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Detrital zircon U-Pb insights into the timing and provenance of the South Pyrenean Jaca Basin

New insights into the South Pyrenean Jaca Basin

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ABSTRACT

In this paper we investigate how sedimentary systems response to tectonic uplift during the last stages of a foreland basin infill. In the Jaca Basin, the western portion of the South Pyrenean foreland, massive conglomeratic deposits characterize the last stage of basin fill. We conducted detrital zircon U-Pb geochronology in a 3000m thick Cenozoic section that contains the transition from deltaic to alluvial environments with the aim of reconstructing provenance changes in this key stage of the basin evolution. The last conglomeratic deposits of the basin belong to the San Juan de la Peña alluvial fan, which has previously been assigned an early Oligocene age. Our new results reveal the presence of earliest Miocene detrital zircons at the base of the fan. Zircon double dating reveals identical U-Pb and (U-Th)/He ages indicative of a volcanic origin for these zircons. Therefore, we conclude that this fan was deposited essentially during early Miocene times.

The new data establishes a new chronologic framework for deformation and sedimentation in the South Pyrenean foreland, with strong implications for the dynamics and palaeogeography governing the last episodes of basin fill. These new results advocate for synchronous sedimentation in the Jaca piggy-back basin and in the autochthonous Ebro basin during the last stages of Pyrenean

compression in the Miocene. This work emphasizes the tectonic control on the drainage basin configuration, and gives new insights of the drainage network evolution in internally drained basins.

Keywords: Provenance, geochronology, zircon, Pyrenees, volcanism

Foreland basins record the erosional history of their source areas providing valuable information about the chronology of deformation and unroofing of the active orogenic wedges (e.g. Dickinson & Suczek 1979; Steidtmann & Schmitt 1988). In order to relate source-to-sink processes and to decipher the tectonic, exhumational, and depositional evolution from the source areas to the sedimentary basin sink, precise timing of the syntectonic foreland basin deposits is essential (e.g. DeCelles and Giles, 1996). The Jaca Basin, in the western portion of the South Pyrenean foreland basin (Fig. 1A), provides an excellent opportunity to investigate the relationship between tectonics and sedimentation in light of a well-established chronostratigraphic framework for the Eocene deep-water stage of foredeep development (Labaume *et al.* 1985; Canudo & Molina 1988; Oms *et al.* 2003; Payros *et al.* 2009; Mochales *et al.* 2012; Scotchman *et al.* 2015). However, there are only sparse and contradictory age constraints on the younger, terrestrial deposition in the basin (Puigdefàbregas 1975; Hogan & Burbank 1996; Oliva-Urcia *et al.* 2015). These younger deposits consist of fluvial to alluvial strata that represent the overfilling basin stage, and occur during the closure and initiation of an internally drained basin period. Sedimentation patterns of these deposits during this stage were highly controlled by the emergence of structures (Hirst & Nichols 1986). Moreover, these systems record the late erosional and exhumational history of the Pyrenees (Puigdefàbregas 1975). The accurate dating of these deposits is crucial not only for better characterising the geodynamics of the Pyrenean belt, but also because the South Pyrenean Basin is a reference model for foreland basins worldwide, and age constraints would allow a more accurate modelling and comparison with analog basins.

This study presents new detrital zircon (DZ) U-Pb data from a 3000 m thick succession of these last alluvial deposits, elucidating their provenance evolution. In addition, selected DZ U-Pb and (U-Th)/He double dating was performed to provide important new constraints on the chronostratigraphy of these strata. The results presented here provide a new stratigraphic template for the Jaca Basin which is an important clue for interpreting both the basin dynamics and tectonic/sedimentation relationships. These results imply a younger age for these fluvial to alluvial deposits and require a revision of both the chronostratigraphic record as well as the late-stage fill history of the Jaca Basin.

GEOLOGICAL SETTING

The Pyrenees formed during late Cretaceous to early Miocene times as a result of the collision between the Eurasian and Iberian plates (Roure *et al.* 1989; Muñoz 1992; Teixell 1998; Vergés *et al.* 2002). The southern side of the Pyrenean belt consists on a south-vergent, basement-involved thrust stack that in the west-central Pyrenees is composed by four main thrust sheets. These are from north to south: the Lakora-Eaux-Chaudes, Gavarnie, Broto and Guarga thrusts (Teixell 1996; Labaume *et al.* 2016) (Fig. 1B). These thrust sheets involve Paleozoic basement and a sedimentary cover consisting of pre-orogenic Mesozoic rocks and Late Cretaceous-early Miocene foreland basin strata -the so-called Jaca thrust-top Basin. The Paleozoic basement constitutes the core of the belt - the Axial Zone- and is mainly composed of Variscan low-grade metamorphic rocks and granitoids, that are unconformably overlain by Permo-Triassic red beds or directly by Cretaceous limestones. South of the Axial Zone, synorogenic rocks of Santonian to Miocene age constitute the South Pyrenean foreland basin, including the Jaca, Ainsa, and Tremp-Graus Basins, which thrust southwards over the Ebro basin (Fig. 1).

The Jaca Basin (Fig. 2) is characterized by deep-water turbidite sedimentation during early-mid Eocene times (Hecho Group turbidites), that evolved to the coastal and fluvial/alluvial environments in the upper Eocene-Oligocene (Campodarbe and Bernués Formations) (Puigdefàbregas 1975). This transition from marine to terrestrial environments occurred diachronously, shifting from east to west (Soler-Sampere & Puigdefàbregas 1970; Dreyer *et al.* 1999), culminating in widespread terrestrial deposition, cessation of marine deposition, and the initiation of an endorheic basin stage at 36 Ma (Ortí *et al.* 1986; Barnolas & Gil-Pena 2002; Costa *et al.* 2010). Stratigraphically above the Eocene-Oligocene Campodarbe Formation, the Bernués Formation consists on massive conglomeratic deposits, mainly represented by the San Juan de la Peña and Peña Oroel alluvial fans (Fig. 2, 3) (Puigdefàbregas 1975). The cessation of sedimentation in the Jaca Basin has been attributed to activity on the Guarga thrust (Oligocene-early Miocene), ultimately resulting in the uplift and erosion of the basin as recorded in the alluvial sedimentation (i.e the Luna alluvial fan) of the Uncastillo Formation, in the Ebro foreland basin (Teixell 1996; Labaume *et al.* 2016).

STRATIGRAPHIC FRAMEWORK OF THE JACA BASIN

The Campodarbe Formation reaches a maximum thickness of more than 3000 m in the central part of the Jaca Basin in the Guarga syncline (Fig. 1B), where two main sediment routing systems merge: an axial east-derived fluvial system that enters through the southeastern part of the basin and a transverse north-derived alluvial fan system that dominates the northern margin of the basin (Puigdefàbregas 1975; Montes & Colombo 1996; Roigé *et al.* 2017). Above the Campodarbe Formation, the conglomerates of the Bernués Formation represent the youngest preserved sedimentation derived from the persistent erosion of the Pyrenees and the emerging fold and thrust belt to the north of the basin. The age of the Campodarbe Formation was originally proposed to be late Eocene-Oligocene (Soler and Puigdefàbregas, 1970), while the age of the overlying Bernués Formation was suggested to be Chattian at the base and potentially Aquitanian to the top (Fig. 2). In contrast, more recently Hogan and Burbank (1996), Montes (2002) and Oliva-Urcia *et al.* (2015) proposed significantly older ages for the top of the Campodarbe Formation and the Bernués Formation, setting a Priabonian to Rupelian age for them.

In this work we investigate the provenance evolution from the fluvial Campodarbe Formation until the alluvial Bernués Formation in order to constraint the palaeogeographic evolution of the Jaca piggy back basin during the last stages of infill.

U-PB SIGNALS FROM POTENTIAL SOURCE AREAS FOR THE JACA BASIN

Potential source areas for the Jaca basin involve different domains of the central and western Pyrenees (Fig. 1). These domains are constituted by the Paleozoic basement of the Axial Zone, the preorogenic Mesozoic cover successions and the synorogenic deposits from the late Cretaceous to middle Eocene.

Ordovician-Devonian metasedimentary deposits of the Axial Zone (Fig. 1) show detrital zircon U-Pb signatures dominated by components ranging from 520 to 700 Ma and minor components of Cadomian ages (420-250 Ma) and >700 Ma (Hart *et al.* 2016; Margalef *et al.* 2016). Carboniferous strata are characterized by the dominance of Cambro-Devonian signals incorporating syndepositional volcanic zircons of around 325 to 360 Ma (Martínez *et al.* 2015). In the central Pyrenees, plutonic rocks are mainly represented by Variscan granitoids with ages ranging from 280 to 315 Ma (Whitchurch *et al.*, 2011 and refs within). Triassic clastic deposits show dominant Cadomian zircon ages and minor Variscan zircons (Hart et al., 2016). Cretaceous siliciclastic rocks show diverse age distributions, ranging from Variscan-dominated signals in the lower Cretaceous (Filleaudeau *et al.* 2012) to the Cadomian-dominated signals for the upper Cretaceous Aren Formation (Whitchurch *et al.* 2011).The Paleocene and lower/middle Eocene formations in the Jaca and in the nearby Ainsa and Tremp basins (Fig.1) show again different detrital zircon distributions, where dominant eastern Pyrenean Cadomian zircons are roughly replaced by dominant central Pyrenean Variscan components diachronously from east to west (Whitchurch *et al.* 2011; Filleaudeau *et al.* 2012; Thomson *et al.* 2017).

METHODOLOGY

The fluvial-alluvial deposits of San Juan de la Peña section of the central Jaca Basin (Fig. 2) were measured and sampled for detrital zircon (DZ) U-Pb and (U-Th)/He geochronologic analysis in order to investigate provenance changes. This analysis allows to obtain the zircon crystallization ages contained in clastics rocks, providing valuable provenance information about the formations represented in the source area. Four medium grained sandstone samples (2-5 kg) were collected (SP17, SP1, SP3 and SP18) along the section seeking for the most representative outcrop exposures. As the effects of hydrodinamic grain size fractionation can introduce an unwanted bias to the results (Malusà *et al.* 2016), all the samples were collected selecting regularly medium to coarse sandstone beds. The lowermost sample (SP17) was obtained from the lower Campodarbe Formation fluvial deposits, while samples SP1, SP3 and SP18 were obtained from the conglomeratic beds of the San Juan de la Peña fan (Fig. 2) (Bernués Formation, according to Puigdefàbregas, 1975). As one sample (SP3) provided the youngest zircon aged grains found in the Pyrenees, (U-Th)/He thermochronologic analysis was performed in these grains in order to resolve their origin. Following standard heavy mineral separation procedures (Mange and Maurer, 1992), samples were crushed and sieved to obtain the 63-250μm fraction. Zircon grains were isolated using the Gemini water table separation, Frantz isodynamic magnetic separation, and heavy liquid separation (sodium metatungstate; ρ=2.87 g/cm^3). Mineral separation was performed in the heavy mineral laboratory of the Department of Biological, Geological and Environmental Sciences at University of Bologna. All DZ U-Pb and (U-Th)/He analyses were conducted at the UTChron geo- and thermochronology laboratory at the University of Texas at Austin following procedures described in Hart *et al.* (2016) for LA-ICP-MS U-Pb dating and Wolfe and Stockli (2010) for ZHe dating.

RESULTS

All DZ U-Pb zircon results are shown in Figure 3 as pie charts, kernel density estimation plots (KDE, Vermeesch, 2012), and histograms (see Supplementary Files S2 and S3 for complete data). For the pie diagrams, DZ U-Pb ages are binned into groups (Fig. 3) that represent the most important magmatic/tectonic phases of the Pyrenean evolution, similar to those established in Thomson *et al.* (2017) for the nearby Ainsa basin, namely: Cenozoic (0-66 Ma), Late Mesozoic (66-180 Ma), Permo-Triassic (180-280 Ma), Late Variscan (280-310 Ma), Early Variscan (310-370 Ma), Cambro-Devonian

(370-520 Ma), Cadomian/Pan-African (520-700 Ma), Neoproterozoic (700-900 Ma), Kibaran (900-1200 Ma), Mesoproterozoic (1500-2200 Ma) and Archean-Paleoproterozoic (2200-4600 Ma).

The results from the four samples selected from the San Juan de la Peña section for DZ U-Pb analysis are here described, from base to the top of the section that includes the Campodarbe and Bernués Formations (Fig. 3). The basal sample (SP17), which belongs to the fluvial Campodarbe Formation, shows three main age components at 310-380 Ma, 500-780 Ma and 900-1120 Ma. It lacks any late Variscan signal (280-310 Ma), but exhibits marked age peaks at 325 Ma and 375 Ma. The overlying San Juan de la Peña conglomeratic strata (samples SP1, SP3, SP18) show minor to absent late Variscan ages, and marked age peaks at 320-370 Ma and 660-700 Ma. Cambro-Devonian age components (370-520 Ma) are low represented. The uppermost sample SP18 shows an important peak at 540 Ma, and 700 to 1200 Ma ages are widely represented. The main trend that can be identified in the analysed samples is a significant up-section increase in Cadomian zircons (520-700 Ma) (Fig. 3). Compared to the Campodarbe fluvial sandstone, the Bernués alluvial conglomerates either lack or show low abundances of 360-400 Ma zircons and are characterized by an increased age component at ~700-900 Ma.

The DZ spectrum of ~120 zircons for sample SP3 (Bernués alluvial conglomerates) yielded a single zircon with a U-Pb age of 22.2±0.6 Ma (Fig. 3), which is the youngest zircon age found in the Southern Pyrenees. Consequently, additional U-Pb DZ analyses were performed, targeting only euhedral grains of variable sizes to verify the presence of young Cenozoic zircons (Fig. 3). These additional analyses of sample SP3 (labeled SP3bis) yielded four more young ages (23.9±0.9 Ma; 26.8±1.1 Ma; 24.3±1.2 Ma and 22.7±0.8 Ma), corroborating the presence of Oligo-Miocene zircons and improving statistics of the determination of the maximum depositional age for the strata (Fig. 4) (Dickinson & Gehrels 2009). Furthermore, in order to resolve the origin of these Oligo-Miocene grains, (U-Th)/(He-Pb) double dating was applied. All young zircons show identical U-Pb and (U-

Th)/He ages implying a volcanic origin for them to constrain the actual (maximum) depositional age (Fig. 5).

DISCUSSION

Provenance constraints for the Jaca basin

In the San Juan de la Peña section, the main U-Pb DZ changes occur between the fluvial Campodarbe Formation (sample SP17) and the Bernués alluvial conglomerates (samples SP1, SP3 and SP18). These changes are likely attributable to provenance shifts resulting from the replacement of an east-derived fluvial system (sample SP17) by a north-derived alluvial system (samples SP1, SP3, SP18), as previously proposed by Puigdefàbregas (1975). The presence of early Variscan age components in the east-derived fluvial system suggests erosion and recycling of Carboniferous strata of the east-central Axial Zone (Roigé *et al.* 2017), which have been shown to contain early Variscan DZ ages (Martínez *et al.* 2015). In contrast, the conglomeratic beds show a pronounced decrease in the 360-440 Ma zircon signal, that could be due to a lack of significant contributions from the Paleozoic basement and a dramatic increase of recycling of the Hecho Group turbidites, forming the tectonically inverting hinterland north of the basin at that time (Puigdefàbregas 1975).

Origin and implications for the Cenozoic zircon aged grains

The Oligo-Miocene zircons contained in the Bernués conglomerates (sample SP3) represent the youngest zircon age found in the South Pyrenean domain and with strong implications for the chronostratigraphy of the Jaca basin.

Regarding to the source for these zircons, as there is no documented felsic Cenozoic volcanism in the Pyrenees that could source these grains, the most plausible origin for them is Oligo-Miocene calc-alkaline magmatism reported from the Mediterranean basin (Fig. 6) related to the opening of the Valencia through (Marti *et al.* 1992; Sabat *et al.* 1995). This hypothesis would assume airborne transport of the volcanic zircons and disposition as airfall either directly to the Jaca Basin or into the hinterland source area. This explanation is also supported by the presence of an ash layer that has been reported in several localities in the Ebro Basin (Fig. 6), which yielded a radiometric sanidine $^{40}Ar/^{39}Ar$ age of 19 Ma (Odin *et al.* 1997).

Concerning to the chronostratigraphic implications for the Jaca basin, the occurrence of earliest Miocene volcanic zircons at the base of the alluvial fan and the >400 m thick sequence of conglomerate above, strongly suggests an early Miocene age for these deposits. This new isotopic maximum depositional age constraints are validated by the early work of Puigdefàbregas (1975) and Arenas (1993) who pointed to the possibility of an Oligo-Miocene age for this fan (Bernués Formation) on the basis of facies correlation to the Uncastillo Formation in the adjacent Ebro Basin (Fig. 7) (Puigdefàbregas 1975; Millán-Garrido *et al.* 1995; Nichols & Hirst 1998). However subsequent works by Hogan (1993), Montes (2002) and Oliva-Urcia *et al.* (2015), based on magnetostratigraphy and facies correlation, suggested a lower Oligocene age for the Bernués Formation (Fig. 7), implying no temporal correlation between it and the Uncastillo Formation. The syntectonic character of these formations and the lack of physical correlation between these units could be a possible explanation for the divergence on age interpretations.

The new DZ U-Pb geochronology results clearly reveal a time equivalence of the Bernués and Uncastillo Formations (Fig. 7). This substantiated correlation between the Bernués and Uncastillo Formations entails a new Oligo-Miocene palaeogeography characterized by alluvial sedimentation (San Juan de la Peña alluvial fan, Bernués Formation) within the Jaca Basin at the same time that the southern portions of the basin were uplifted and subjected to erosion and shed into the basin through large alluvial fans (i.e. the Luna alluvial fan, Uncastillo Formation) in the Ebro foreland basin. Therefore, our results allow to infer a particular drainage configuration for the Jaca and Ebro basins since they were internally drained. The Luna alluvial fan was able to erode and bypass the western portion of the Jaca piggy back basin and part of the western Pyrenees (Hirst & Nichols 1986) without disturbing the sediment accumulation of the San Juan de la Peña alluvial fan in the eastern part of the basin. This drainage configuration is here interpreted as being promoted by the variation of structural displacement of the Guarga thrust, which was higher in the eastern Jaca basin, and produced a structural load that could assist to preserve the sedimentation of the San Juan de la Peña fan (Fig. 8).

In addition, the new proposed age has also implications on the sedimentation rate calculated for the Jaca basin. While Costa *et al.* (2010) proposed an increase of the sediment rates from 25 cm/kyr to 63 cm/kyr (Fig. 9) during the transition from marine to terrestrial environments in the southern part of the basin, our results imply a much lower sedimentation rate and closer those defined for the eastern Ebro Basin. Considering that in the San Juan de la Peña section, the 2460m of stratigraphic thickness encompasses the last marine deposits (~36 Ma, Costa *et al.* 2010) and the layer containing the volcanic grains (~23 Ma), we can broadly calculate an approximate average sedimentation rate of 16 cm/kyr (Fig. 9). Although this value is only a rough approximation assuming a continuous sedimentation rate, this lower sedimentation rate would be consistent with the response of the sedimentary systems to the basin closure, in which a base level rise in a stage of aggradation is expected, as observed in other localities of the Pyrenees (Coney *et al.* 1996).

Moreover, the change in age of the last preserved synorogenic deposits in the Jaca basin has implications on the source area configuration established in previous provenance studies in the area. Petrographic results concerning to the terrestrial deposits of the Jaca Basin presented in Roigé *et al.* (2017) pointed to the existence of a source area mainly represented by the former turbiditic basin, and by rocks cropping out in the North Pyrenean Zone. According to these petrographic results, a drainage water divide placed further to the north of its present day location was inferred during Eocene-Oligocene times. Time constraints presented in this work allow to extend this source area configuration from at least Oligocene-Miocene times.

This change in age of the synorogenic deposits also requires a reconsideration of the chronology of thrust activity with respect to the basin stratigraphy. The alluvial sedimentation in the Jaca Basin was linked to the Gavarnie thrust (Teixell 1998; Labaume *et al.* 2016; Roigé *et al.* 2016, 2017), while the Guarga thrust was assumed to set up the uplift and the interruption of sedimentation in the Jaca Basin, which then shifted to the Ebro Basin. However, the new proposed Miocene age for the San Juan de la Peña strata implies that the accumulation of the conglomerates and other clastic sediments was linked to activity along the Guarga thrust (dated independently from thrust emergence in the External Sierras) and that the tectonic uplift did not impede the sedimentation within the basin (Fig. 8). It follows that the Jaca Basin was a thrust-top or piggy-back basin until approximately the end of the Pyrenean orogeny in Miocene times. The episode of coeval sedimentation in the Jaca and Ebro Basins can be correlated with the strong period of exhumation in the western Axial Zone during the Miocene recorded by thermochronology (Bosch *et al.* 2016; Labaume *et al.* 2016).

Although our results are restricted to the northern part of the Jaca Basin, they emphasize the need for better timing constraints for the syntectonic conglomerates of the southern Pyrenees, which constitute the clues to decipher the last stages of the Pyrenean belt tectono-sedimentary evolution. In addition, this work provides new insights on the response of drainage networks in internally drained basins, specifically in active settings, were tectonics can exert a high control on sediment flux distribution.

CONCLUSIONS

New U-Pb detrital zircon results in the Jaca thrust-top basin of the Southern Pyrenees allow to characterize the provenance changes that occur in the upper fluvial-alluvial deposits of the basin. Fluvial sediments of the late Eocene to Oligocene Campodarbe Formation are characterized by the dominance of early Variscan zircons that are consistent with the erosion of the Carboniferous strata of the Axial Zone or the east-central Pyrenees. However, the overlying alluvial conglomerates of the San Juan de la Peña fan show a progressive decrease on the Variscan signals, that could be associated to the replacement of the eastern Paleozoic source area by a northern source area that produced the recycling of the Eocene Hecho Group turbidites from a less exhumed hinterland.

DZ U-Pb analysis yielded four Cenozoic aged zircons at the base of the San Juan de la Peña fan. According to (U-Th)/(He-Pb) double dating results, these grains have a volcanic origin, likely interpreted as linked with the distant Oligo-Miocene Mediterranean volcanism. This finding challenges current thinking of the chronology of the Jaca basin, allowing to propose a Miocene age for the San Juan de la Peña fan, an age much younger than considered before. Therefore, we can infer a new Oligo-Miocene palaeogeography for the South Pyrenean foreland characterized by alluvial sedimentation within the Jaca Basin, at the same time that parts of it were uplifted and submitted to erosion by the Guarga thrust, and recycled into the large alluvial fans of the Ebro foreland Basin. This particular drainage configuration is here interpreted as being controlled by the variation of structural relief within the Jaca and Ebro basins.

This study provides new insights about how sedimentary systems react to basin closure in active tectonic settings, were variance on the structural relief can have a great impact into the sediment flux distribution.

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FIGURE CAPTIONS

Fig. 1. (**A**) Simplified geological map of the Pyrenees (redrawn from Teixell, 1996), showing the location of the study area (white frame). White line indicates cross-section in Figure 1B. Lk: Lakora

thrust; Ga: Gavarnie thrust. (**B**) Crustal cross-section of the west-central Pyrenees (simplified from Teixell et al., 2016), showing the Jaca thrust-top Basin of the Southern Pyrenees.

Fig. 2. Geological map of the central part of the souhern Jaca Basin and northern margin of the Ebro Basin (modified from Puigdefàbregas, 1975). White-purple line shows the location of the San Juan de la Peña stratigraphic section analyzed in this work. Circles and triangle show the position of the analysed samples. Map coordinates for bottom right are (30T) 721339E/4676503N, and top left are (30T) 666069E/4715901N.

Fig. 3. Detrital zircon U-Pb results for the San Juan de la Peña section (see location in Figure 2), with the stratigraphic log and position of the analyzed samples. Color legend used for Pie diagrams is also represented in the Kernel (KDE) and histogram diagrams for a better visualization of data. Note that SP3 bis is labeled as "euhedral grains", as it represents the population of euhedral grains of sample SP3.

Fig. 4. Zircon U-Pb ages of the Cenozoic grains. Weighted mean ages are calculated with Isoplot program following the procedure described in Dickinson and Gehrels (2009). Black boxes are the error bars (2σ error). Horizontal grey band shows the probable age of the zircon population.

Fig. 5. (U-Th)/(He) age versus U-Pb age for double dated Cenozoic grains (red error bars represents 2σ error) of sample SP3 from the basal Bernués Formation.

Fig. 6. Simplified geological map of northeastern Iberia, showing the location of the study area (Jaca Basin), the reported outcrops of a Miocene volcanic ash layer in the Ebro Basin (Lanaja, Tardienta and Peñalba) and the position of Oligo-Miocene volcanic domes in the Mediterranean basin.

Fig. 7. Stratigraphic chart showing the datings and time equivalences between fluvial-alluvial sedimentary formations of the Jaca and Ebro basins proposed by different authors, and the results obtained by this work. Also shown is the timing of the thrusts defined for the Jaca Basin (after Labaume *et al.*, 2016).

Fig. 8. (**A**) Paleogeographic reconstruction of the Jaca piggy back basin and Ebro foreland basin for the late Oligocene-early Miocene, showing the main uplifting areas that trapped the San Juan de la Peña alluvial fan while the Luna alluvial fan was depositing in the Ebro basin (modified from Hirst and Nichols, 1986; Puigdefàbregas, 1975; Arenas, 1993). (**B**) Simplified cross section across the center of the Jaca basin during the late Oligocene-early Miocene stage, showing synchronous deposition in both basins.

Fig. 9. Sedimentation rates for the Jaca Basin and eastern Ebro Basin modified from Costa *et al.*, (2010). The yellow dashed line represents the inferred sedimentation trend from the zircon ages presented in this work.

SUPORTING INFORMATION

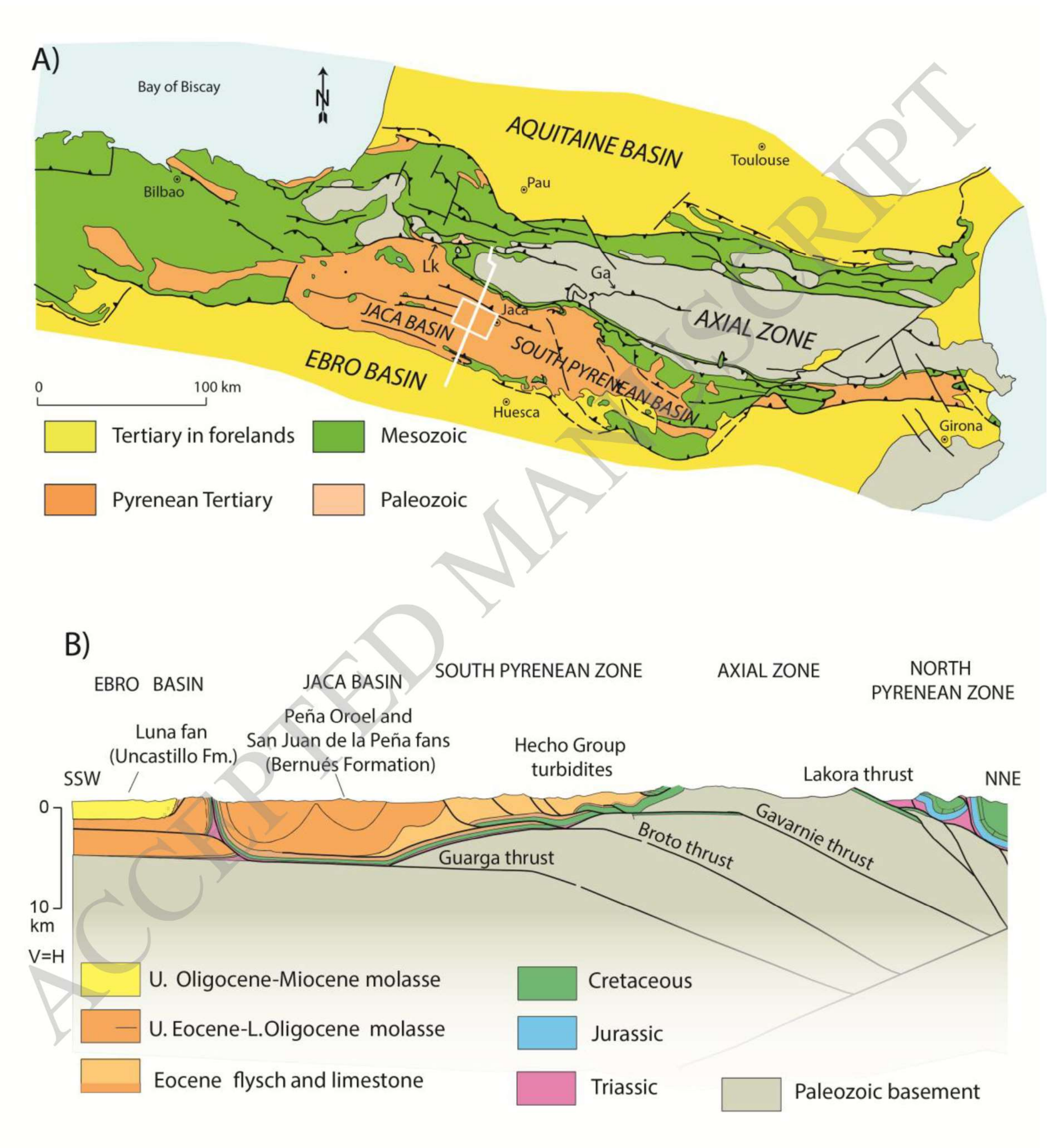
S1 Extended Zircon U-Pb LA-ICP-MS methodology.

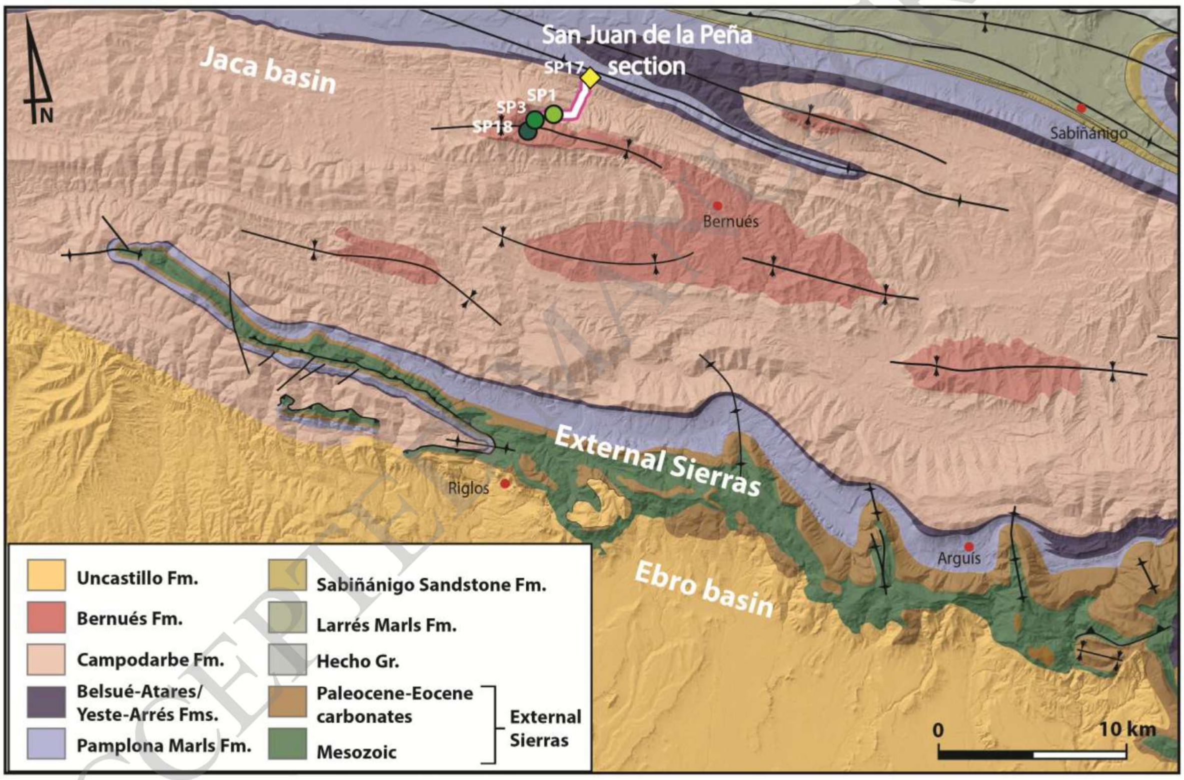
S2 Reduced detrital zircon U-Pb dataset for all analysis.

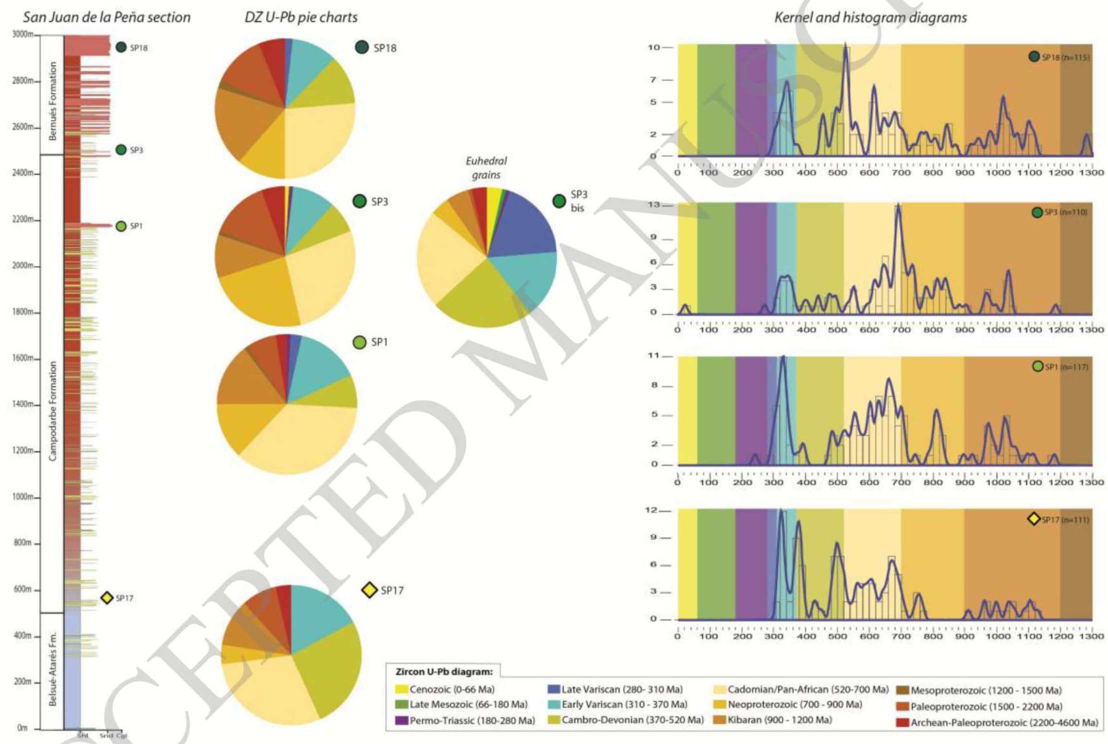
S3 Full detrital zircon U-Pb spectra from 0 Ma to 3500 Ma, displayed as kernel density estimators (KDE) and histograms (Vermeesch, 2012). Nonadaptive KDE bandwidth of 8 Ma, histogram bin width of 20 Ma.

S4 Reduced detrital zircon double dating (U-Th)/(He-Pb) data for Cenozoic aged zircons.

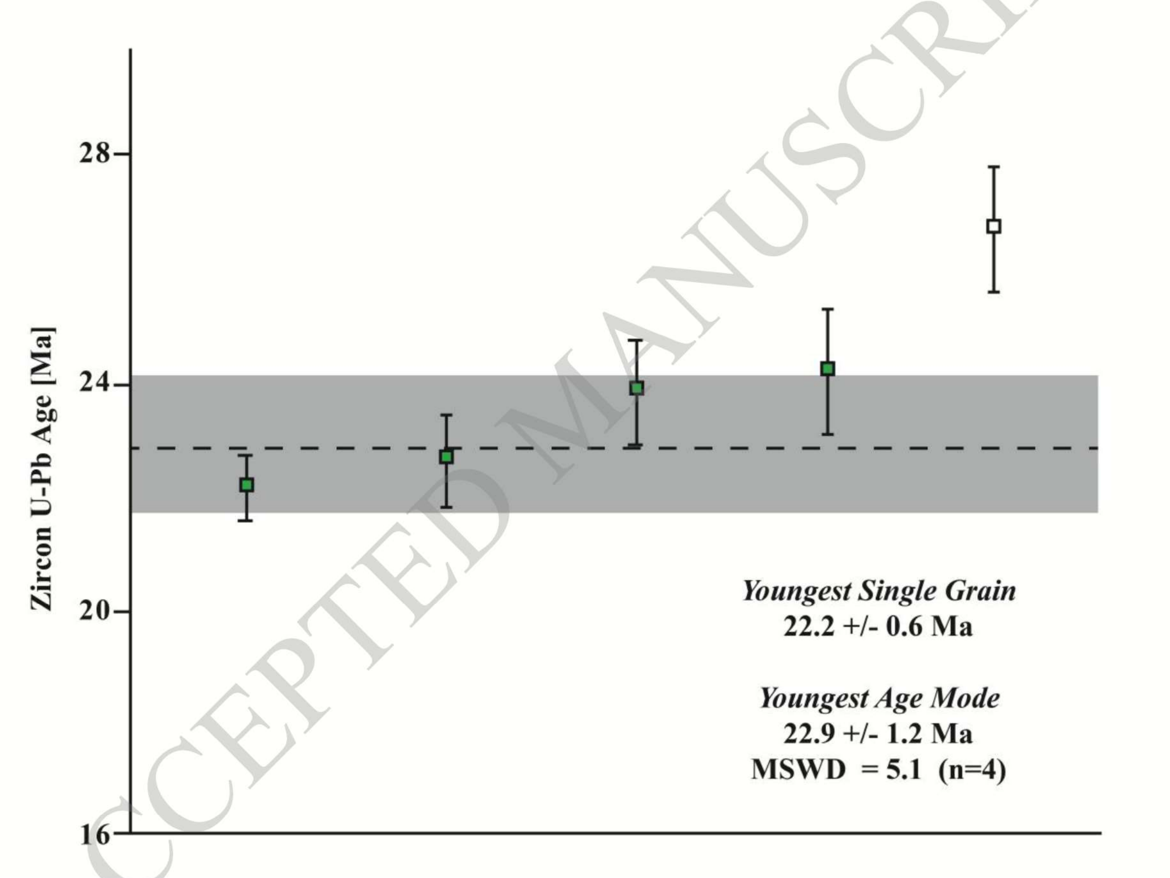
S5 Sample location for the analyzed samples.

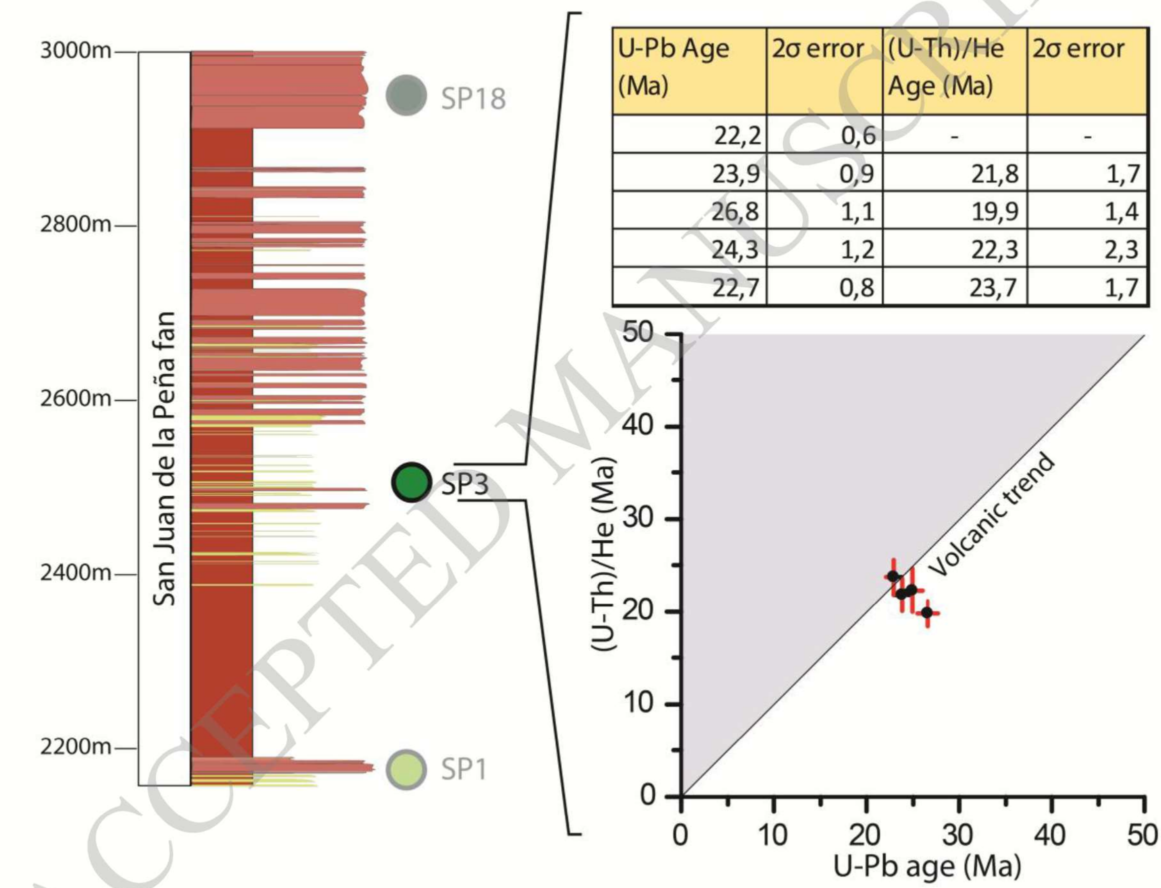

A)
Bay of Biscay
N
AQUITAINE BASIN
Toulouse
Pau
Bilbao
Lk
Ga
Jaca
JACA BASIN
AXIAL ZONE
SOUTH PYRENEAN BASIN
EBRO BASIN
Huesca
Girona
0
100 km
Tertiary in forelands
Mesozoic
Pyrenean Tertiary
Paleozoic
B)
EBRO BASIN
JACA BASIN
SOUTH PYRENEAN ZONE
AXIAL ZONE
NORTH PYRENEAN ZONE
Luna fan (Uncastillo Fm.)
Peña Oroel and San Juan de la Peña fans (Bernués Formation)
Hecho Group turbidites
Lakora thrust
SSW
NNE
0
10 km
V=H
Guarga thrust
Broto thrust
Gavarnie thrust
U. Oligocene-Miocene molasse
U. Eocene-L.Oligocene molasse
Eocene flysch and limestone
Cretaceous
Jurassic
Triassic
Paleozoic basement


San Juan de la Peña section
Jaca basin
SP17
SP1
SP3
SP18
N
Sabiñánigo
Bernués
External Sierras
Riglos
Arguis
Ebro basin
Uncastillo Fm.
Bernués Fm.
Campodarbe Fm.
Belsué-Atares/ Yeste-Arrés Fms.
Pamplona Marls Fm.
Sabiñánigo Sandstone Fm.
Larrés Marls Fm.
Hecho Gr.
Paleocene-Eocene carbonates
Mesozoic
External Sierras
0
10 km

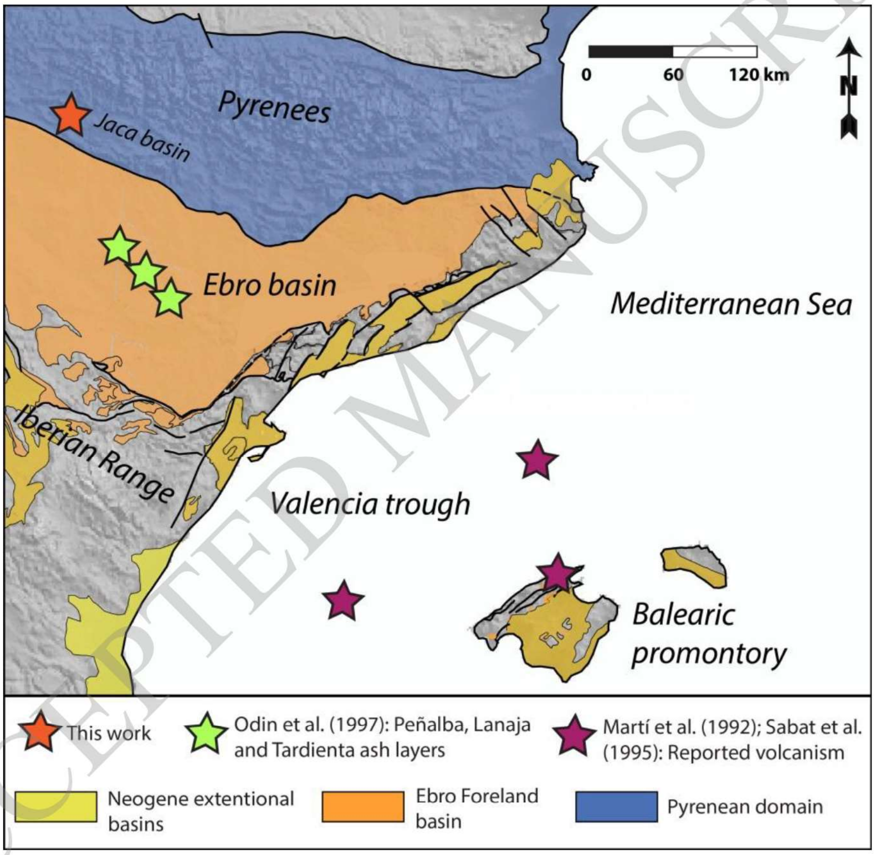


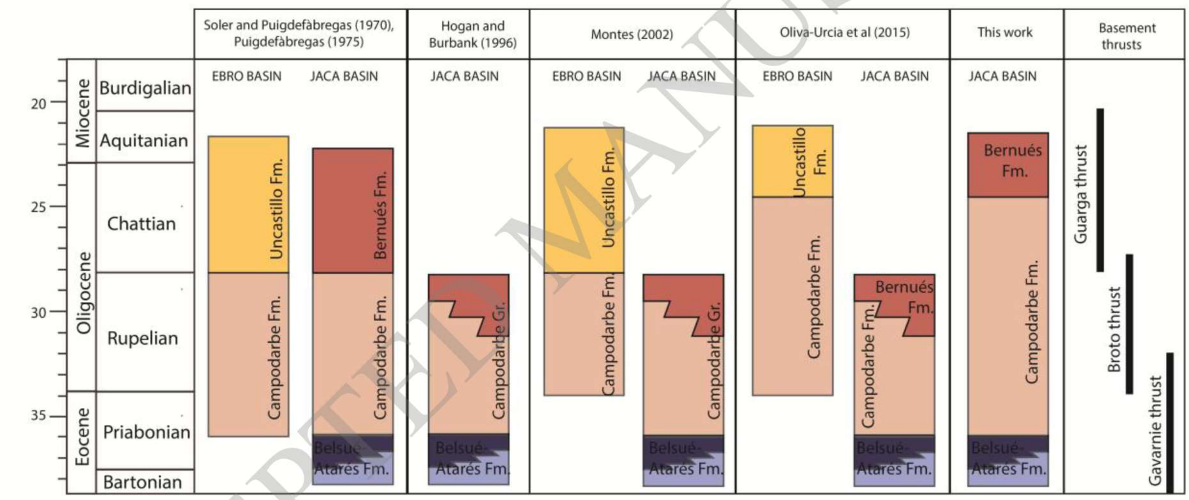
San Juan de la Peña section
DZ U-Pb pie charts
Kernel and histogram diagrams
Bernués Formation
Campodarbe Formation
Belsué-Atarés Fm.
SP18
SP3
SP1
SP17
Euhedral grains
SP3 bis
SP18 (n=115)
SP3 (n=110)
SP1 (n=117)
SP17 (n=111)
Zircon U-Pb diagram:
Cenozoic (0-66 Ma)
Late Mesozoic (66-180 Ma)
Permo-Triassic (180-280 Ma)
Late Variscan (280- 310 Ma)
Early Variscan (310 - 370 Ma)
Cambro-Devonian (370-520 Ma)
Cadomian/Pan-African (520-700 Ma)
Neoproterozoic (700 - 900 Ma)
Kibaran (900 - 1200 Ma)
Mesoproterozoic (1200 - 1500 Ma)
Paleoproterozoic (1500 - 2200 Ma)
Archean-Paleoproterozoic (2200-4600 Ma)


Zircon U-Pb Age [Ma]
28
24
20
16
Youngest Single Grain
22.2 +/- 0.6 Ma
Youngest Age Mode
22.9 +/- 1.2 Ma
MSWD = 5.1 (n=4)

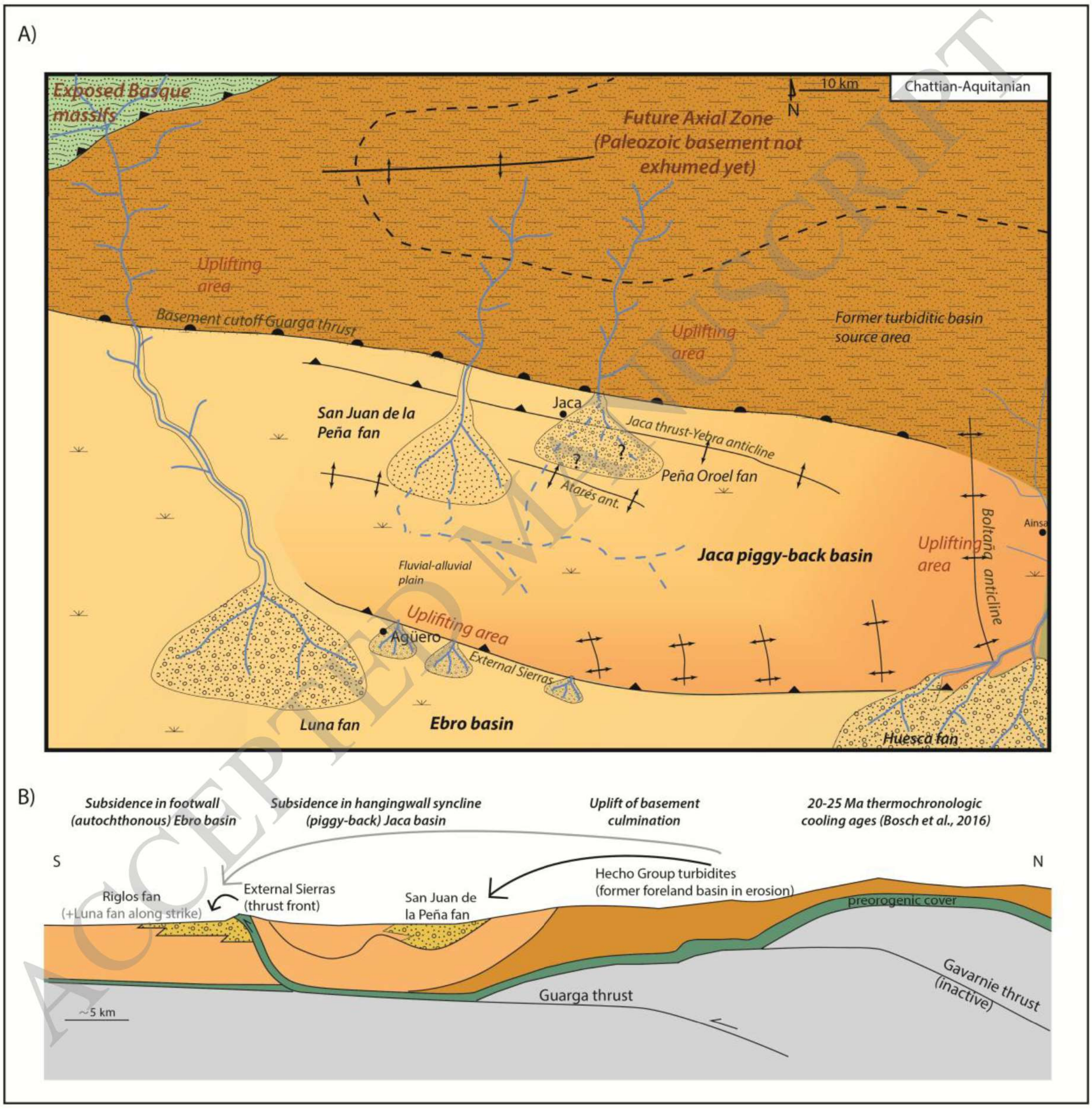


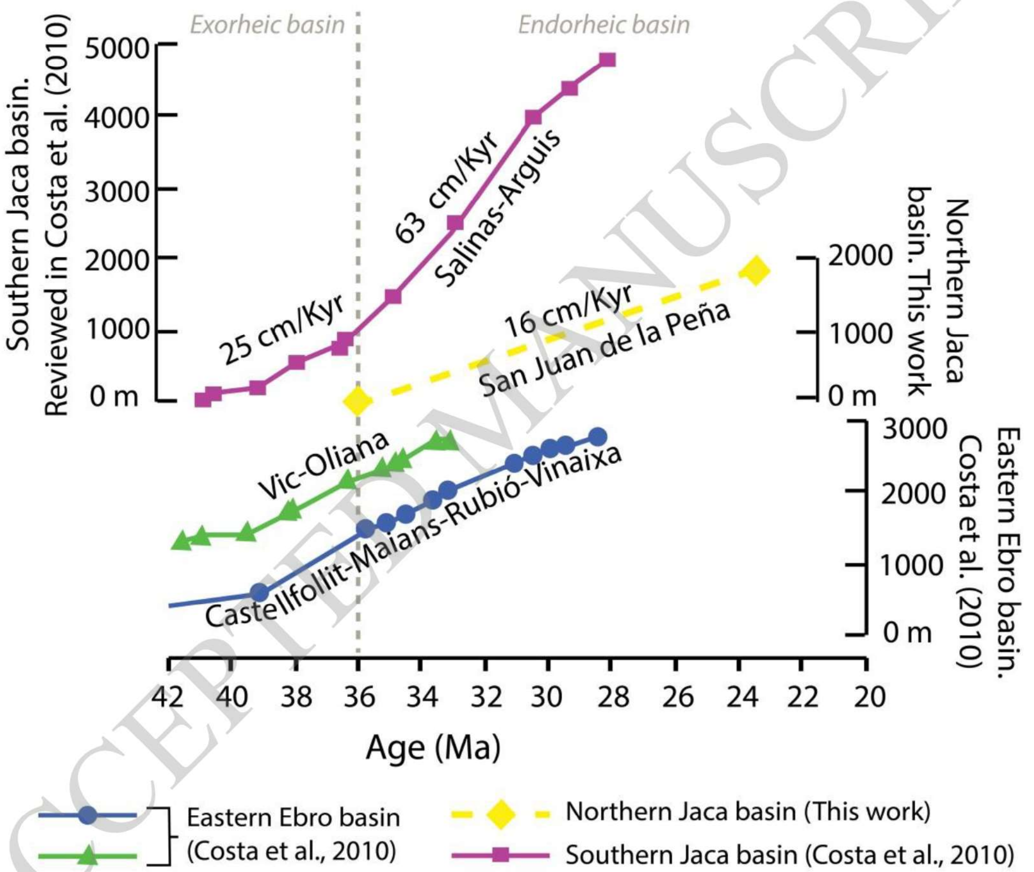
U-Pb Age (Ma)	2σ error	(U-Th)/He Age (Ma)	2σ error
22,2	0,6	-	-
23,9	0,9	21,8	1,7
26,8	1,1	19,9	1,4
24,3	1,2	22,3	2,3
22,7	0,8	23,7	1,7


0
60
120 km
N
Pyrenees
Jaca basin
Ebro basin
Mediterranean Sea
Iberian Range
Valencia trough
Balearic
promontory
This work
Odin et al. (1997): Peñalba, Lanaja
and Tardienta ash layers
Martí et al. (1992); Sabat et al.
(1995): Reported volcanism
Neogene extentional
basins
Ebro Foreland
basin
Pyrenean domain



Soler and Puigdefàbregas (1970), Puigdefàbregas (1975)
Hogan and Burbank (1996)
Montes (2002)
Oliva-Urcia et al (2015)
This work
Basement thrusts
EBRO BASIN
JACA BASIN
Miocene
Oligocene
Eocene
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
20
25
30
35
Uncastillo Fm.
Bernués Fm.
Campodarbe Fm.
Campodarbe Gr.
Belsué-Atarés Fm.
Guarga thrust
Broto thrust
Gavarnie thrust


A)
Exposed Basque massifs
10 km
N
Chattian-Aquitanian
Future Axial Zone (Paleozoic basement not exhumed yet)
Uplifting area
Basement cutoff Guarga thrust
Uplifting area
Former turbiditic basin source area
San Juan de la Peña fan
Jaca
Jaca thrust-Yebra anticline
Peña Oroel fan
Atarés ant.
Ainsa
Boltaña anticline
Uplifting area
Jaca piggy-back basin
Fluvial-alluvial plain
Uplifting area
Agüero
External Sierras
Luna fan
Ebro basin
Huesca fan
B)
Subsidence in footwall (autochthonous) Ebro basin
Subsidence in hangingwall syncline (piggy-back) Jaca basin
Uplift of basement culmination
20-25 Ma thermochronologic cooling ages (Bosch et al., 2016)
S
N
Hecho Group turbidites (former foreland basin in erosion)
Riglos fan (+Luna fan along strike)
External Sierras (thrust front)
San Juan de la Peña fan
preorogenic cover
Gavarnie thrust (inactive)
Guarga thrust
~5 km


Exorheic basin
Endorheic basin
Southern Jaca basin. Reviewed in Costa et al. (2010)
5000
4000
3000
2000
1000
0 m
25 cm/Kyr
63 cm/Kyr
Salinas-Arguis
16 cm/Kyr
San Juan de la Peña
Northern Jaca basin. This work
2000
1000
0 m
Vic-Oliana
Castellfollit-Maians-Rubió-Vinaixa
3000
2000
1000
0 m
Eastern Ebro basin. Costa et al. (2010)
42 40 38 36 34 32 30 28 26 24 22 20
Age (Ma)
Eastern Ebro basin (Costa et al., 2010)
Northern Jaca basin (This work)
Southern Jaca basin (Costa et al., 2010)