of Iberia respect to Europe during the Late Jurassic to Aptian (Mouthereau *et al.*, 2014 and references therein). These pre-orogenic movements are debated since they also influence the convergence in the Pyrenees. In recent papers, hyperextension (crustal thinning to ≤10 km; Hart *et al.*, 2016 and references therein) during Aptian-Albian times in the Iberian/European plate boundary explains the exhumation of the upper mantle along strike (Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010; Mouthereau *et al.*, 2014; Teixell *et al.*, 2016 among others). However, former interpretations explained the exhumation of the mantle rocks due to a major transcurrent plate boundary fault accommodating distributed continental extension as Cretaceous pull-apart basins (Mouthereau *et al.*, 2014 and refe-

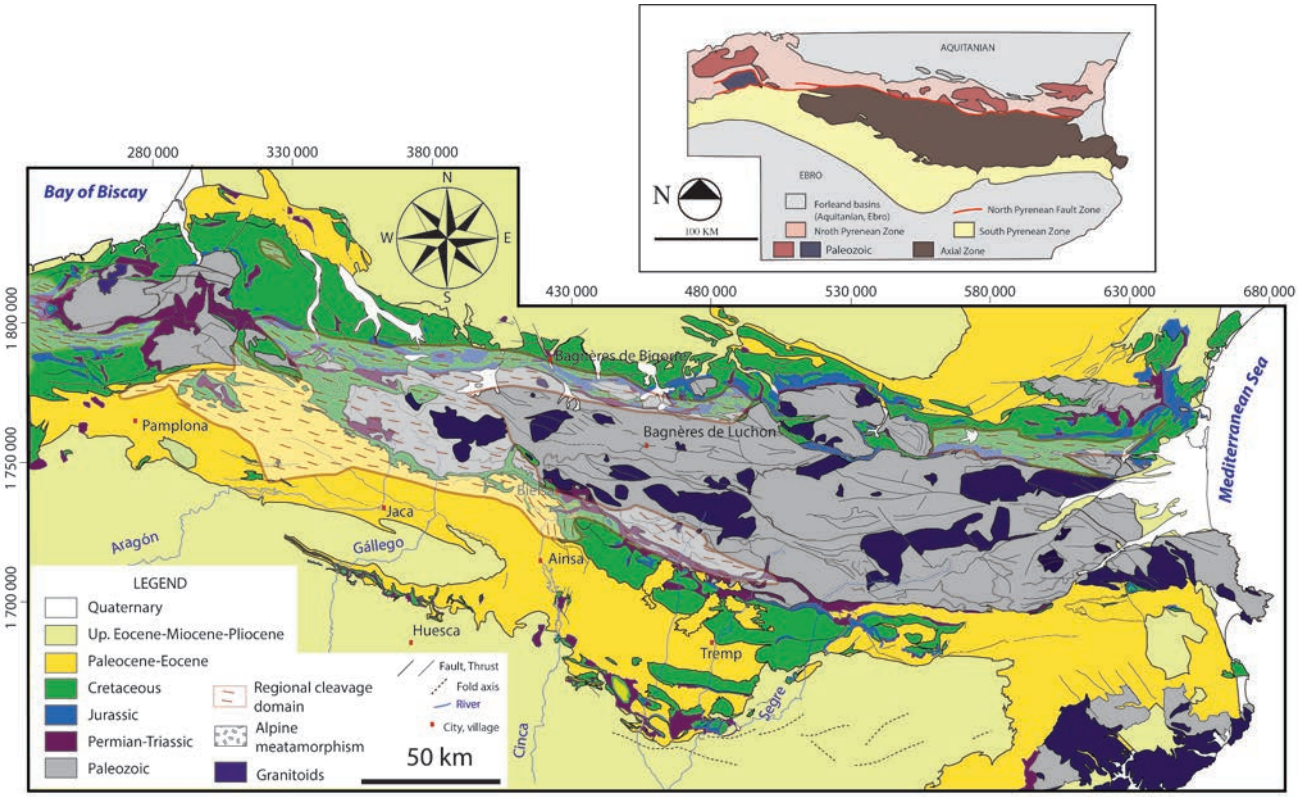

Fig. 2.- Geological maps simplified from Choukroune and Séguret's (1973) and 1:400,000 geological map from Bureau de Recherches Géologiques et Minières/Instituto Geológico y Minero de España (BRGM/IGME) maps. The cleavage domain was slightly modified from Choukroune and Séguret (1973) after Izquierdo-Llavall *et al.* (2013) considering (i) paleothermal data and (ii) the observation of a continuous cleavage (whose spacing ranges between < 1 cm and > 10 cm) that forms an angle to bedding and affects the marly beds of the turbiditic sequence. The map on top represents the structural units (simplified after 1:400,000 geological map from BRGM/IGME).

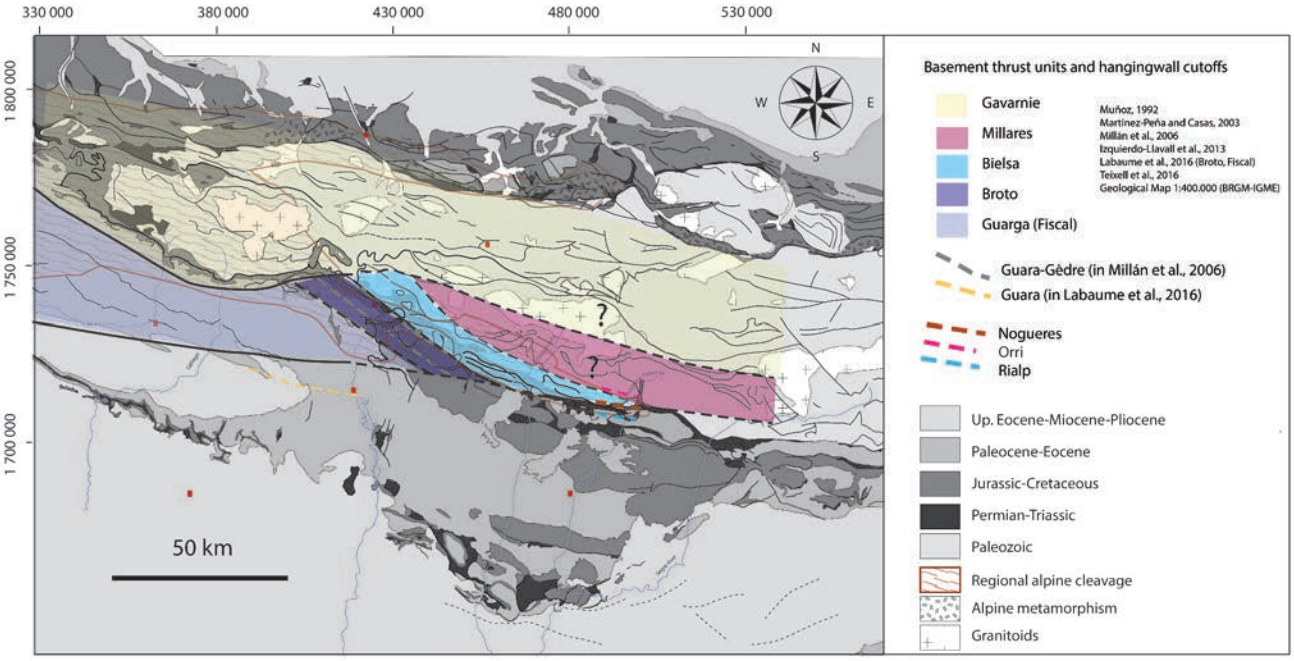

Fig. 3.- Geological map (as in Figure 2) where colours represent basement thrust and the extent to the hangingwall cut off. Names of cities and rivers in Figure 2.

rences therein). These models were already discussed in Roure *et al*. (1989), where they discarded the hyperextension model (called detachment faulting and denudation of the crust model, Fig. 5 in Roure *et al.*, 1989) since this model did not account neither for the eastward movement of Iberia respect to the European plate due to the opening of Biscay and the transtensive left lateral-normal fault movement nor for the presence of high temperature fluids localized in metamorphic facies. These authors favored a steep strike-slip fault model (Fig. 7 in Roure *et al.*, 1989) since it accounted for the observed pre-orogenic events: 1) granulitic and lherzolitic bodies could have been exhumed along the North Pyrenean Fault; 2) fluid circulation and metamorphism may be related to a thinned crust; and 3) Cretaceous basins are small, elongated troughs along the North Pyrenean Fault or related strike-slip faults and interpreted as pull-apart basins. More data has been collected since then, but the debate is still open.

The ocean magnetic anomaly models also vary when calculating shortening for the convergence (83 Ma onwards). While for some authors the shortening reconstructed from the ocean magnetic anomalies during the convergence is apparently similar, ~180 km, (Mouthereau *et al.*, 2014 and references therein), for others it is clear that this shortening varies from east to west from 144 to 206 km (differently to shortenings calculated from balanced cross-sections; Teixell, 1998; Muñoz, 1992; Vergés *et al.*, 1995), being 160-170 km the total convergence between Iberia and Europe since chron 34 (83 Ma), in the central Pyrenees (Rosenbaum *et al.*, 2002). However, in a recent southern North Atlantic plate model using a new technique to obtain plate motions from magnetic anomalies, a partitioning of deformation between the Pyrenees and the Eastern Betics during Late Cretaceous-Oligocene times is shown, whereas the shortening has been calculated to be 125 km in the central part of the Pyrenees, a value much closer to the first calculations from the balanced cross-sections (Macchiavelli *et al.*, 2017; Roure *et al.*, 1989). Prior to this last work, the larger discrepancies between the shortening calculated from magnetic anomalies of previous models compared with the balanced cross-sections had been explained by a variable amount of subduction due to, for example, lateral changes in the architecture of the continental margins of Iberian-European plates (Mouthereau *et al.*, 2014). However, the lack of correspondence between the shorten volume in the upper crust with the shorten volume in the lower crust and lithospheric mantle (Butler, 1986; Muñoz 1992), was classically explained by subduction of the continental crust (Pous *et al.*, 1995 and references therein). Still, the recent investigations combining new magnetic anomaly models with geological and other geophysical data (paleomagnetism, seismic tomography) challenge previous publications and point to a search of consensus.

In addition, the shortening calculated from balanced cross-sections does not take into account internal deformation, which can increase the shortening between 15-30% in areas with regional cleavage development (Holl and Anastasio, 1995). In this part of the Pyrenees, the cleavage development area extends from the AZ to the turbiditic Jaca-Pamplona basin (north of the cover Oturia thrust) as shown by the cartography of Choukroune and Séguret (1973).

Geophysical information

Gravimetry (Wehr *et al.*, 2018 and references therein), seismic tomography (Wang *et al.*, 2016 and references therein) or magnetotelluric surveys (Pous *et al.*, 1995) have been performed at orogen scale to further infer the deep structure of the Pyrenean Chain in the last 30 years, and in some cases, it has been taken into account to interpret the geological structure (*i.e.*, Muñoz, 1992; Teixell *et al.*, 2018).

Also before this date, geophysical constraints in reconstructions by Choukroune and Mattauer (1978) of the North Pyrenean fault show a strong change in thickness of the continental crust. A summary of 2D and 3D gravity models and recent advances on 3D models can be found in Wehr *et al.* (2018). These authors summarize the findings of gravimetry analyses where the positive Bouguer anomalies beneath the NFZ where interpreted as slices of mantle or lower crustal material (Torné *et al.*, 1989), and in the western and central profiles as slices of exhumed mantle during the transtensional motion of Iberian plate respect to European plate prior to convergence (Casas *et al.*, 1997) also confirmed by tomographic images (Soriau and Granet, 1995). Combination of gravity and tomography was carried out in Wang *et al.* (2016), revealing an extreme thinning of the crust in the NW Pyrenees (beneath the Mauléon basin) interpreted as mantle exhumation during the rifting episode of the Cretaceous. These anomalies disappear towards the east, interpreted as less intense rifting or opposite polarity of the rift (Tugend *et al.*, 2014; Wehr *et al.*, 2018). A link between the structure of the deep lithosphere and present day seismicity in the upper crust seems plausible (Dufréchou *et al.*, 2018).

At local scale, gravimetry surveys have been crucial in determining the volumetric importance of Triassic facies such as the Keuper shales and evaporites (the regional detachment level in the SPZ when present) and their role in the tectonic models. For example, a gravity survey has been essential in disentangling two different structural models in the External Sierras: 1) ramp anticline (Teixell, 1996) with lower Keuper facies volume than 2) a detachment fold (Millán Garrido *et al.*, 1995) with larger volume of Keuper facies in the core of the anticline. This anticline is related to the frontal thrust in the west-central part of the Pyrenees. Two gravity section models adjust better to the second model, although a ramp is also necessary in the eastern section (Calvín *et al.*, 2018). Accordingly, in other areas where salt tectonics has claimed the attention of researchers, gravity-constrained cross-sections allow distinguishing two types of diapirs in the Sierras Marginales Unit (south central Pyrenees). vertically well-developed and poorly developed, and to characterize the relationships between thrusting and diapirism during Eocene-Oligocene time (*i.e.*, Santolaria *et al.*, 2017).

Nevertheless, the transfer of the deformation from east to west and the along strike differences in shortening should imply vertical axis rotations and out of plane movements occurring during shortening along certain structures. For example, at regional/local scale, vertical axis rotations (VARs) also occur related to the differential shortening of the South Pyrenean frontal thrust (Gavarnie, Guarga basement thrusts) in the N-S anticline structures in the External Sierras and other N-S deformation structures to the east (Boltaña, Mediano anticlines). Paleomagnetism is the tool that allows to calculate VARs (later section).

Geochemical data: fluid inclusions, paleotemperatures, thermochronology

The isotopic and geochemistry analyses of fluid inclusions from quartz and calcite veins developed during the Pyrenean convergence allow to determine the fluid history and temperatures under which they developed. Combined with other burial and paleotemperature indicators (*i.e.*, vitrinite reflectance) allow to determine the depth at which they were during their geological history. Thermochronological data allow, when conditions are optimal, to determine the age at which the uplift in the inner part of the orogen occurred. These data combined with classical geological observations has become more and more utilized to obtain ages for the observed structures and timing of the deformation. A summary of those data is presented here without critically analizing the results in terms of reliability, which is beyond the scope of the paper.

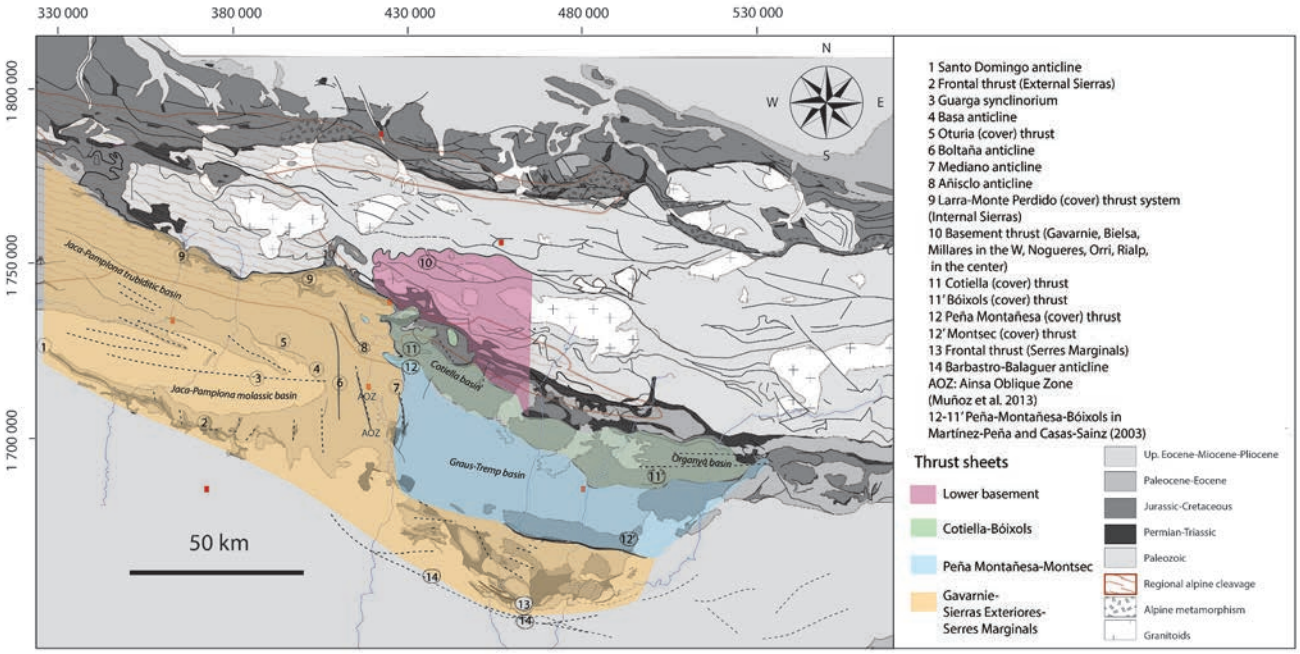

Fig. 4.- Geological map (as in Figure 2) showing the location of the main structures and basins mentioned in the text, and the extension of cover thrust sheets in colour. Names of cities and rivers in Figure 2.

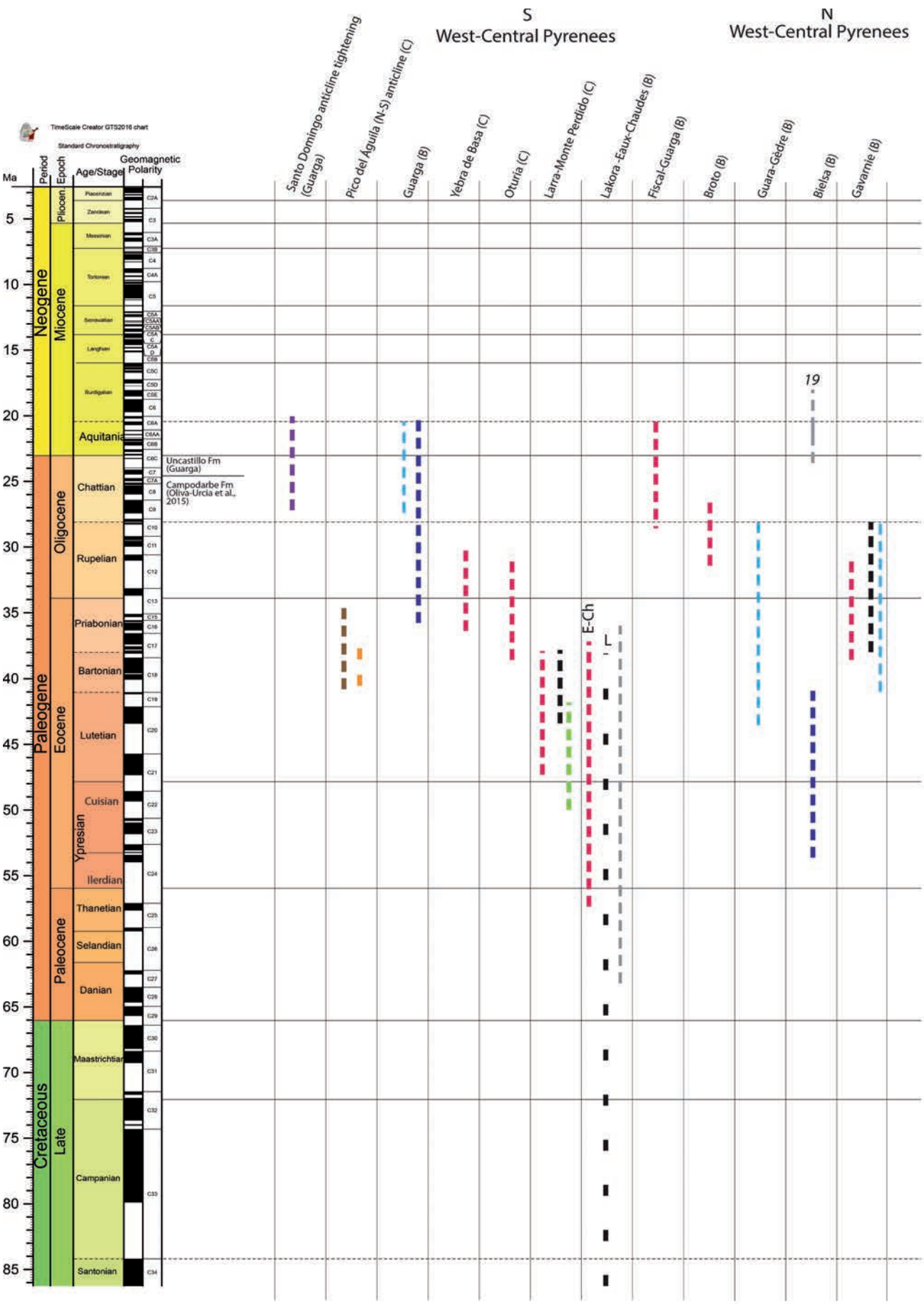

Fig. 5.- Compilation of the activity of thrusts (basement: B, and cover: C) and folds from the literature, based on sedimentation-tectonic relationships and thermochronological data.

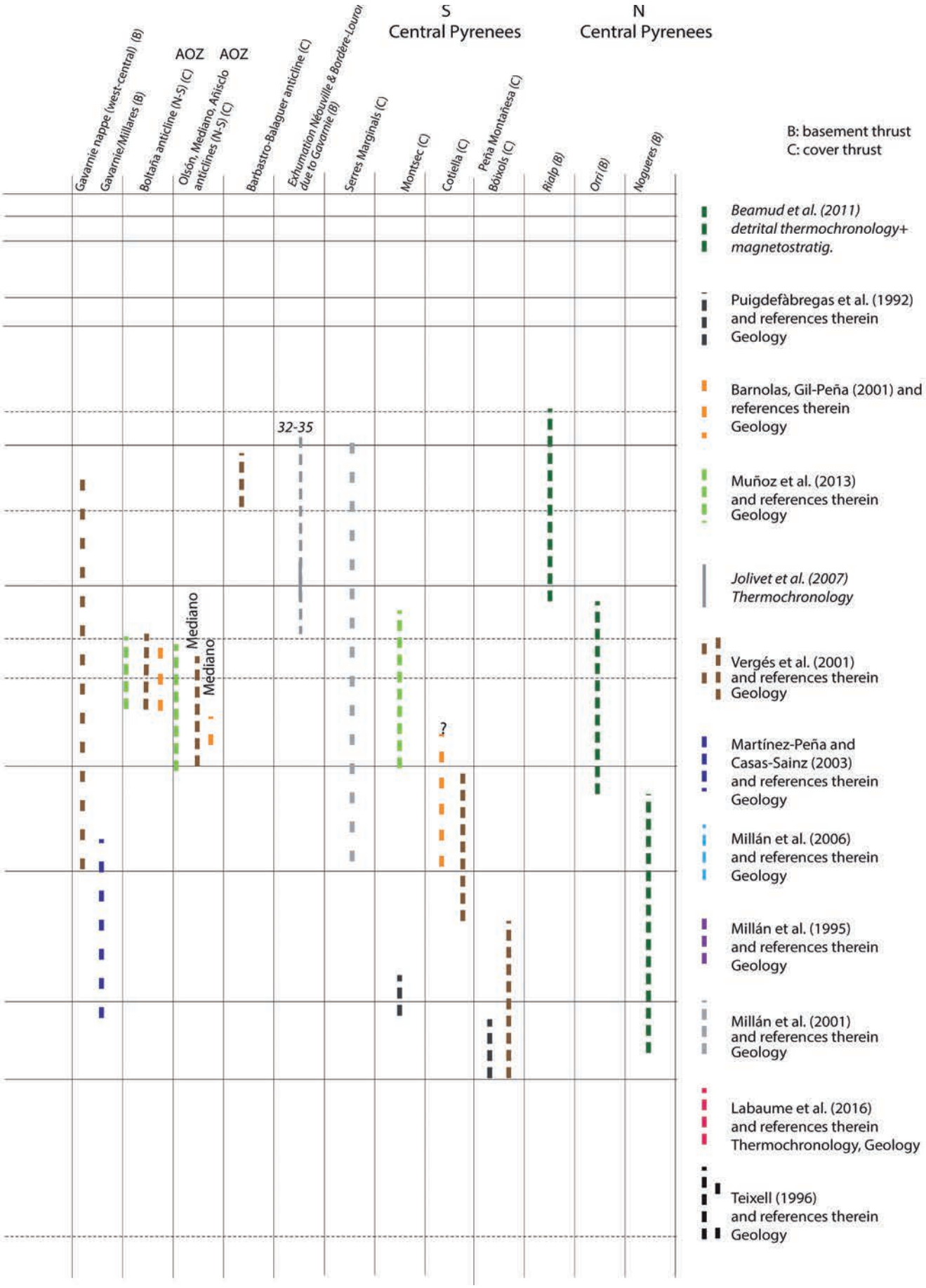

Fig. 5 cont.- (see figure caption in Figure 5).

Fluid flow, temperature and geological history from fluid inclusions

From fluid inclusion in the inner part of the Pyrenean Orogen, it is inferred that brines due to Triassic evaporites percolated through the Lower Triassic and Paleozoic basement rocks during the Permian-Triassic extension. The Triassic evaporites were almost totally eroded (La Larri-Neouvielle area). It has been also suggested that those brines are decisive for the Pb-Zn ores in Parzán-Liena mines, in the Bielsa granodiorite. When convergence started, overpressured fluids were expelled through faults and thrusts. In addition, the generated relief collected meteoric and connate waters mobilized due to gravity. Both fluids, brines and surficial, mixed at temperatures ~ 200-250ºC and depths of 5 to 8 km (McCaig *et al.*, 2000).

In external parts of the SPZ, in the Ainsa oblique zone (south of the Cotiella thrust sheet), fluid inclusions and isotopic ratios reveal that the composition of the fluids included Eocene marine water, with influence of meteoric water and/or channelized fluids through internal thrusts. Temperatures are ~ 200º C (Travé *et al.*, 1998).

The diachrony on the deformation evolution from east to west has also influenced the formation of fluid inclusions in the Jaca-Pamplona turbiditic basin and in the Internal Sierras. In this work, the authors also analyze orientation of filled fractures and veins, defining two sets: transverse (longitudinal), and parallel (longitudinal) to the strike of the Pyrenees. They found two stages of vein precipitation in the northern turbiditic basin and Internal Sierras: 1) one with temperatures of 155-205ºC and salinities lower than sea water; 2) the second stage records higher temperatures 215-270ºC and composition indicates a mixing with exotic brines (from Triassic evaporites). Considering the geology of the area, the authors relate the first stage to the Eaux-Chaudes thrust (Lutetian-Bartonian) with a burial depth of ~ 5 km. The second stage is related with ~7 km burial, coeval with Gavarnie thrust (Priabonian-Early Rupelian) (Crognier *et al.*, 2018).

These burial depths are similar to the ones inferred from fluid inclusions, vitrinite reflectance, and illite content in mixed layer (paleotemperature information) which are related to the boundaries of the regional cleavage domain in the Pyrenees during convergence (Izquierdo-Llavall *et al.*, 2013). For the west-central part of the Pyrenees, the development of regional cleavage took place between 140-160 to 215ºC and 4 to 6 km burial. In addition, at least 4 km of turbiditic sequence covered the Internal Sierras and the AZ in its southern part. These results are similar to the ones obtained for the same area using also stable isotopes analyses, although these authors found three different stages (conditions) which can be related to the activity of thrusts, that is: 1) emplacement of Monte-Perdido thrust during middle Eocene at a temperature of ~208ºC and burial of 5.7 km; 2) fault reactivation at a temperature of ~240ºC and burial of 6.5 km; and 3) last event at deeper burial due to the emplacement of the Gavarnie basement thrust (late Eocene-Oligocene). The hydrological system was closed, implying that no significant fluid flow along faults occurred (Lacroix *et al.*, 2011).

Thermochronology

Different thremochronometers have been used in the Pyrenees: apatite fission track (AFT) has become more significant along the years. The first study in the Pyrenees is from Morris *et al.* (1998). AFT are used to reconstruct the thermal history of rocks between ~120ºC and ~60ºC, and hence, exhumation. The AFT anneal rapidly at temperatures higher than ~120ºC (the upper limit of the partial annealing zone), whereas below ~60ºC the annealing is dramatically decreased (Fitzgerald *et al.*, 1995; Gallagher *et al.*, 1998; Labaume *et al.*, 2016). Analyses from $^{39}Ar/^{40}Ar$ correspond to cooling temperatures ~ 300ºC (150-250 ºC) on bitotie (K-feldespar) (Dodson, 1973; Lovera *et al.*, 1989). Also, apatite Helium thermochronometer (U-Th)/He (AHe) is sensitive to 40-110ºC (Farley, 2000).

These studies have been done in the AZ and in the SPZ (detrital AFT). The studies vary in their timing for the exhumation of the AZ, especially when trying to date every single basement thrust. However, some studies provide *ca.* ages at which the activity of the orogen coincides in a general sense, for example two main uplift events for the central Pyrenees have been interpreted at 50-40 Ma and 30 Ma to 25 Ma, and a poorly defined cooling episode at ~70-60 Ma from thermochronology data in granite syntectonic boulders (Beamud *et al.*, 2011) which roughly agrees with the cooling events detected in detrital AFT in Ainsa Basin, ~ 56 Ma (orogenesis), ~ 80 Ma (initial basin inversion); they also found two younger ones related to earlier tectonic phases (Thomson *et al.*, 2017). However, when looking at certain concrete ages of uplift events related to activity of basement thrusts, deformation does not seem to prograde to the west (Labaume *et al.*, 2016, when comparing with data from, for example, Jolivet *et al.* (2007).

Analog models

Scaled analog models of Coulomb wedges are a very useful tool in accretionary prism and double vergent orogens (as the Pyrenees) to obtain information about geometries and kinematics (Davis *et al.*, 1983; Malavielle, 1984; Storti and McClay, 1995 and references therein). Over the last decades, quite a few analog models have been developed to study different factors that may influence and/or explain geological observations about the kinematic evolution of the Pyrenees. For example, similarities between analog models and geological observations in the Pyrenees are: 1) thrusts starting as piggyback fashion remain active through time or reactivate as out-of-sequence thrusts (Vergés and Muñoz, 1990; Storti *et al.*, 2000 and references therein); 2) the last stage of the central Pyrenees is the amount of syntectonic sedimentation, which provoked the burial of the prowedge, causing a renewal of the internal deformation (Coney *et al.*, 1996) a situation found also in analog models (Storti and McClay, 1995); and 3) analog models also inform that wedges formed by constant convergence will show a progressively decreasing shortening rate through time (Storti *et al.*, 2000).

The variation of lateral thickness in the pre-kinematic sedimentary wedge, as it happens in the central Pyrenees (Montsec unit and oblique structures in its western termina-

tion) can account for the formation of oblique structures when shortening direction is at high angle respect to the strike of the thickness gradient (Soto *et al.*, 2002). Oblique structures have been also reproduced in the laboratory with analog models when considering differential propagation of the deformation front above mechanical contrasts in the basal décollement (Vidal-Royo *et al.*, 2009).

The along strike variation of the thickness of the backstop (European crust) has also influenced the westward decrease of the AZ (elevation and width) and the decrease in the distance of the deformation front from the backstop in the Southern Pyrenees (Soto *et al.*, 2006).

Paleomagnetism and magnetic fabric data

Vertical axis rotations (VARs)

Paleomagnetic analyses have been performed since the 60's in the Pyrenees with two main objectives: 1) to confirm the existence and to quantify vertical axis rotations; and 2) dating syntectonic sediments to determine the timing of the deformation.

The first (relative to this summary starting in 1988) VARs determined in red beds were related to the movement of the Basque Variscan Massifs during convergence (Schott and Peres, 1988). Since then, thousands of data have been produced in the Pyrenean domain from ~30 different groups that have demagnetized more than 20,000 individual samples, over 1,500 points including more than 70 km of magnetostratigraphic section (more than 200 profiles) during the development of 35 PhDs and other research projects comprising a total of more than one hundred SCI papers (see data base summaries from Pueyo *et al.*, 2006; López *et al.*, 2008; Pueyo *et al.*, 2017).

The potential of paleomagnetism for detecting and quantifying vertical axis rotations in the SPZ is applied particularly to specific structures which usually account for along strike differential shortening. VARs have been determined for example, in the the lateral boundaries of the South Pyrenean Central Unit (Dinarès *et al.*, 1992), in the N-S striking anticline-related faults, in the western part of the External Sierras (Pueyo *et al.*, 2002, 2003), in the Boltaña anticline (Mochales *et al.*, 2012), in the Balcés anticline (Rodríguez-Pintó, 2010, 2016), and in the Ainsa fold system (Muñoz *et al.*, 2013). Apart from quantifying the rotation, timing and rate of rotations are essential to constraint the deformation. VARs are calculated comparing the new paleomagnetic data with a stable reference paleomagnetic direction of the age of the paleomagnetic data acquisition.

Some discrepancies concerning the rotation age and therefore rotation rates may be related to the sampling strategy since for example, for the Boltaña anticline, ~52º of clockwise rotation during Ypresian-Priabonian times (~1º/My during Ilerdian-middle Lutetian, and ~10º/My during late Lutetian-Priabonian 42-37 My), has been calculated, which implies a partially post-folding rotation (Mochales *et al.*, 2012), whereas a 45º rotation of the total 55º clockwise rotation for the Boltaña anticline has been deduced to occur from early Lutetian to late Bartonian, a synfolding rotation, with the last ~10º rotation taking place since the Priabonian (Muñoz *et al.*, 2013). This rotation is interpreted to be related to differential shortening calculated along 50 km of the Gavarnie thrust (Muñoz *et al.*, 2013).

Magnetic fabric

The magnetic fabric of a rock represents the measurement of the magnetic susceptibility in all directions of the space. Magnetic susceptibility (k) is the property of every material to become magnetized (M) under a given magnetic field (H), M = k H. It is represented by a second rank tensor, and as an ellipsoid in 3D. The orientation of three axis of the ellipsoid and other scalar values can be used in structural geology to infer strain, when strain markers are scarce. This method has been largely used in the Pyrenees for the last three decades and has provided information about strain in weakly deformed rocks which show no evidence for deformation. The inferred strain increases from the outer part of the Ebro foreland basin to a piggyback basin closer to the orogen, showing a transition in the position of the magnetic ellipsoids axis as deformation increases (Parés *et al.*, 1999). The sensitivity of magnetic fabric as strain marker has been demonstrated at orogen scale particularly in areas with a moderate degree of deformation (Pocoví-Juan *et al.*, 2014), in the foreland Ebro basin (Soto *et al.*, 2009) and in N-S structures separating the influence of the near- and far-field effect deformation (Boltaña anticline; Mochales *et al.*, 2010). Magnetic fabric can act as a passive kinematic indicator, particularly when the long axes of the ellipsoid (k_{max}) are passively rotated with a similar value as the rotations calculated by paleomagnetic data (Pueyo-Anchuela *et al.*, 2012). Magnetic fabric has been also used to disentangle the strain axis of the basinal stage in the Organyà basin (NE South Pyrenean Central Unit), with contrasting results (Gong *et al.*, 2009; Oliva-Urcia *et al.*, 2011). The use of this method in the Pyrenees has allowed constraining deformation at regional scale.

Remagnetizations and VARs

In the search for potential VARs, a post-folding regional remagnetization has been also determined in the west central Pyrenees, in the Internal Sierras. Since remagnetizations can have many different origins, from chemical to thermal, the Pyrenean post-folding remagnetization is also informing about physico-chemical processes during the evolution of the orogen. Furthermore, this post-folding remagnetization component is slightly rotated respect to the paleomagnetic reference in the Internal Sierras, in the SPZ next to the AZ (Oliva-Urcia and Pueyo, 2007). A diachronous remagnetization event was later described occurring during the convergence and prior to the post-folding remagnetization event in the same area (Izquierdo-Llavall *et al.*, 2015). Whereas in the Cotiella Massif, in the NW of the South Pyrenean Central Unit a syntectonic remagnetization event was determined also related to the orogenic evolution (Garcés *et al.*, 2016).

Remagnetizations add information to the physico-chemical processes affecting the orogen evolution. The final cause is still a matter of debate, although several hypotheses may apply, related to the fluid migration during cleavage deve-

lopment (Oliva-Urcia *et al.*, 2008), remobilization of iron during the orogenic evolution and in relation to sedimentary and/or tectonic load and migration of orogenic fluids can be considered (Izquierdo-Llavall *et al.*, 2015 and references therein) and/or burial diagenesis which includes bacteria-mediated sulphate reduction causing removal of detrital (and biogenic) magnetite grains carrying a primary remanence. At greater depths, temperature gradient favoured conditions for inorganic precipitation of fine-grained magnetite, inducing a higher-intensity, reversed-polarity remagnetization (Garcés *et al.*, 2016 and references therein).

In the western sector of the Internal Sierras, the post-folding remagnetization rotation is associated with the basement thrust system below the Gavarnie unit (Bielsa, Guara-Gèdre and Guarga thrusts; Oliva-Urcia and Pueyo, 2007; Izquierdo-Llavall *et al.*, 2015). Thereby, the timing of the post-folding remagnetization postdates the tilting of the Internal Sierras due to Gavarnie basement thrust (Oliva-Urcia and Pueyo, 2007). Assuming that no rotation occurs prior to the post-folding remagnetization, it is possible to reconstruct the Internal Sierras front, which was originally a curved front reactivated by basement thrusts during the Pyrenean compression (Izquierdo-Llavall *et al.*, 2015).

Magnetostratigraphy

Dating syntectonic sediments in the foreland of the Pyrenean front is a technique used, on one hand, to decipher the age of the structures in the orogen, and, on the other hand, to control the evolution of the sedimentary systems in the foreland basin. This technique has been used in the Ebro foreland basin and in syntectonic sediments now transported in piggyback basins as deformation in the orogen progresses (Bentham *et al.*, 1992; Bentham and Burbank, 1996; Hogan and Burbank, 1996; Barberà *et al.*, 1994; 2001; Taberner *et al.*, 1999; Beamud *et al.*, 2003, 2011; Pérez-Rivarés *et al.*, 2004, 2018; Larrasoaña *et al.*, 2006; Costa *et al.*, 2010; Valero *et al.*, 2014; Oliva-Urcia *et al.*, 2015). All these magnetostratigraphic studies require a solid stratigraphic interpretation to relate and correlate with the sedimentary arquitecture of the basin. In the Ebro basin there is a solid stratigraphic foundation (Anadón *et al.*, 1989; Nichols, 1989; Arenas and Pardo, 1999; López-Blanco *et al.*, 2000; Arenas *et al.*, 2001; Barnolas and Gil-Peña, 2001; Pardo *et al.*, 2004; Luzón, 2005; Luzón *et al.*, 2002, among many others).

From magnetostratigraphic studies, four recently derived conclusions are summarized here, not only related to the tectonic imprint in sedimentation but also to the influence of climate changes related to Milankovic cycles in the sedimentation of the center of the Ebro basin:

1) The climatic signature on sedimentation in the central part of the Ebro foreland basin has been inferred after dating the sediments and thanks to frequency analyses of the lithological variations. These investigations reveal the influence of the Milankovic cycles in the sedimentation, with a correlation with 100-kyr, 400-kyr and 2.4 Myr eccentricity cycles. In addition, these long period orbital cycles results are a fundamental target for interpreting the large scale stratigraphic architecture in foreland systems when comparing with magnetostratigraphic data at the boundary of the foreland basin, where sedimentation is mainly tectonic-driven (Valero *et al.*, 2014).

2) The closing and continentalization of the Ebro basin seemed to occur at ~36 Ma, coetaneously in the eastern and western sectors of the basin, suggesting a rapid overall regression after disconnection with the open ocean. The continentalization is due to progressive tectonic uplift of the western Pyrenees from the Middle Eocene (Costa *et al.*, 2010 and references therein).

3) The approach of the temporal character of the boundaries of tecto-sedimentary units (TSU: a three-dimensional body of sedimentary rocks that has a definite vertical trend and is bounded by regional unconformities and their correlative conformities; the boundaries between TSUs should represent synchronous geologic timelines where they are conformable). This approach is essential in order to date the boundaries in the center of the basin respect to date the boundaries in the border of the basin in order to consider the tectonic influence in sedimentation of a foreland basin. Recent investigations conclude that the boundaries of three TSU along a 200 km transect with E-W orientation from the basin center to the SW boundary of the Ebro basin are diachronous only by less than 0.3 Ma, probably due to allogenic, largely tectonic processes occurring in the catchment areas and to methodological inaccuracies. Therefore, the boundaries of the TSU are only slightly diachronous (Pérez-Rivarés *et al.*, 2018).

4) When it is possible to combine paleomagnetic dating of syntectonic continental conglomerates with thermochronology analyses from the granite boulders found in the same syntectonic section, is its possible to determine the course of the sediments from the uplifted source area to the sedimentation sink (source-to-sink). These investigations were performed in late Lutetian to Oligocene syntectonic sediments of piggy-back basins of the Central Pyrenees. Results suggest two well-defined periods of rapid cooling in the hinterland at 50-40 Ma and 30 to 25 Ma, and a poorly defined cooling episode a ~70-60 Ma. The combination with the magnetostratigraphic data indicates, for the period between 40 to 25 Ma, exhumation rates of 0.3 km/Myr and sedimentary rates varying from 0.28 to 0.005 km/Myr except for the Oligocene, with > 1 km/Myr and an accumulation rate of 0.1 km/Myr. These data point to the syntectonic character of those studied sediments, contrary to previous considerations. Thermochronological data also confirm the burial of the South Pyrenean fold and thrust belt by Late Paleogene and their subsequent reexcavation of the fluvial system (Beamud *et al.*, 2011 and references therein).

Provenance of sediments

The petrographic, mineral and heavy minerals analyses can provide information about the provenance of sediments. In the Pyrenean foreland basin there have been several studies, in the continental Oligocene-lower Miocene sediments (*i.e.*, Yuste *et al.*, 2004), which have allowed determining the source area of the alluvial fans and connect that information to the tectonic activity in the area. The cannibalization of the

Jaca-Pamplona piggy-back basin is clarified with these studies, where the alluvial fans in the center of the piggy-back basin record the changes in provenance that inform about the response of drainage systems to uplift and tectonic evolution in the hinterland (Roigé *et al.*, 2017).

Also in the turbiditic deposits of the Jaca-Pamplona basin of Middle-Upper Eocene, the provenance analyses reveal a period of northern provenance of sediments during Lutetian-Bartonian transition, interpreted as related to the activity of the Eaux-Chaudes/Lakora basement thrust. The provenance of the lower turbiditic sequence is deduced to be from the east (Roigé *et al.*, 2016)

Post-orogenic evolution of the Ebro basin from models and dated fluvial terraces

The Ebro foreland basin was syntectonically (due to flexural subsidence) and post-tectonically "backfilled" (Coney *et al.*, 1996) up to the Miocene with conglomerates burying most of the frontal tectonic structures of the southern Pyrenees (García-Castellanos *et al.*, 2003). Combining fluvial sediment transport, crustal-scale tectonic deformation, and lithospheric flexural subsidence in 3D numerical models of the Ebro foreland basin, reveal that the transition from endhoreic to exhoreic basin took place between 13 and 8.5 Ma (García-Castellanos *et al.*, 2003). Later considerations of the opening of the Ebro basin combining flexural isostatic compensation and eroded volume with constraints on sediment age (by magnetostratigraphy in four sections) allow constraining the post-tectonic evolution of the basin. This new modelization provides a basin opening ages of 12-7.5 Ma with a maximum paleoelevation of the basin of 535-750 m. The model also suggests an isostatic uplift in response to the erosion by the fluvial system that may prevent the presence of a canyon excavated by the Ebro River during the Mediterranean sea-level fall associated with the Messinian salinity crisis at about 6 Ma (García-Castellanos *et al.*, 2003). However, for other authors, the transition from endorheic to exorheic conditions in the central sector of the Ebro basin did not start before than 3.2 Ma, based on terrace ages, the altitude of the youngest sediments in the central Ebro basin and steady incision rates of the fluvial system during the Quaternary (Sancho *et al.*, 2016). These authors also summarize the claimed sources for explaining fluvial incision in NE Iberia: 1) related to isostatic uplift due to crustal thickening (Casas-Sainz and de Vicente, 2009; Fernández-Lozano *et al.*, 2011); 2) isostatic adjustment due to erosional unloading (García-Castellanos *et al.*, 2003; Stange *et al.*, 2016); 3) isostatic adjustment due to mantle dynamics (Lewis *et al.*, 2000), due to 4) orogenic rebound in the Pyrenees (Gunnell *et al*., 2008) and 5) fluvial erosion due to Pleistocene climate changes (Lewis *et al.*, 2009). The recent evolution of river terraces in the Ebro basin suggests a near-uniform regional uplift due to tectonic uplift related to lithospheric thickening and isostatic rebound in response to regional denudation unloading, after the connection of the Ebro basin with the Mediterranean Sea (Lewis *et al*., 2017). The timing in younger exorheism is also found with morphological analysis and numerical modeling of landscape evolution (Babault *et al.*, 2006).

Thermochronological data also provide different information: in some studies they do not find rejuvenation of exhumation in Late Miocene or Pliocene related to base-level changes or climate changes (Gibson *et al.*, 2017), others found a re-excavation of valleys during the Miocene (pre-Messinian; Fillon *et al.*, 2013), while others find a last cooling episode starting around 5 Ma which interpret as related to the Pliocene re-excavation of the southern and northern flanks of the Pyrenees (Jolivet *et al.*, 2007; Beamud *et al.*, 2011)). Their AFT model agrees with prior results from Fitzgerald *et al.* (1999), they detected similar data in Maladeta and can reasonably be attributed to erosion during re-excavation of both the northern (Néouvielle and Bordères-Louron massifs) and southern (Bielsa massif) flanks of the Pyrenees (Jolivet *et al.*, 2007).

Summary: temporal evolution of deformation

In this section a temporal reconstruction of the kinematic evolution of the west-central Pyrenees during convergence is summarized. The data shown in Figure 5 comes from the mentioned works. The figure evidences the lack of unanimity even in the latest publications regarding age and lateral conection of the deformation.

The Pyrenean deformation has been dated thanks the good preservation of foreland basin deposits studying their relationship with folds and thrusts: the interaction between sedimentation and thrusting. In general, the deformation follows an overall foreland propagation (Vergés *et al.*, 2002). The South Pyrenean basin during the Eocene experienced the tectonic inversion of previous structures from the Cretaceous extension, which produces the division of the foreland basin into subordinate sub-basins at the end of the Ilerdian (Barnolas and Gil-Peña, 2001).

The first Pyrenean thrust developed as reactivation of the Early Cretaceous extensional faults during the late Santonian, producing the deposition of the Vallcarga Formation (Central Pyrenees). As convergence continued during the Maastrichtian, progressive unconformities were produced in the Arén Formation in relation to the Bóixols thrust (Puigdefàbregas *et al.*, 1992 and references therein). Between the end of the Maastrichtian and the Paleocene, the Tremp Formation was deposited (Garumnian) and conglomerates covered the Bóixols thrust. The Montsec thrust was coeval with the deposition of Garumnian. During Early-Middle Eocene elongated turbiditic troughs developed due to the surficial loading and subcrustal forces. During Late Eocene-Oligocene alluvial fan deposition occurs together with an increase of erosion due to the growth of the basement antiformal stack, although subsidence decreases (Puigdefàbregas *et al.*, 1992 and references therein), as it is also inferred from analog models. This chronology cannot be applied to other transects due to diachroneity of deformation (Choukroune, 1976), being younger to the west in the Pyrenean front (Millán Garrido *et al.*, 2000). In the west-central Pyrenees, the Larra-Monte Perdido thrust system has been interpreted to occur during mid-late Lutetian to Bartonian times (Teixell, 1996 and references therein) and the Lakora basement thrust (to which the cover Larra-Monte Perdido is assumed to connect) may have initiated in upper Santonian times, but its duration is difficult to deter-

mine. The Gavarnie basement thrust is related to Priabonian-Rupelian times (Teixell, 1996). In the External Sierras the deformation progrades toward the west from the Eocene and Miocene, together with the generation of the N-S anticlines (younger to the west) and their clockwise rotations. The final tightening of the E-W striking Santo Domingo detachment anticline reactivates thrust detachments younger towards the east from Oligocene to Miocene, being the detachment level the Triassic (Millán Garrido *et al.*, 1995; 2000).

Despite the abundant data and knowledge about the kinematics of the Pyrenees, there are unresolved questions and contradictions that need for the seek to critically revise quality data, to combine the data (as it appears in recent papers, where for example, combination of thermochronological data with balanced cross-sections or magnetostratigraphic data appear) and to comprehend data from different parts of the Pyrenean Chain in order to achieve a general consensus about the evolution of the Pyrenees.

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