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Recycling effects in detrital zircon U—Pb signatures in a foreland basin: Identifying the multicyclic sediment sources of the Eocene-Miocene Jaca basin (southern Pyrenees, Spain)

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ABSTRACT

This work deals with the provenance evolution of the mid Eocene to early Miocene clastic deposits of the Jaca basin (southern Pyrenees), which record a main drainage network reorganization during the progressive tectonic uplift of the Pyrenean orogen. We present new detrital zircon U—Pb data which show a Variscan-dominated detrital zircon signature for the Lutetian Hecho Group turbidites, while the overlying late Eocene to early Miocene alluvial fan sediments record a Cadomian-dominated detrital zircon signature, allowing to document a major change in the source area. Moreover, a tectono-stratigraphic cyclicity can be identified in each of the turbidite systems that conform the upper Hecho Group, featuring an enrichment of the Variscan detrital zircon signal at the base of the system, which can be interpreted as the result of an efficient sediment transfer from distant Axial Zone sources during relative sea-level lowstands, while a dilution of this signal occurs during highstands, at the top of each system, due to the reduced erosion capability of the fluvial network. Integration of detrital zircon U—Pb data with sandstone petrography allows for improved resolution of the source-area shifts, for discrimination between first-cycle and multi-cycle zircons, and to identify that the detrital zircon signal of the alluvial fans does not fully represent the source area configuration. This study illustrates the importance of combining petrography with detrital zircon U—Pb data to improve provenance reconstructions and to identify the role of sediment recycling during progressive foreland evolution.

1. Introduction

Sedimentary provenance studies have long contributed elucidating source-to-sink processes in a wide range of tectonic settings across the geological time. During the past decade, detrital zircon U—Pb geochronology has seen an important proliferation due to rapid data acquisition via laser-ablation inductively-coupled-plasma mass-spectrometry and became a powerful and widely-applied provenance tool in a plethora of case studies around the globe (e.g., Davis and Lin, 2003; Fedo et al., 2003; Gillis et al., 2005; Gehrels, 2014). This approach is based on the fact that zircon is a heavy mineral that is represented in most crustal rocks and is extremely resistant to weathering and diagenetic processes. Detrital zircon U—Pb provenance studies are chiefly based on distinct and diagnostic differences in source area magmatic ages or sources from recycled sedimentary strata with diagnostic age distributions (e.g., Roback and Walker, 1995; Gillis et al., 2005). Moreover, this technique can be applied to fine-grained deposits, such as siltstones, commonly avoided by other classical provenance techniques, such as sandstone petrographic analyses.

Nonetheless, the resolving power of detrital zircon U—Pb studies can be limited by the presence of multiple source areas with similar or monotonous detrital zircon age distributions, or recycling and/or cannibalization of older siliciclastic sedimentary rocks, potentially yielding a distorted image of the source area (Dickinson et al., 2009; Garzanti et al., 2013). Other limitations such as zircon fertility (Moecher and Samson, 2006; Dickinson, 2008), hydraulic sorting and grain size variations (Garzanti et al., 2009; Malusà et al., 2016) or climatic and weathering effects (Amidon et al., 2005) in the source area, can be complicating factors for a high-resolution and high-fidelity provenance reconstruction. In these cases, it has been shown that these limitations can be (partially) overcome through the integration with other

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provenance techniques or zircon geochemical signatures to help refine interpretations and insights from provenance studies (e.g., Rahl et al., 2003; Dickinson et al., 2009; Nie et al., 2012; Garzanti et al., 2016).

In the southern Pyrenees, the alluvial fan deposits of the Eocene-Miocene Jaca basin record the protracted recycling of the former deep marine turbidites (Puigdefàbregas, 1975). The Eocene Hecho Group turbidites were tilted, uplifted and eroded during folding and thrusting along the tectonically active northern margin of the Jaca basin and recycled and re-deposited into the overlying late Eocene to early Miocene alluvial fan deposits (Puigdefàbregas, 1975; Teixell and García-Sansegundo, 1995; Roigé et al., 2017; Coll et al., 2022). The excellent exposures of the transition from deep-marine to alluvial depositional environments have motivated a substantial number of stratigraphic, sedimentological and structural/tectonic studies (e.g., Soler-Sampere and Puigdefàbregas, 1970; Puigdefàbregas, 1975; Mutti, 1985; Barnolas and Teixell, 1994; Payros et al., 1999; Oms et al., 2003; Remacha et al., 2005; Labaume et al., 2016; Oliva-Urcia et al., 2019; Vinyoles et al., 2020). This extensive research includes provenance studies, mainly applying conventional methods such as sandstone petrography and heavy mineral analysis (Valloni et al., 1984; Fontana et al., 1989; Gupta and Pickering, 2008; Caja et al., 2010; Roigé et al., 2016; Coll et al., 2017; Roigé et al., 2017). These studies, integrated with paleocurrent analysis, have contributed to the knowledge of the evolution of the sediment routing systems during progressive Pyrenean foreland basin development. It has been well documented that a main sediment dispersal reorganization occurred in response to the switch from deep-marine turbidite deposition to fluvial-alluvial sedimentation (Puigdefàbregas, 1975), which coincides with the change from axial sediment delivery, sourced from the east (central and eastern Pyrenees), to transverse-dominated delivery systems with a northern provenance (western Pyrenees). In terms of provenance, this change is characterized by a very different nature in the source area bedrock. It consists of axial sources tapping mainly into Paleozoic basement rocks and Mesozoic carbonate platforms in the central and eastern Pyrenees, while transverse delivery systems were mainly sourced from Mesozoic sedimentary rocks and recycling of Eocene siliciclastic rocks from the southern flank of the western Pyrenees (Puigdefàbregas, 1975; Roigé et al., 2016).

In order to investigate the impact of this major reconfiguration of the catchment areas, we apply for the first time detrital zircon U—Pb analyses in the transition from deep marine to terrestrial deposits of the Jaca basin. The main aim of this study is to (a) characterize zircon populations that are represented in the turbidites, deltas and alluvial fan systems of the Jaca basin, (b) compare these results with more proximal, time equivalents of the nearby Ainsa and Tremp-Graus basins (Whitchurch et al., 2011; Filleaudeau et al., 2012; Michael, 2013; Thomson et al., 2017; Odlum et al., 2019; Thomson et al., 2020), and (c) contribute to the knowledge of the propagation and modification of detrital zircon signatures during recycling processes. With that purpose, the clastic succession of the northern limb of the Jaca basin has been chosen as the main objective of this study because it concentrates the Eocene clastic turbiditic sedimentation (e.g., Mutti, 1985) and also displays the onset of the north-derived alluvial fan sedimentation (Puigdefàbregas, 1975). In order to explore, and ultimately minimize the limitations of detrital zircon U—Pb-based provenance studies, we illustrate the power of integration of the detrital zircon U—Pb results with the sandstone petrography, using results previously published by Roigé et al. (2016) and Roigé et al. (2017).

2. Geological setting

2.1. Geological and stratigraphic framework

The study area is located in the Jaca basin, which constitutes the western portion of the southern Pyrenean foreland basin (Fig. 1A). The Eurasian and Iberian plate collision led to the formation of the Pyrenean fold-and-thrust belt, which grew diachronously as a result of the oblique character of the collision from late Cretaceous to early Miocene times (Roure et al., 1989; Muñoz, 1992; Teixell, 1996; Vergés et al., 2002; Ford et al., 2022). The North Pyrenean Zone (Fig. 1) that forms the northern side of the orogen, preserves parts of the pre-collisional rift axis, and is bordered to the north by the Aquitaine retro-wedge foreland basin (e.g., Masini et al., 2014). To the southern side, known as the South Pyrenean Zone, the shortening was accommodated by a basement-involved thrust stack that in the west-central Pyrenees is composed by four main thrust sheets, including the Lakora-Eaux-Chaudes, Gavarnie, Broto and Guarga thrust sheets, and is flanked to the south by the Ebro basin (e.g., Labaume et al., 2016) (Fig. 1B). This thrust stack involves Paleozoic basement and a cover of pre-orogenic Paleozoic and Mesozoic sedimentary rocks, and in the frontal portion also deformed late Cretaceous-early Miocene foreland basin strata. The Paleozoic basement constitutes the core of the Pyrenean orogen, and is mainly constituted by low-grade Paleozoic metamorphic rocks and Ordovician and Permo-Carboniferous granitoids, that are unconformably overlain either by Permo-Triassic red beds, or directly by early Cretaceous limestones (e.g., Mey et al., 1968; Zwart, 1986). Synorogenic rocks associated with late Santonian to early Miocene shortening deformation constitute the south Pyrenean foreland basin (Séguret, 1972; Nijman and Nio, 1975). This foreland basin recorded a major drainage reorganization in mid-late Eocene times triggered by the progressive fold-and-thrust belt deformation, resulting in the replacement of a predominantly axial drainage network parallel to the orogenic front with a large transverse sediment delivery system coming from the north (Whitchurch et al., 2011).

During Eocene times the Àger and Tremp-Graus basins (Fig. 1A) were characterized by fluvio-deltaic environments and a sediment routing system that funneled sediment axially down the foredeep to the west, and transitioning from fluvio-deltaic to slope and deep-marine turbidite sedimentation in the Ainsa and Jaca basins (Nijman and Nio, 1975; Puigdefàbregas et al., 1992; Caja et al., 2010). In the Jaca basin (Fig. 2), the basin fill consists of deep-marine turbidites of the lower-mid Eocene Hecho Group and the Sabiñánigo and Belsué-Atarés deltas as well as the late Eocene-early Miocene alluvial molasse deposits of the Campodarbe Group, deposited during the overfilled stage of the Jaca basin (Puigdefàbregas, 1975; Labaume et al., 1985; Mutti, 1985; Teixell, 1996; Roigé et al., 2019).

The Lutetian Banastón and Jaca turbidites (Labaume et al., 1985; Oms et al., 2003) constitute the upper part of the Hecho Group and represent sheet-like deep-water fan lobes changing to basin plain facies to the west (Remacha and Fernández, 2003; Remacha et al., 2005), which are punctuated by several carbonate megaturbidites (Fig. 3). These Hecho Group turbidites were fed axially from the east, mainly sourced from erosion of the uplifting central and eastern Pyrenees, including the South Pyrenean Central Unit (Séguret, 1972), and the Ebro massif to the south (Caja et al., 2010; Gómez-Gras et al., 2016; Thomson et al., 2020). The last stage of turbidite sedimentation is represented by channelized facies (e.g., Rapitán channel) transversely derived from emerging new source areas located within the western Pyrenees to the north of the Jaca basin (Remacha and Picart, 1991; Roigé et al., 2016). Deep-water turbidite sedimentation was abandoned during the Bartonian, and the deltaic sedimentation started with the progradation of the Sabiñánigo Sandstone and Belsué-Atarés formations (Canudo and Molina, 1988; Hogan and Burbank, 1996; Oms et al., 2003; Vinyoles et al., 2020), which display competing sourcing from both eastern and northern source areas until the establishment of full-blown alluvial-fluvial environments (Puigdefàbregas, 1975; Roigé et al., 2017). Coastal and alluvial-fluvial deposits of the Jaca basin constitute the so-called Campodarbe Group (Fig. 3), which is often subdivided into the Campodarbe and Bernués formations (Puigdefàbregas, 1975). These represent two main sediment routing systems: an east-derived fluvial system that entered through the southeastern zone of the basin, and north-derived alluvial fan systems that dominated the northern limb of the basin (Puigdefàbregas, 1975; Montes, 2002). The north-derived

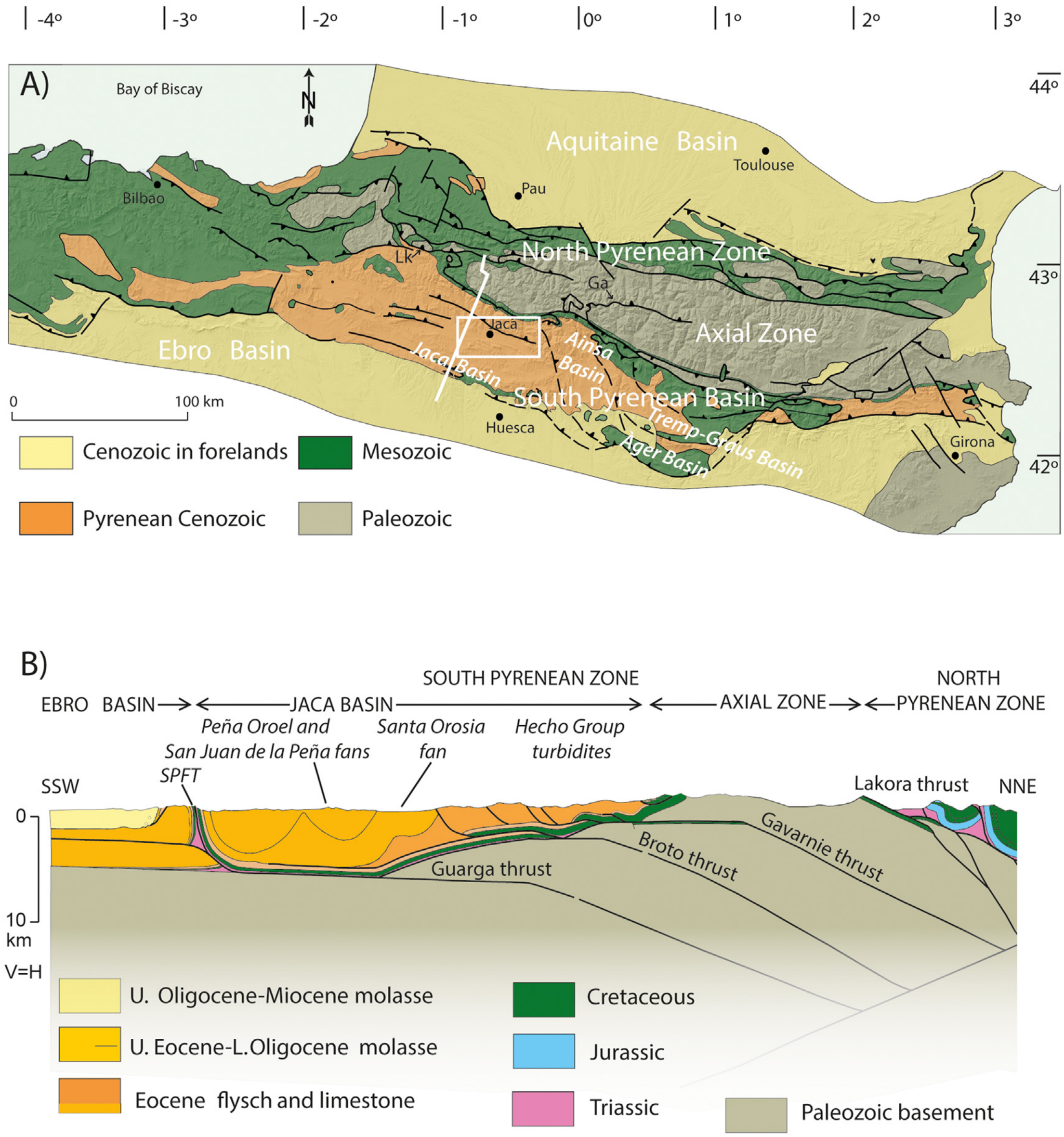

Fig. 1. (A) Simplified geological map of the Pyrenees (redrawn from Teixell, 1996), showing the location of the study area (white frame). White line indicates cross-section in panel B. Lk: Lakora thrust; Ga: Gavarnie thrust. (B) Crustal cross-section of the west-central Pyrenees (simplified from Teixell et al., 2016), showing the South Pyrenean, Axial and North Pyrenean zones. SPFT: South-Pyrenean Frontal Thrust.

alluvial fan deposits, which are the main focus of this study, were mainly sourced from the older Hecho Group turbidites that were uplifted by the Gavarnie thrust as well as Mesozoic and Paleozoic sedimentary and meta-sedimentary units of the South and North Pyrenean Zone (Roigé et al., 2017).

2.2. U—Pb characterization of potential source areas

In order to make sense of the detrital zircon data from the Jaca basin, it is necessary to review the age signatures of the different possible sources. The main potential sediment sources pertinent for this work comprise the different tectonic domains of the eastern, central and western Pyrenees (Fig. 4), including the Paleozoic metasedimentary and igneous basement of the Axial Zone, the preorogenic Mesozoic sedimentary cover successions and early synorogenic late Cretaceous to mid Eocene deposits.

The clastic sedimentary and metasedimentary succession of the Axial Zone (Cambrian-Ordovician-Silurian-Devonian) displays detrital zircon U—Pb signatures dominated by >700 Ma age modes, with an important Cadomian component (ca. 520–700 Ma), and a subsidiary ca. 420–520 Ma population (Hart et al., 2016). Orthogneissic rocks of the crystalline core of the Pyrenees mainly yield early Ordovician protolith ages (Hart et al., 2016; Margalef et al., 2016). Carboniferous strata are characterized by the dominant recycling of Cambro-Devonian zircons and the incorporation of syndepositional volcanic zircons of ca. 325 to ca. 360 Ma (Martínez et al., 2015). The igneous Paleozoic basement rocks have been dated using zircon U—Pb geochronology and are dominated by Variscan granitoids with ages ranging from ca. 280 to ca. 315 Ma in the central Pyrenees. In contrast, the eastern Pyrenees exposes numerous Ordovician orthogneisses containing zircons of ca. 460 to ca. 475 Ma (Whitchurch et al., 2011 and references within) and late Cadomian intrusive and extrusive rocks dated between ca. 540 and ca. 580 Ma (Castiñeiras et al., 2008 and references within). Permian and upper Triassic-lower Jurassic volcanic and subvolcanic rocks in the region are mainly mafic in composition and hence are not expected to contribute with a significant amount of zircon grains (Rodríguez et al., 2013). The zircon ages from these Permian magmatic rocks oscillate between ca. 272 and ca. 278 Ma for the andesites from

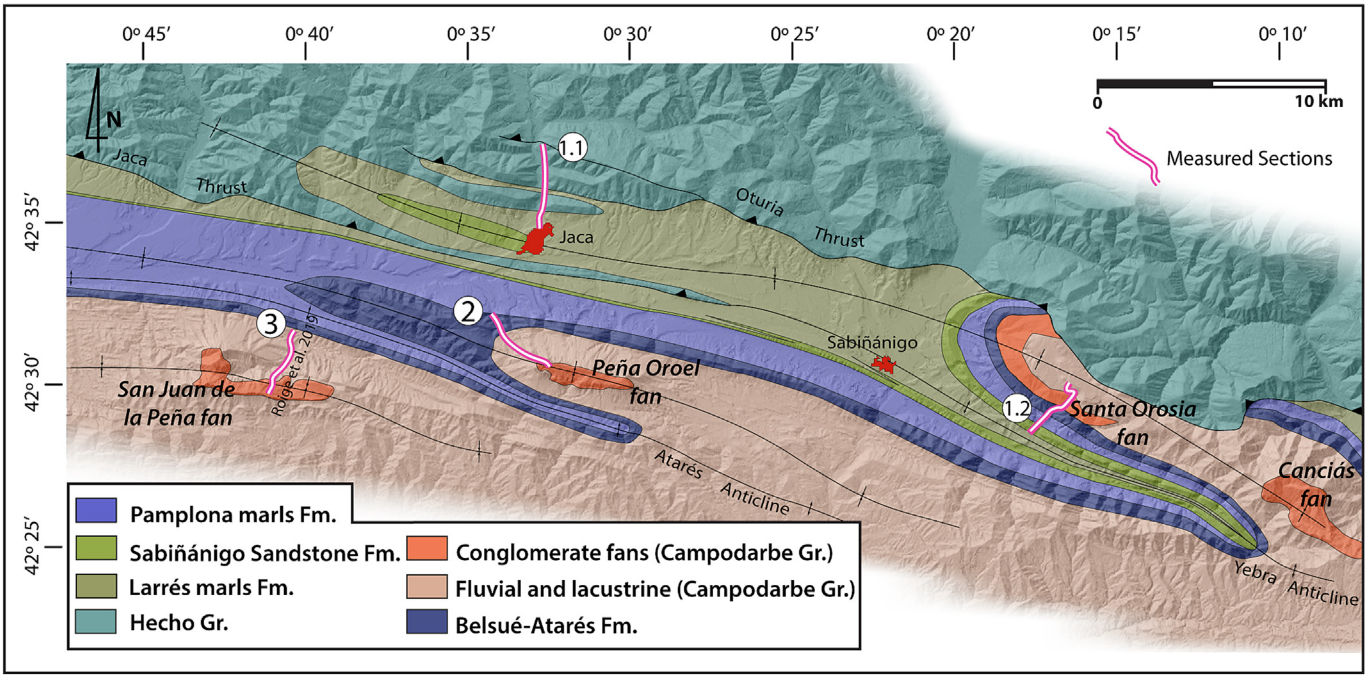

Fig. 2. Geological map of the northern sector of the Jaca basin showing the study area (modified from Puigdefàbregas, 1975). White-purple lines show the location of the three measured sections. Numbers refer to each section: (1.1 and 1.2) Jaca-Santa Orosia composite section; (2) Peña Oroel section; (3) San Juan de la Peña section (published in Roigé et al., 2019).

the western Pyrenees (Briqueu and Innocent, 1993), and 259 ± 3.2 Ma for the basic dykes from the central Pyrenees (Rodríguez et al., 2013). The upper Triassic-lower Jurassic tholeiitic dolerites located in the North Pyrenean Zone display an U—Pb zircon age of 199 ± 2 Ma (Rossi et al., 2003). Permian granitic rocks also exist in the western Pyrenes, like the Aya pluton, which contains zircons of 267.1 ± 1.1 Ma (Denèle et al., 2012). Permian and Triassic clastic deposits are characterized by a main detrital age component ranging from ca. 534 Ma to 719 Ma (Cadomian-Pan-African) and minor Variscan zircons (Hart et al., 2016). Cretaceous siliciclastic rocks are relatively rare but are

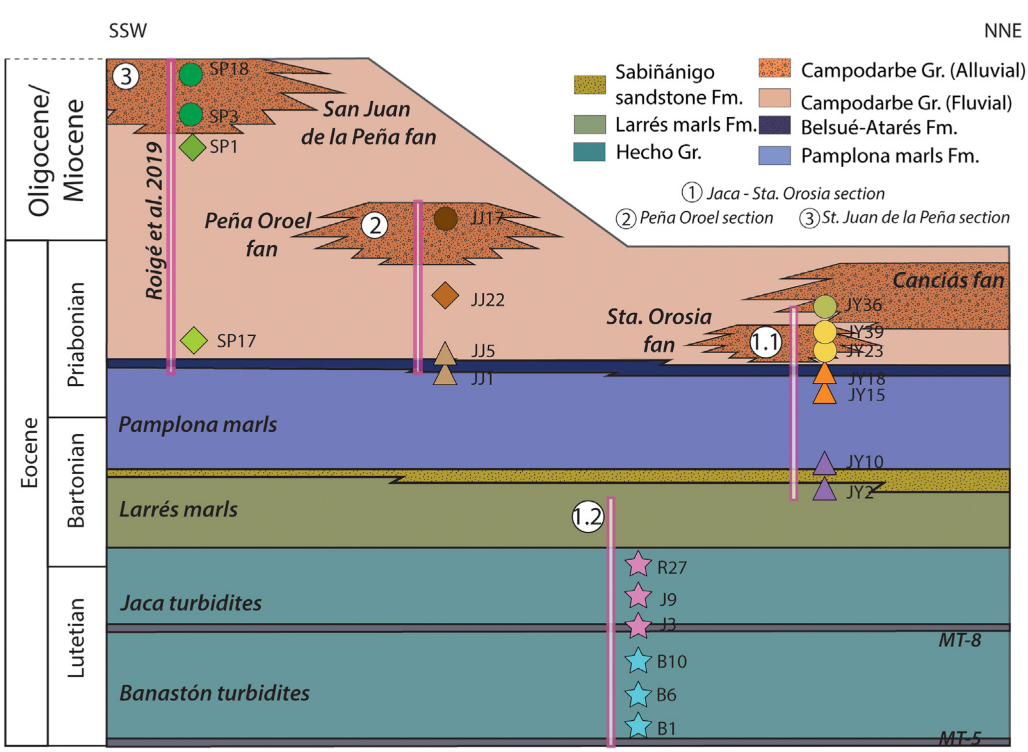

Fig. 3. General stratigraphic sketch summarizing the relationships of the analyzed sedimentary systems of the Jaca basin. Stratigraphic ages extracted from Labaume et al. (1985), Hogan and Burbank (1996) and Oms et al. (2003). White-purple bars indicate the position of the measured stratigraphic logs, and analyzed samples are represented according to their relatively stratigraphic position.

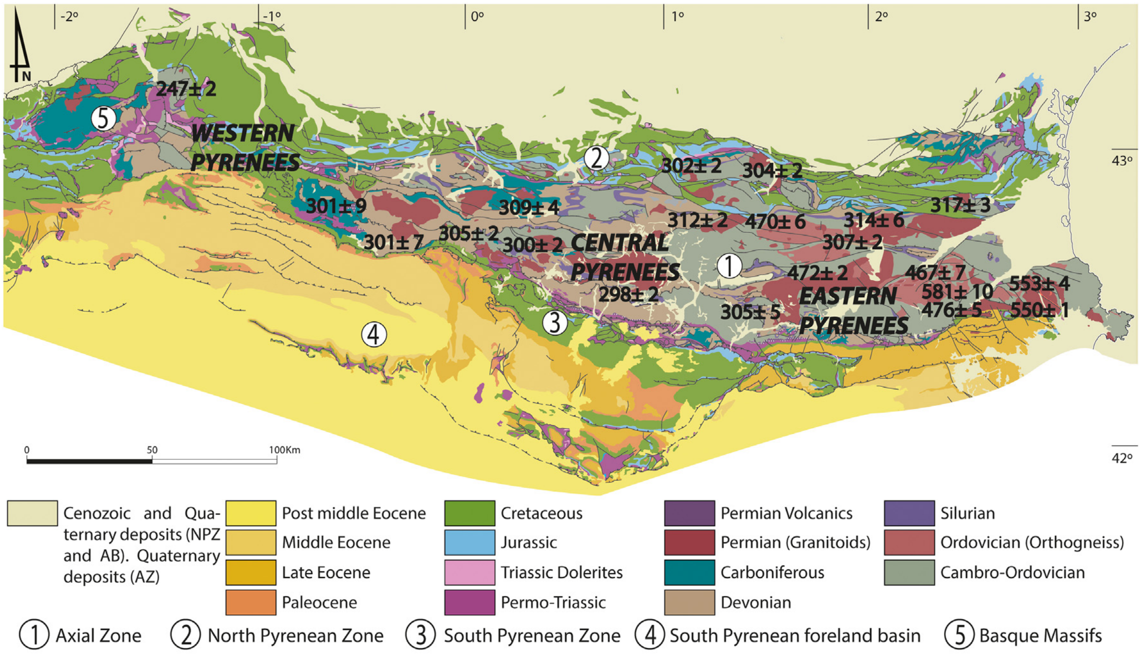

Fig. 4. Geological map of the Pyrenees (modified from synthesis by Rodríguez-Fernández et al., 2015) showing the potential source terrains for the mid Eocene-early Miocene systems of the Jaca basin. Ages with errors refer to zircon U—Pb crystallization ages from igneous rocks of the Axial Zone (extracted from Whitchurch et al., 2011; Denèle et al., 2014; Martínez et al., 2015; Guille et al., 2019; Martí et al., 2019 and references within).

characterized by very different detrital zircon age distributions, ranging from Variscan-dominated signatures in the lower Cretaceous Turbon Formation (Filleaudeau et al., 2012) and in the upper Cretaceous Adraent Formation (Odlum et al., 2019), to Cadomian-dominated signatures for the upper Cretaceous Aren Formation (Whitchurch et al., 2011). Samples from the upper Cretaceous Adraent and Bona formations (eastern Pyrenees) also contain zircons dated at ca. 76 Ma, evidencing the presence of Cretaceous igneous rocks probably located in the Pyrenees and/or the Catalan Coastal Ranges (Odlum et al., 2019). Cretaceous volcanism has also been reported in the North Pyrenean Zone, and in the central and eastern Pyrenees, yielding crystallization ages ranging from ca. 80 to ca. 100 Ma (Ubide et al., 2014). The Paleocene and Eocene strata in the south-central Pyrenean Ainsa, Tremp and Àger basins (Fig. 4) exhibit variable detrital zircon distributions reflecting the evolving provenance of these sedimentary systems, with dominant eastern Pyrenean Cadomian and Ordovician zircons being replaced by dominant central Pyrenean Variscan components through time due to progressive tectonic unroofing and migration of contractional deformation from east to west, and supplementary sources from the Ebro massif providing abundant Cadomian and Variscan components (Whitchurch et al., 2011; Filleaudeau et al., 2012; Thomson et al., 2017; Odlum et al., 2019; Thomson et al., 2020). Finally, the Oligo-Miocene calc-alkaline magmatism in the Mediterranean basin related to the opening of the Valencia Gulf (Martí et al., 1992) could supply Cenozoic zircons transported by ash clouds (Roigé et al., 2019).

The variability on zircon fertility among all the described source lithologies might have an impact on the amplitudes of detrital zircon age distributions of the studied deposits (Moecher and Samson, 2006; Dickinson, 2008; Malusà et al., 2016). While no quantitative studies exist regarding zircon fertility in the Pyrenees, Thomson et al. (2017) described a qualitative approach. Variscan granitoids are likely to have the highest zircon fertility, while fine-grained Cambro-Ordovician metasedimentary formations are expected to have only moderate zircon fertility (Hart et al., 2016). Triassic sandstones are in contrast expected to have a high zircon fertility due to their dominant arkosic composition and sourcing from crystalline basement. Cretaceous to Paleocene formations are mainly represented by carbonates, and are therefore, expected to have a very low to negligible zircon fertility.

Eocene clastic formations, including the Hecho Group turbidites, are here assumed to be moderate in zircon fertility, depending mainly on their sandstone compositional variations. Turbidites with high carbonate rock fragments are expected to have a lower fertility than those with higher amounts of siliciclastic content. Among the siliciclastic fraction of these turbidites, sourcing from felsic igneous rocks will produce higher zircon fertility when compared to sourcing of metasedimentary basement rocks.

Variations in zircon fertility and even grain size of the source rocks are likely assumed to present a secondary effect in the Pyrenees and do not affect presence or absence arguments with respect to detrital zircon modes. Nonetheless, comparison with other provenance techniques like sedimentary petrography is applied in this work to explore this effect.

3. Samples and methods

For this study, we measured and sampled for detrital zircon U—Pb geochronology the Jaca and Santa Orosia sections (these two are combined into a composite section), and the Peña Oroel section (Fig. 2). Samples from the Jaca section belong entirely to the Hecho Group turbidites, and represent the deep marine environments of the basin, while samples from the Santa Orosia section record the first irruption of deltaic and alluvial environments (Fig. 3). Samples from the Peña Oroel section, located to the west of the Santa Orosia section, are also collected from the deltaic units and the overlying thick conglomerate units. In total, twenty samples (2–5 kg) were collected from these stratigraphic sections (Figs. 2, 3) selecting the most representative outcrop exposures. Samples were collected from medium to coarse sandstone beds, avoiding locally reworked deposits to minimize the effects of hydrodynamic grain size fractionation (Malusà et al., 2016). Following the standard heavy mineral separation methods, samples were crushed and sieved to obtain the <250 μm fraction (e.g., Gehrels, 2000; Fedo et al., 2003; Gehrels et al., 2008). Zircon grains were concentrated using the Gemini water table and separated using Frantz isodynamic magnetic separation and Bromoform and Methylene Iodide heavy liquid separations. Mineral separation was performed in the heavy mineral separation laboratory of the Department of Biological, Geological and Environmental Sciences of the University of Bologna according to procedures described by Mange and Maurer (1992). All U—Pb analyses were performed at the UTChron facility at the University of Texas at Austin. Zircon grains were mounted onto double-sided adhesive plastic pucks and left unpolished for depth-profile analysis (Campbell et al., 2005; Gehrels et al., 2008; Hart et al., 2017). For each sample, 120 zircons were selected randomly and analyzed using the laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) U—Pb geochronology (see supplementary data for detailed methodology), in order to obtain a statistically robust and representative provenance dataset (Vermeesch, 2004).

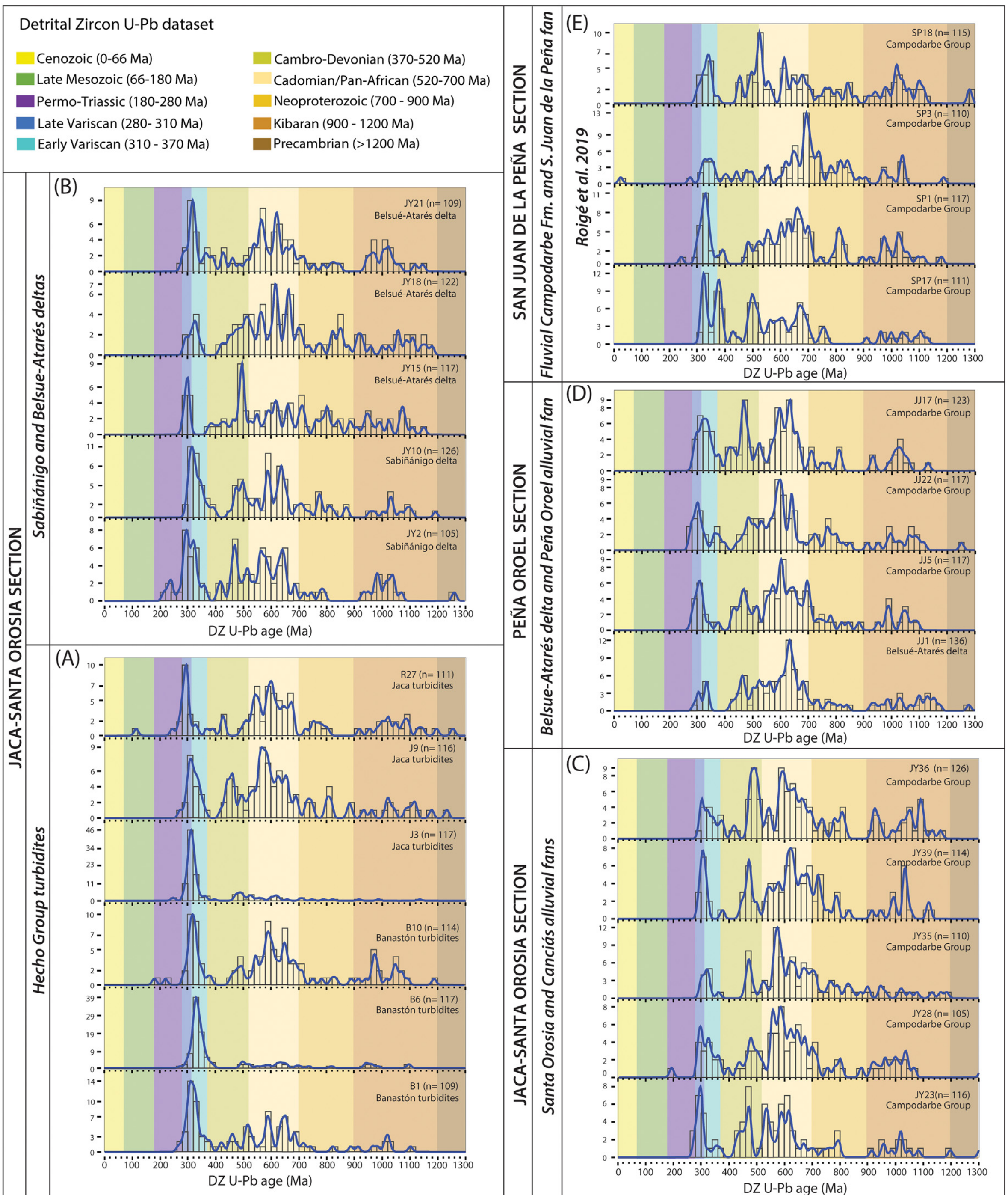

Fig. 5. Detrital zircon U—Pb results for the Jaca section, which includes (A) the Hecho Group turbidites; (B) the Sabiñánigo and Belsué Atarés deltaic units and (C) the Santa Orosia and Canciás alluvial fan systems, and also the (D) Peña Oroel and (E) San Juan de la Peña sections (see location in Fig. 3). Detrital zircon U—Pb results are represented as Kernel density estimators (KDE) and histogram diagrams from 0 to 1300 Ma. Non-adaptative KDE bandwidth of 8 Ma; histogram bin width of 20 Ma.

Detrital zircon U—Pb results for the San Juan de la Peña section (Fig. 2) are already published in Roigé et al. (2019) and are here included for integration with the results of the Jaca-Santa Orosia and Peña Oroel sections (Fig. 5). Results from published sandstone petrography analyses obtained by Roigé et al. (2016) and Roigé et al. (2017) from the Jaca and Santa Orosia sections are coupled (see supplementary data) with the new U—Pb detrital zircon provenance data to refine provenance interpretations and to address and quantify the role of sediment recycling and cannibalization of older foreland basin strata within the deforming fold and thrust belt.

We applied Multi-Dimensional Scaling (MDS) and Correspondence Analysis (CA) as exploratory compositional data analysis tools to assess similarities/dissimilarities between samples (Vermeesch, 2012; Vermeesch, 2018). Results are displayed as biplots to facilitate the visualization and result interpretation. Statistical treatment was done using the Provenance R-package (Vermeesch et al., 2016; Vermeesch, 2018).

4. Results

In summary, detrital zircon U—Pb LA-ICP-MS analysis of twenty samples from the three measured sections (Jaca, Santa Orosia and Peña Oroel sections) in the Jaca basin yielded a total of two thousand four hundred fifty-five grain ages (see supplementary data for full data). All detrital zircon U—Pb results are shown as percentages of components (Table 1) as kernel density estimation plots (KDE; Vermeesch, 2012) and histogram diagrams in Fig. 5 and as pie charts in Fig. 6. Detrital zircon age populations are subdivided as follows: 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) and Precambrian (>1200 Ma).

The Jaca section starts with the Banastón turbidites (Lutetian), which are the oldest rocks analyzed here. Samples from these turbidites (samples B1, B6 and B10) are dominated by Variscan age components (ca. 280 to ca. 370 Ma). At the base of this system early Variscan ages are more abundant (up to 57 %, sample B6), displaying a main age mode of ca. 330 Ma (Figs. 5A, 6). Upsection, the age mode of these Variscan ages decreases and is also progressively replaced by a Cadomian age component (up to 37 % of ca. 520–700 Ma component). The overlying Jaca turbidites (samples J3 and J9) display a similar trend and start with a marked increase on the Variscan ages (~67 %), while upsection this age component decreases and is also replaced by Cadomian (~35 %) and >700 Ma age modes (Figs. 5A, 6).

The youngest turbidite system, represented by the Rapitán channel (sample R27), shows a major reduction in the Variscan detrital zircon component (~14 %), while Cadomian (~36 %) and >700 Ma (~40 %) ages dominate (Figs. 5A, 6). The Rapitán channel also marks the first occurrence in the section of Mesozoic detrital zircon grain ages with age peaks at ca. 115 Ma and ca. 250 Ma.

The Santa Orosia section forms the middle portion of our composite section of the Jaca basin and stratigraphically sits atop of the Jaca section (Fig. 6). When compared to the last turbidites from the Rapitán channel (sample R27), the first deposits of the Sabiñánigo delta (samples JY2 and JY10) display even a more pronounced Permian-Triassic age component, ranging from ca. 200 to ca. 280 Ma (up to 5 %), and a persistent occurrence of the Cadomian age mode (~29 %). Variscan detrital zircon grains slightly increase (~22 %, sample JY10). The overlying Atarés delta (samples JY15, JY18 and JY21) exhibits an upsection decrease in Variscan detrital zircon ages (~8 %), while Cadomian and >700 Ma detrital zircon ages dominate (~23 % and 52 % respectively) (Figs. 5B, 6).

The first alluvial conglomerates of the Jaca basin in the Santa Orosia fan (samples JY23, JY28, JY35 and JY39) and Canciás fan (sample JY36) are all characterized by three main age modes at ca. 280 to ca. 380 Ma, ca. 450 to ca. 850 Ma and ca. 900 to ca. 1200 Ma. Overall, these alluvial fan deposits exhibit homogenous age distributions with only minor upsection changes. While in general rather monotonous, the late Variscan component decreases toward the upper part of the section (ranging from 3 % to 10 %) while the input of Cadomian (up to 43 %) and >700 Ma (up to 25 %) detrital zircon ages increase (Figs. 5C, 6).

Toward the west of the Santa Orosia section, the Belsué-Atarés deposits in the Peña Oroel section (samples JJ1 and JJ5) also display detrital zircon age spectra dominated by Cadomian detrital zircon grains (36 to 37 %) with minor Variscan U—Pb ages (~8 %) (Figs. 5D, 6). The overlying conglomerates of the Peña Oroel fan (samples JJ17 and JJ22) show similar detrital zircon age distributions, with a slight increase on Variscan U—Pb ages (~15 %) and Cambro-Devonian (dominant peak at ca. 475 Ma) detrital zircon ages. Overall, detrital zircon ages ranging from ca. 440 Ma to ca. 880 Ma dominate (>50 %) through all these alluvial fans and display detrital zircon age distribution similar to those of the Santa Orosia fan samples.

Multi-Dimensional Scaling (MDS) and correspondence analysis (CA) allow to visualize the main trends of the Jaca basin samples based on age populations (Figs. 7A, B) and age components (Figs. 7C, D). All the biplots display a clear differentiation between the turbidites (mainly samples belonging to the lower segment of

Table 1
Detrital zircon U—Pb results of the mid Eocene-Oligocene Jaca basin deposits summarized in component percentages.

Section	Formation	Sample	n	0–65	65–180	180–280	280–310	310–370	370–520	520–700	700–900	900–1200	>1200
Jaca-Santa Orosia	Banaston turbidites	B1	108	0.0	0.0	1.9	10.2	19.4	12.0	27.8	4.6	7.4	16.7
Jaca-Santa Orosia	Banaston turbidites	B6	116	0.0	0.0	0.9	5.2	56.9	7.8	12.1	2.6	6.9	7.8
Jaca-Santa Orosia	Banaston turbidites	B10	113	0.0	0.0	1.8	6.2	15.0	8.8	37.2	6.2	15.0	9.7
Jaca-Santa Orosia	Jaca turbidites	J3	116	0.0	0.0	1.7	26.7	40.5	9.5	12.1	4.3	2.6	2.6
Jaca-Santa Orosia	Jaca turbidites	J9	116	0.0	0.0	0.9	5.2	10.3	12.9	37.9	8.6	9.5	14.7
Jaca-Santa Orosia	Rapitán channel	R27	110	0.0	0.9	2.7	11.8	2.7	6.4	35.5	6.4	15.5	18.2
Jaca-Santa Orosia	Sabiñánigo delta	JY2	105	0.0	0.0	4.8	10.5	10.5	16.2	28.6	3.8	12.4	13.3
Jaca-Santa Orosia	Sabiñánigo delta	JY10	125	0.0	0.0	0.0	5.6	17.6	14.4	28.8	11.2	9.6	12.8
Jaca-Santa Orosia	Atarés delta	JY15	111	0.0	0.0	0.0	9.0	0.0	18.0	19.8	17.1	15.3	20.7
Jaca-Santa Orosia	Atarés delta	JY18	121	0.0	0.0	0.0	2.5	5.0	12.4	27.3	11.6	14.0	27.3
Jaca-Santa Orosia	Santa Orosia fan	JY21	109	0.0	0.0	0.9	3.7	14.7	10.1	33.9	7.3	15.6	13.8
Jaca-Santa Orosia	Santa Orosia fan	JY23	115	0.0	0.0	2.6	10.4	2.6	13.9	28.7	6.1	9.6	26.1
Jaca-Santa Orosia	Santa Orosia fan	JY28	105	0.0	0.0	1.0	5.7	8.6	11.4	36.2	7.6	12.4	17.1
Jaca-Santa Orosia	Santa Orosia fan	JY35	110	0.0	0.0	0.0	2.7	6.4	9.1	43.6	15.5	10.0	12.7
Jaca-Santa Orosia	Santa Orosia fan	JY39	113	0.0	0.0	0.0	7.1	3.5	11.5	36.3	10.6	12.4	18.6
Jaca-Santa Orosia	Canciás fan	JY36	125	0.0	0.0	0.0	4.0	5.6	18.4	32.8	8.0	18.4	12.8
Peña Oroel	Atarés delta	JJ1	135	0.0	0.0	0.0	3.0	3.7	11.9	36.3	5.9	13.3	25.9
Peña Oroel	Atarés delta	JJ5	116	0.0	0.0	0.0	6.9	4.3	15.5	37.1	8.6	9.5	18.1
Peña Oroel	Peña Oroel fan	JJ22	110	0.0	0.0	2.7	7.3	4.5	13.6	34.5	11.8	11.8	13.6
Peña Oroel	Peña Oroel fan	JJ17	122	0.0	0.0	0.0	4.9	12.3	19.7	31.1	6.6	9.0	16.4

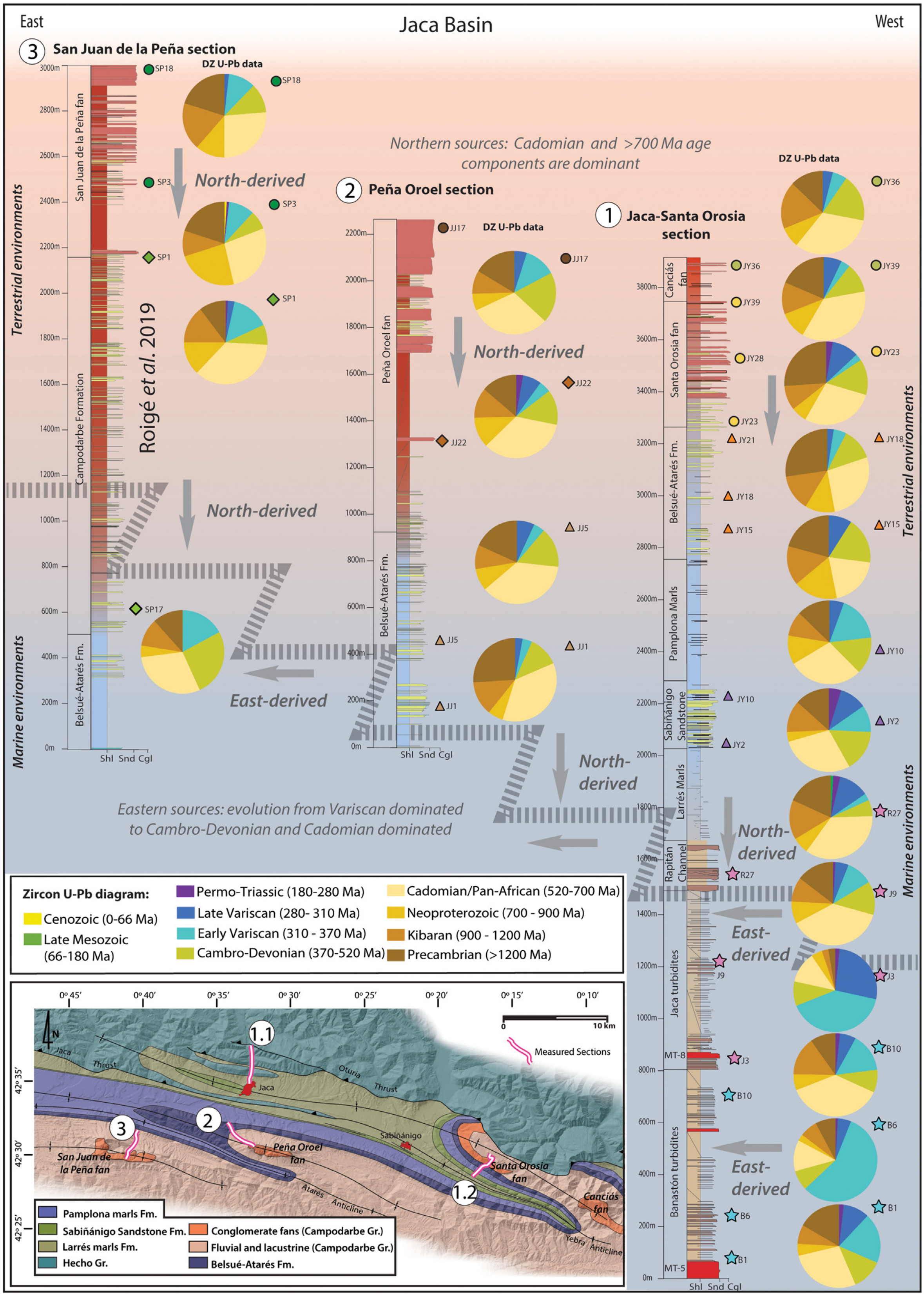

Fig. 6. Stratigraphic sections of Jaca-Santa Orosia, Peña Oroel and San Juan de la Peña showing the transition from deep-marine to terrestrial environments of the Jaca basin. Detrital zircon U—Pb results are represented along the sections as pie charts.

each turbiditic system), which exhibit the highest contents of Variscan aged zircons, and the overlying delta and alluvial deposits, which are characterized by Cadomian and >700 Ma age populations.

Among the turbidite samples, it is important to note that the Rapitán sample (R27) can be clearly grouped with the overlying alluvial fan samples (Fig. 7A, B).

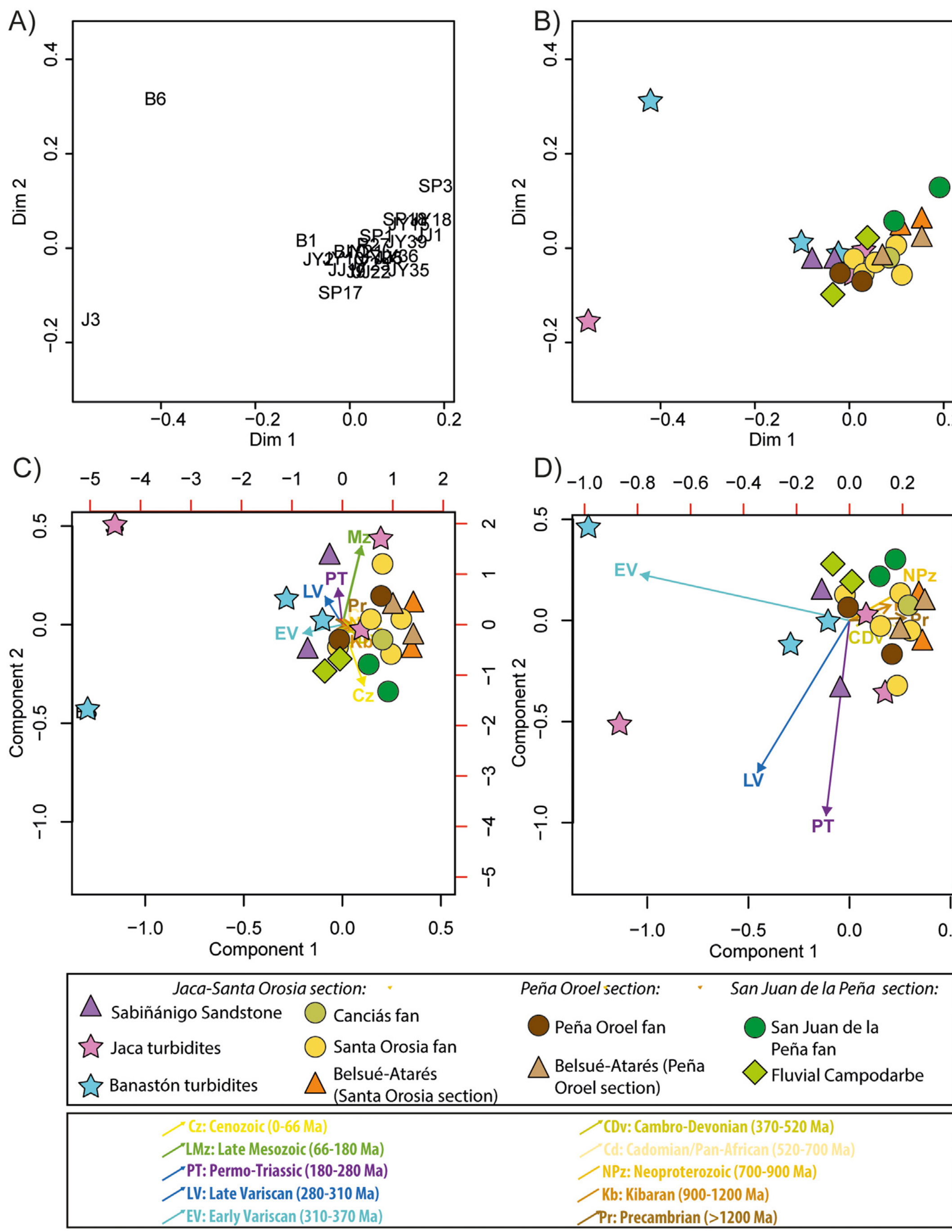

Fig. 7. Multi-Dimensional Scaling (MDS) of U—Pb ages of the Jaca basin displayed with: (A) sample names and (B) sample symbols. Correspondence Analysis (CA) of U—Pb age components of the Jaca basin, where (C) includes all the detrital zircon U—Pb age components, while (D) shows all the detrital zircon U—Pb age components excepting the Cenozoic and late Mesozoic age components (0–180 Ma) which are only represented in two samples (samples R27 and SP3).

5. Discussion

5.1. Detrital zircon U—Pb data coupled with sandstone petrography

In this study, we integrate previous sandstone petrographic data with the detrital zircon U—Pb dataset to compare and complete the detrital provenance dataset, to refine provenance interpretations in the Jaca basin and the entire south Pyrenean foreland basin, and to identify the role of sedimentary recycling and its impact on provenance interpretations. The sandstone petrography results were already published in Roigé et al. (2016, 2017) and are summarized in Fig. 8 in order to illustrate the main compositional trends.

A composite section through the marine to continental basin fill, constructed from the Jaca and Santa Orosia transects, shows clear changes upsection in the detrital zircon U—Pb age spectra. These changes are characterized by the replacement of the initially dominant Variscan detrital zircon age component by Cadomian and >700 Ma age components, which become dominant in the stratigraphically higher units (Fig. 8). Sandstone petrography records a simultaneous compositional shift with the replacement of siliciclastic, metamorphic and plutonic rock fragments by recycled turbidite fragments. In the Hecho Group turbidite section, samples with higher ca. 280 to 310 Ma (late Variscan) age peaks, show a higher proportion of K-feldspar and plutonic rocks fragments (Fig. 8). In contrast, those rich in early Variscan

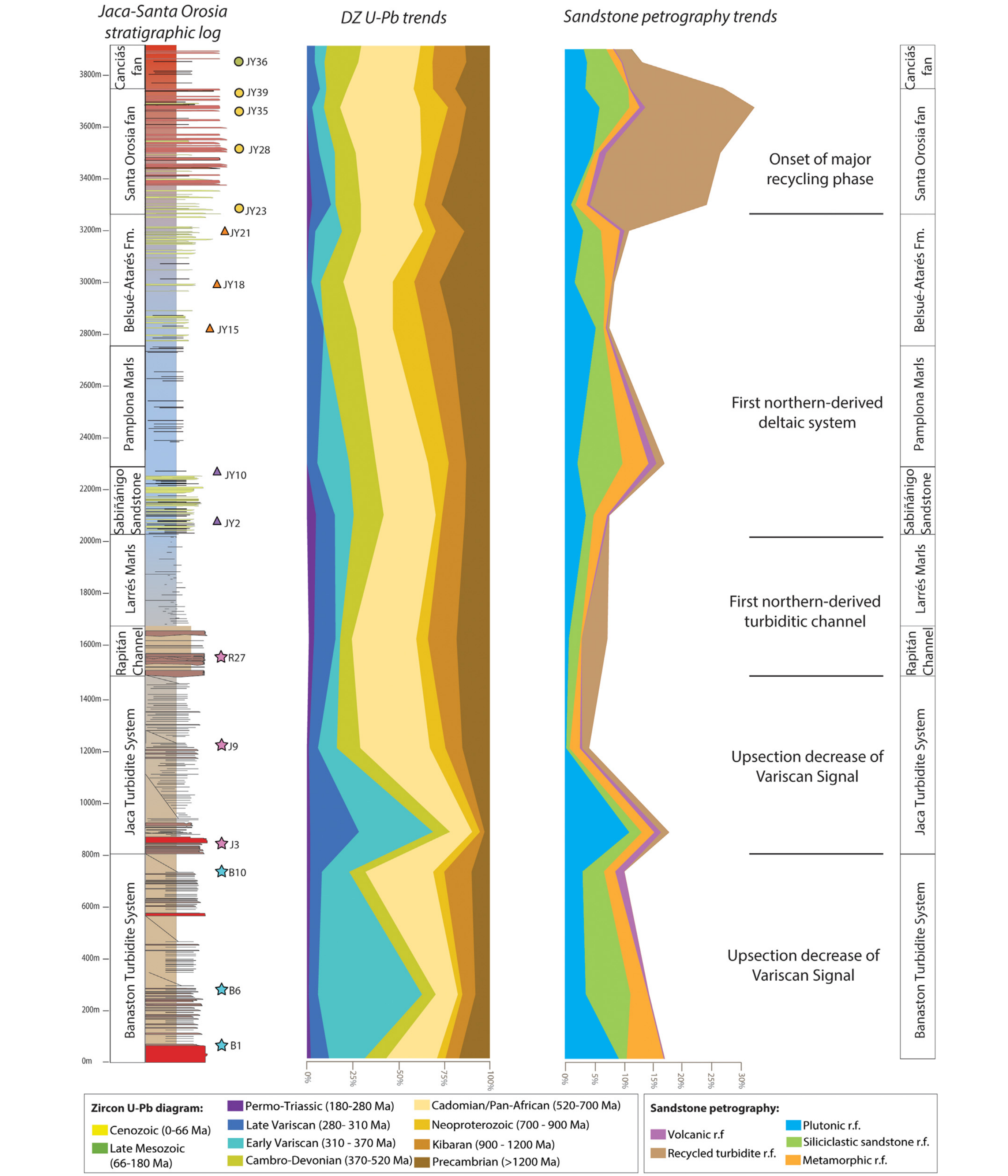

Fig. 8. Jaca-Santa Orosia stratigraphic section with detrital zircon U—Pb age trends faced with the sandstone petrography compositional trends of the main components able to provide zircons. Sandstone compositional modes are extracted from Roigé et al. (2016, 2017).

detrital zircon ages are associated with higher concentrations of sandstone and metamorphic rock fragments (Fig. 8). Based on Pyrenean source characteristics, we conclude that late Variscan detrital zircon spectra in conjunction with plutonic rock fragments are indicative of direct supply from the late Variscan granitoids (i.e. Denèle et al., 2014), while early Variscan detrital zircon signatures coupled with siliciclastic sandstone rock fragments suggest erosional derivation from the Carboniferous flysch (Martínez et al., 2015). No correlation between volcanic rock fragments and Permo-Triassic detrital zircon ages is observed, which is consistent with the low fertility of the upper Triassic sub-volcanic mafic rocks in the Pyrenees (Rodríguez et al., 2013). As observed in Fig. 7, the percentage of late Variscan detrital zircon ages is very sensitive to small variations in the concentration of plutonic rock fragments, likely resulting from the high zircon fertility of the crystalline rocks in the source area. In contrast, fluctuations in the proportion of recycled turbidite sandstones appear to have only a minor impact on the detrital zircon age distributions, which remain fairly constant in the younger deltaic and alluvial fan deposits (Fig. 8).

Moreover, a bipartite provenance pattern can be identified from the coupled sandstone petrography and detrital zircon U—Pb data in the turbidite packages, which can be linked to tectono-stratigraphic cycles. In the Banastón and Jaca turbidite systems, Variscan detrital zircon components and plutonic rock fragments both decrease upsection, while Cadomian detrital zircon ages increase – a trend that is repeated within individual stratigraphic packages bound by sequence boundaries (Fig. 8). This cyclicity has been already identified in these Pyrenean turbidite systems, where proportions of intrabasinal carbonate grains also increase from base to top of each turbiditic system (Fontana et al., 1989; Caja et al., 2010; Roigé et al., 2016). The relatively reduced contribution of intrabasinal components at the base of each turbiditic system has been associated with increased tectonic activity and associated relative sea level fall (lowstand stage) (Fontana et al., 1989), which coincides with the highest contributions of Variscan detrital zircon components and plutonic rock fragments. On the other hand, the increase of carbonate intrabasinal components toward the uppermost part of each turbidite system is associated with episodes of carbonate platform development related to reduced tectonic activity and relative sea level rise (highstand stage), which coincides with the record of dominant Cadomian detrital zircon components. Therefore, we interpret these compositional trends as the product of tectono-stratigraphic cycles (i.e., each turbidite system), which are comprised within the larger scale basin cyclicity (i.e., Jaca-Santa Orosia section). We hypothesize that lowstand stages, the enhanced tectonic activity yielded to high erosion rates in the headwater catchments, where the Variscan granitoids largely cropped out (Axial Zone), and subsequent fluvial incision due to base-level lowering transferred efficiently the distant Variscan detrital zircon signal to the deep-marine sink (Fig. 9A). Conversely, during periods of relative sea level rise the fluvial graded profile and sedimentary systems became less erosive, and therefore the transmission from the Axial Zone Variscan detrital zircon signals was less effective and Variscan zircons were partially trapped in intramountainous basins, located upstream. Thus, during highstand periods the turbidite wedge received a diluted signal from the Axial Zone resulting into a relatively enriched Cadomian detrital zircon signal derived from the erosion of the more proximal South-Central Pyrenean cover rocks (Fig. 9B). Similar trends associated to sea level and climate fluctuations have also been identified in the Amazon river (Mason et al., 2019), where detrital zircon populations are also interpreted to be sensitive to periods of rise and fall of the sea level.

5.2. Provenance evolution of the Jaca basin

Published data on facies architecture, paleocurrents and sandstone petrographic analyses on the Hecho Group turbidites from the Jaca basin allow to infer a persistent sediment provenance derived from the east for most of the foredeep stage (e.g., Soler-Sampere and Puigdefàbregas, 1970; Remacha and Fernández, 2003; Caja et al., 2010). The detrital zircon U—Pb age spectra and their progressive evolution in the Banastón and lower Jaca turbidites are very similar to those documented for the proximal stratigraphic age equivalents in the upper Hecho Group of the Ainsa basin (Whitchurch et al., 2011; Thomson et al., 2017). The dominant Variscan ages (Figs. 7, 8) indicate erosion of Variscan plutonic rocks of the central Pyrenees, which were located farther to the east of the studied area (Fig. 9). The presence of apatite in the heavy mineral suite also supports erosion from plutonic sources (Coll et al., 2020). In contrast, the uppermost turbidites (Rapitán channel) display a pronounced change in the detrital zircon ages (Figs. 7, 8) which is likely associated with a switch in sediment routing signaling the replacement of central Pyrenean sources by a northern source in the western Pyrenees, constituted by less Paleozoic igneous basement rocks, and more Paleozoic metasedimentary rocks and Mesozoic and Cenozoic sedimentary strata. This scenario is supported by the presence of 250 Ma zircons derived from Triassic sub-volcanic rocks and 115 Ma zircons (Fig. 7C) likely sourced from Aptian volcanic rocks within the Early Cretaceous *syn*-rift successions of the western Pyrenees (Rossy et al., 1992). Paleocurrents (Remacha and Picart, 1991), sandstone petrography (Roigé et al., 2016), and the heavy mineral association (Coll et al., 2020) also support this paleogeographic configuration, where the activity of the Lakora-Eaux Chaudes thrust (Labaume et al., 2016) would have promoted the creation of newly emerged terrains toward the north of the Jaca basin.

During the Bartonian, the end of the turbidite sedimentation preceded the first deltaic incursions in the basin, represented by the Sabiñánigo and the Belsué-Atarés deltas (Puigdefàbregas, 1975). These deltas are characterized by the continued occurrence of an important Cadomian age mode (~29 %) supporting a persistent input from northern source areas (Figs. 5E, 6), accompanied by the introduction of significant amounts of volcanic rock fragments and some plutonic and metamorphic detritus (Roigé et al., 2016). The persistence of transverse, north-derived systems, would have been promoted by the activity of tectonic structures (such as the Yebra de Basa and Atarés anticlines; Labaume et al., 2016) (Fig. 2), that could have prevented the axial, east-derived systems reaching the northern sector of the Jaca basin (Roigé et al., 2017). The onset of the alluvial sedimentation of the Jaca basin (Bartonian-Priabonian according to Vinyoles et al., 2020) does not exhibit any important change in the detrital zircon spectra and only minor upsection changes can be identified (Figs. 7, 8), supporting the continuous erosion of a persistent northern source area composed by the Hecho Group turbidites. This is evidenced by the high contents of recycled turbidite clasts (Puigdefàbregas, 1975) and the ultrastable (zircon-turmaline-rutile) heavy mineral association resulting from the high degree of recycling in the Santa Orosia and Canciás alluvial fans (Coll et al., 2020).

A similar trend can be identified in the Peña Oroel section, located farther to the west, where the Belsué-Atarés deltaic deposits display a detrital zircon age dataset very similar to that recorded in the Santa Orosia fan (Figs. 6, 7), supporting the proposed stratigraphic synchroneity of these deposits based on sandstone compositional data (Roigé et al., 2017). On top of this section, the Peña Oroel alluvial conglomerates still show Cadomian-dominated detrital zircon populations pointing to the persistence of northern sources which dominate the alluvial sedimentation of the northern part of the basin during the late Eocene-early Oligocene. As for the Santa Orosia and Canciás fans, the pebble population points to a northern source area mainly constituted by the former Hecho Group turbidites (uplifted by the activity of the Gavarnie thrust), and by the Mesozoic cover and Paleozoic basement rocks from the North Pyrenean Zone, as evidenced by documented diagnostic pebbles (e.g., the calcareous Cenomanian-Turonian flysch) (Roigé et al., 2017).

The San Juan de la Peña section, already published in Roigé et al. (2019), is genetically correlated with the Peña Oroel and Jaca-Santa Orosia sections (located to the east), and detrital zircon results are here integrated for a better understanding of the sediment routing functioning of the Jaca basin (Figs. 5E and 6). The fluvial Campodarbe Formation detrital zircon suite is dominated by Cambro-Devonian and Cadomian age components but it lacks the late Variscan signature (Figs. 6, 7). The presence of early Variscan and Cambro-Devonian detrital zircon U—Pb age components in this fluvial system is consistent with the erosion and recycling of Carboniferous flysch (Roigé et al., 2019), while the Cadomian age peaks can be linked to the central Axial Zone based on petrographically observed metamorphic rock fragments (Roigé et al., 2017). All these compositional attributes together

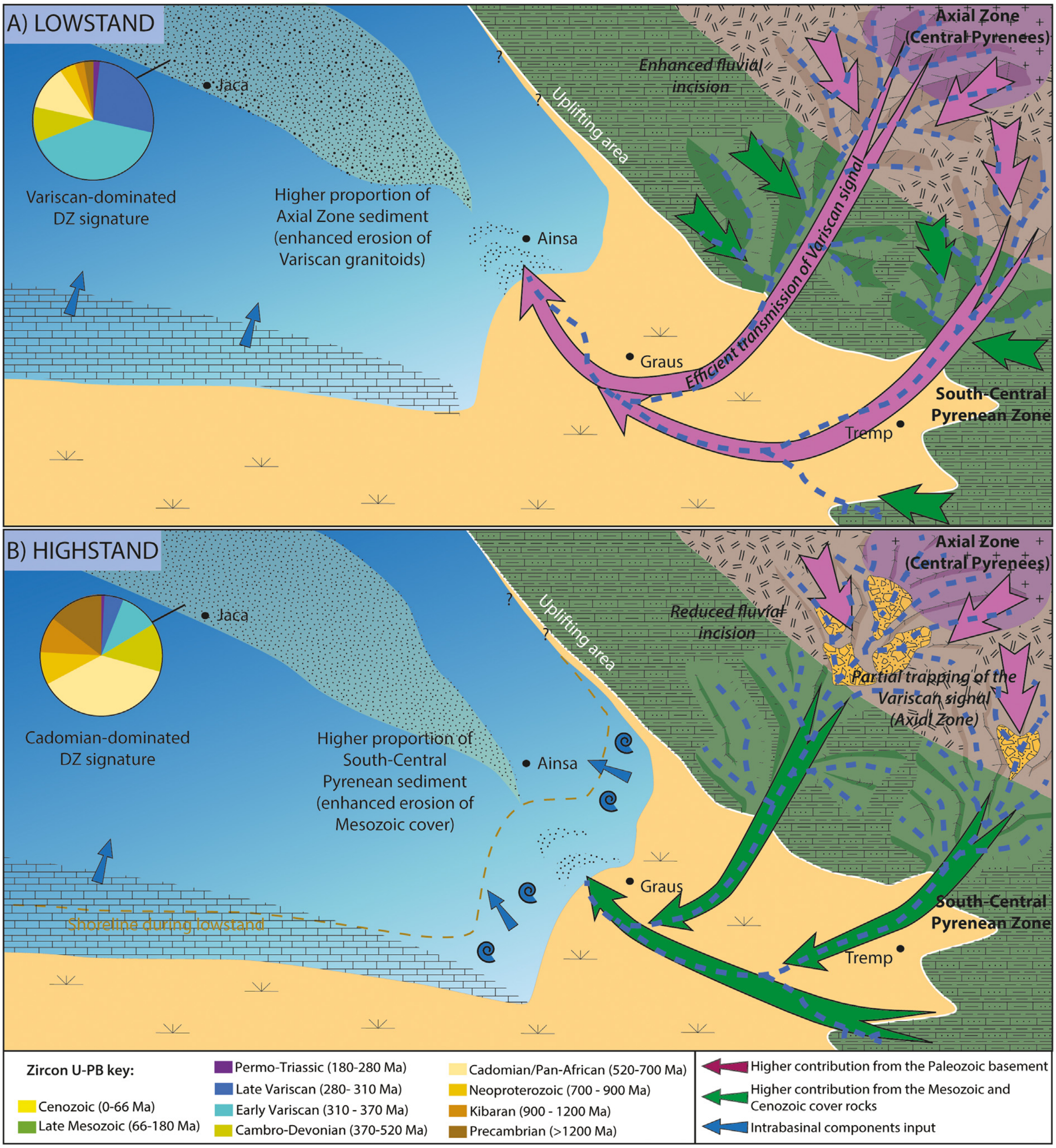

Fig. 9. Paleogeographic interpretation of the sediment routing system functioning of the South-Central Pyrenean basin during (A) lowstand and (B) highstand periods. The lowstand turbidite wedge received an increased Variscan signal derived from the enhanced erosion of the Variscan plutons (Axial Zone), located in the uppermost course of the drainage area (headwaters of the source area). In contrast, the lowered river incision during highstand sea level produced a reduction of the transport efficiency, which resulted on a relatively higher proportion of sediment derived from the Mesozoic and Cenozoic cover rocks (cropping out in the lower, more proximal segment of the source area).

with the west-directed paleocurrents (Montes, 2002) allow to interpret these fluvial deposits as an axial, east-derived, sediment routing system, fed from an eastern source area located in the central Pyrenees. In contrast, the overlying conglomeratic beds of the San Juan de la Peña show a decrease in the 360 to 400 Ma detrital U—Pb zircon signal, suggesting a lack of significant contributions from the Paleozoic crystalline basement. The pebble population of this alluvial fan is dominated by Hecho Group turbidite clasts, which can reach proportions up to 85 % of the total framework clasts (Roigé et al., 2017). This change can be directly related to a provenance shift resulting from the transition from axial, east-derived fluvial to transverse, north-derived alluvial systems as described by Puigdefàbregas (1975). The presence of Miocene volcanic zircons in these alluvial deposits implies a Miocene maximum deposition age for the San Juan de la Peña fan. This Miocene age allows to infer a particular paleogeographic evolution during the last episodes of basin infill, where sediment accumulation in the Jaca basin was simultaneous to erosion of some sectors of the basin which were resedimented into the main Miocene alluvial fans of the Ebro foreland basin (Roigé et al., 2019).

5.3. Evolution of the south Pyrenean basin source areas

The late Cretaceous-early Miocene strata of the south Pyrenean basin reveal the continuous evolution of the source area regions and the active tectonics that contributed to the formation and emergence of new provenance domains. The first clastic input to the basin occurred during the

Santonian (Mey et al., 1968) and was derived from southern sources, located in the Ebro Massif, which produced high mature quartz-felspathic sandstones (Gómez-Gras et al., 2016), a detrital zircon U—Pb suite highly dominated by Variscan ages and a thermochronological signature of >200 Ma based on zircon (U—Th)/He (Filleaudeau et al., 2012; Odlum et al., 2019; Thomson et al., 2020). During the Maastrichtian, the active tectonics started to compartmentalize the basin (Cuevas, 1992; Muñoz, 1992), resulting in the accumulation and concentration of south-derived sediments (Ebro Massif source) in the southern sector of the basin, while the northern sectors started to register the erosion of new uplifted source areas (Rosell et al., 2001) composed by carbonate and siliciclastic Mesozoic cover rocks, located in the emerging Pyrenees (Gómez-Gras et al., 2016). After that time period, Whitchurch et al. (2011), Filleaudeau et al. (2012) and Thomson et al. (2017) documented the progressive evolution from sedimentary delivery systems dominated by Cadomian and >700 Ma detrital zircon ages, to systems dominated by Variscan detrital zircon ages during Eocene times in the nearby Ainsa and Tremp-Graus basins. This change has been interpreted by Whitchurch et al. (2011) and Filleaudeau et al. (2012) to represent the shift from a drainage network eroding Cadomian rocks of the eastern Pyrenees to a drainage network tapping Variscan plutonic rocks of the central Pyrenees, which is consistent with the east to west diachronous uplifting trend of the Pyrenean belt.

Our new results show that the deep-water upper Hecho Group turbidites in the Jaca basin (Banastón and Jaca turbidite systems, Fig. 8) show dominant Variscan age components, confirming their stratigraphic age equivalence with the Lutetian turbidite deposits of the Ainsa basin (Mutti, 1985), and their axial origin, fed from the central Pyrenees (Fig. 9). Results from Thomson et al. (2017) confirm this equivalence showing important Variscan age peaks in the Ainsa and Morillo turbidite systems, which are age equivalents of the Banastón and Jaca turbidite systems (Cantalejo et al., 2020). However, in the Bartonian-Priabonian of the Jaca basin, the axial east-derived sediment input (shallow to continental strata) was displaced to the southern part of the basin due to the progradation of north-derived alluvial fan systems (i.e. Santa Orosia and Canciás alluvial fans) (Puigdefàbregas, 1975). These prograding transverse systems were fed from northern source areas delivering sediment dominated by Cadomian and >700 Ma detrital zircon age distributions (Fig. 10). Although south Pyrenean foreland deposits with Cadomian and >700 Ma detrital zircon age distributions have been frequently linked with erosion from the eastern Pyrenean Paleozoic terrains, several studies have demonstrated that these detrital zircon signatures can also be derived from recycling of Mesozoic and Paleozoic rocks from other sectors of the Pyrenees (Hart et al., 2016), as in the case of the north-derived alluvial fans of the present study. During this tug-of-war between axial (east-derived) and transverse (north-derived) sediment delivery systems during the evolution of the Jaca basin, the axial, east-derived systems also underwent a shift in detrital zircon age characteristics. This change in the axial system is recorded both in sandstone petrography and detrital zircon U—Pb ages (Michael, 2013) and it is expressed as a shift from plutonic input (Variscan age-dominated detrital zircon spectra), active during deposition of Hecho Group turbidites, to more metamorphic and

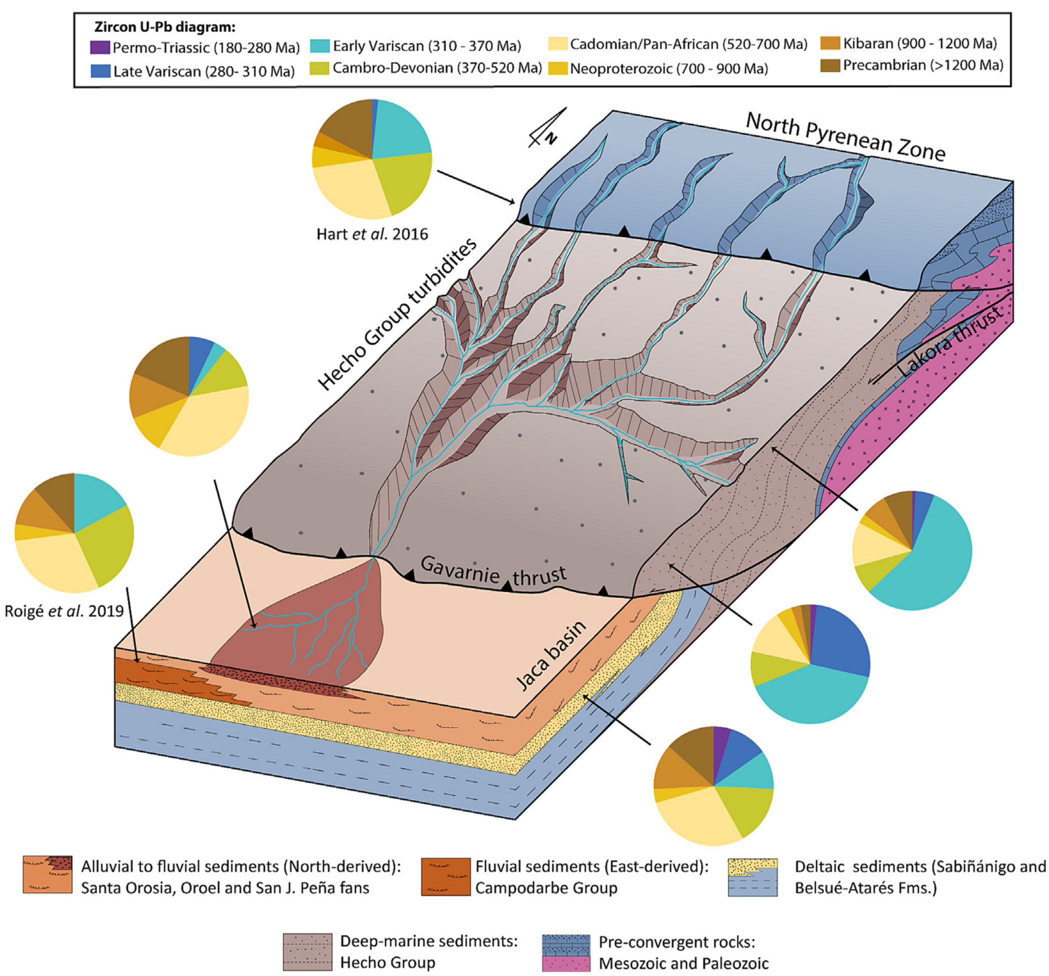

Fig. 10. Model sketch for the sedimentary systems of the Jaca basin during the late Eocene-Miocene alluvial sedimentation, with U—Pb pie charts for the Hecho Group turbidites (samples B6 and J3), deltaic deposits (sample JY2), east-derived fluvial Campodarbe (sample SP17) and for the north-derived alluvial fans (sample JY39). Detrital zircon U—Pb pie chart for the North Pyrenean Zone is extracted from Hart et al. (2016), and corresponds to sample 12WPY21, belonging to the clastic Mendibelza Formation (Cretaceous). Note the different age signatures between the alluvial fans, and their main source area (Hecho Group turbidites).

recycled siliciclastic input (Cambro-Devonian and Cadomian age-dominated detrital zircon spectra), active during the fluvial Campodarbe Group (Roigé et al., 2019) (Fig. 10). This change into the detrital zircon age signals has also been identified in the Eocene Escanilla fluvial system in the Ainsa basin, where the basal Escanilla shows a detrital zircon distribution highly dominated by Variscan ages, while the upper Escanilla records an increase of the Cambro-Devonian and Cambrian detrital zircon age distributions, which is interpreted as resulting from a new reorganization of the catchment areas in the central Pyrenees (Michael, 2013). This compositional evolution of the central Pyrenees source area implies that the Variscan plutonic rocks, that were eroded during the deep-water sedimentation, became less represented while the Paleozoic metasedimentary rocks gained in sediment contribution (Michael, 2013). This compositional change is also coeval with the first irruption of Buntsandstein pebbles in the Eocene alluvial fans of the south-central Pyrenean basin (Burrel et al., 2021). This change has been interpreted as the result of the southward migration of the water divide in the central Pyrenees during the Bartonian, which displaced the main drainage area toward the southern edge of the Nogueres thrust sheet (Burrel et al., 2021; Coll et al., 2022). However, recent findings on the heavy mineral suite of the fluvial Campodarbe Formation in the Jaca basin (Coll et al., 2022) challenge its correlation with the fluvial Escanilla Formation of the Ainsa basin. This is based on the epidote content, which is prevalent in the fluvial sediments of the Escanilla Formation and the Campodarbe deposits located at the southeastern margin for the Jaca basin, but completely absent in the western sector of this basin. For that reason it can be demonstrated that an additional source area contributed to the fluvial sediment routing of the Campodarbe Formation, probably located in the eastern Pyrenees (Pedraforca-Segre valley area), where the epidote is absent (Coll et al., 2022). Therefore, it is important to emphasize the need to integrate multi-method provenance proxies when dealing with multiple sources in active tectonic settings, which normally experience a very dynamic source area evolution (Garzanti et al., 2007). Similar difficulties produced by the use of a single provenance technique have been also highlighted in other settings, like in the Garumnian facies of the south Pyrenean basin, where Thomson et al. (2020) identified multiple source areas for deposits showing almost identical detrital U—Pb zircon signatures.

5.4. Recycling effect on detrital zircon U—Pb spectra

The overwhelming presence of recycled turbidite clasts in the Santa Orosia, Peña Oroel and San Juan de la Peña alluvial fans unequivocally indicates that the source area for these fans was mainly constituted by the Hecho Group turbidites of the northern Jaca basin (Roigé et al., 2017). This appears to be contrary to what one would interpret based on the detrital zircon U—Pb age data of the alluvial fan samples (dominant Cadomian and >700 Ma detrital zircon ages), as they are very different from the detrital zircon signatures of the Hecho turbidites (dominant Variscan detrital zircon ages) (Fig. 10). Three main hypotheses are presented here to explain this discrepancy and explain the recycling effect on the evolution of detrital zircon U—Pb signatures.

(1) The lower Hecho Group turbidites, not analyzed in the Jaca basin, could have a different detrital zircon U—Pb signature than the upper Hecho Group, and could be more similar to the detrital zircon age distribution observed in the alluvial fans (i.e., dominant Cadomian and >700 Ma detrital zircon ages) (Fig. 10). However, the detrital zircon age signatures of the lower Hecho Group turbidite equivalents in the Ainsa basin (Thomson et al., 2017) also show detrital zircon signatures with a strong Variscan signature. Therefore, it can be assumed that the lower Hecho Group turbidites in the Jaca basin will record a similar detrital zircon population. This assumption is based on the fact that the upper Hecho Group turbidites in both basins display a very similar detrital zircon signature, and therefore, processes like hydraulic sorting and/or sediment buffering, which can have a downstream impact into detrital zircon (Li et al., 2019), are not expected to highly affect to the detrital zircon signatures. Therefore, this hypothesis is here discarded.

(2) Potential bias or difference introduced by grain size difference between the parent rocks affecting the detrital zircon U—Pb age distributions. Some studies have pointed to the possible effect of grain size on variations in detrital zircon U—Pb interpretations (Garzanti et al., 2008, 2009; Malusà et al., 2016). In our case study, only medium-fine grained sandstone turbidite samples were targeted for detrital zircon U—Pb analysis. However, turbidites of the Jaca basin mainly represent distal deposits consisting of fine to very fine grained sandstones (Remacha and Fernández, 2003; Remacha et al., 2005). Therefore, if substantial differences in detrital zircon U—Pb age distributions would occur in the Hecho Group turbidites, our detrital zircon U—Pb results for the medium grained turbidites would not be representative of the entire drainage area (Fig. 10). While more scrutiny is needed to discard this hypothesis, there does not seem to be any systematic variability in detrital zircon distributions between fine and medium size grained samples that would support this explanation.

(3) Differences in spatial distribution, zircon fertility and disproportioned contribution from the source rocks. Recent research has found that detrital zircon datasets from modern sandy deposits do not always represent precisely the areal distribution of the source rocks in their catchment areas (Jackson et al., 2019; Castillo et al., 2022). While fine-grained, well-cemented Hecho Group turbidites have the propensity to produce sedimentary clasts, their sand to silt size fraction does not yield a fair proportional representation of their detrital zircon age signature. In contrast, North Pyrenean rocks with higher zircon fertility (Dickinson, 2008) have a higher propensity to produce a medium-grained sand fraction. This situation would result in the over-representation of the North Pyrenean source signals in the drainage basins (Fig. 10). Some intrinsic factors of the Hecho Group turbidites such as their high degree of cementation could also explain their resistance to be disaggregated into sand- and silt-sized fraction during their transport to the Jaca basin sink. These intrinsic factors have already been proved to have an impact when reading provenance signatures (Amidon et al., 2005; Capaldi et al., 2017)

In addition, distal sources located in the headwaters (North Pyrenean Zone) would be more easily disaggregated into sand and silt-sized grains while proximal source areas (Hecho Group turbidites) (Fig. 10) would be preferentially fragmented into clast-size fragments, also influenced by the weaker weathering processes affecting the newly exposed source. This situation has also been described in geological settings with contrasting weathering processes affecting source rocks, and therefore having a clear impact on the detrital zircon signal delivered into the sediment routing (Nesbitt et al., 1996; Jackson et al., 2019). Moreover, according to all these characteristics the source rock distribution (inferred from the clast counting and sandstone petrography) would not provide the expected representation of zircon grains. This effect can also be observed when comparing the sand-sized and pebble fractions of the alluvial fans, where turbidite fragments are more represented in the coarser fractions (Roigé et al., 2017).

Moreover, this last hypothesis is also supported by the fact that the Rapitán turbidite channel is assumed to be mainly sourced from the North Pyrenean Zone, with little recycling from the former turbidites, and shows an U—Pb zircon distribution very close to that recorded in the overlying alluvial fans whose feeding systems clearly eroded the Hecho Group turbidites.

Our results emphasize that the Jaca basin is as an excellent setting for investigating the impact of sediment recycling on detrital zircon U—Pb provenance studies, where different factors such as grain sorting, weathering and transport can play an important role.

6. Conclusions

New detailed detrital zircon U—Pb geochronology analysis allows to characterize the provenance changes that occurred during mid Eocene to early Miocene times in the Jaca foreland basin. Our results reveal a very different detrital zircon provenance signature between the Hecho Group turbidites and the younger alluvial fans that conform the basin infill, which can be attributed to major changes in sediment routing and sourcing during progressive tectonic evolution of the southern Pyrenees. The turbidite deposits show a detrital zircon age distribution dominated by Variscan signals, which can be clearly associated with detrital input funneled axially through the Ainsa basin and derived from source areas characterized by Paleozoic crystalline basement in the central Pyrenean Axial Zone. Coupling of sandstone petrography and detrital zircon U—Pb data has allowed identifying compositional trends that are here interpreted as tectono-stratigraphy cyclicity, which can be identified in each of the analyzed turbidite systems. This cyclicity consists of an enrichment of the Variscan detrital zircon signal at the base of the systems, which can be associated with an efficient sediment transfer from distant Axial Zone source rocks during relative lowstand periods, while a dilution of this signal occurs during highstand periods, at the top of each system, due to the lowered erosion capability of the fluvial network.

In contrast, the overlying late Eocene-early Miocene fluvial to alluvial systems display dominant Cadomian and >700 Ma detrital zircon age signatures, which are linked to newly uplifted northern sources, with drainage areas eroding into former uplifted turbidites and the rocks of the North Pyrenean Zone located in their headwaters.

Despite the abundance of recycled turbidite clasts, alluvial fan detrital zircon age distributions are not identical to those of the Hecho turbidites, highlighting the complexity introduced by sediment recycling, which is dependent on a wide range of factors. We propose that intrinsic factors such as the degree of cementation, composition or zircon fertility of source rock lithologies, transport distance and/or differential weathering processes may affect detrital zircon age distributions and decouple petrography from detrital zircon signatures. If this assertion is correct, recycling in the alluvial fans of the Jaca basin may cause detrital zircon age spectra to not fully and accurately represent the source area provenance signature. Our results, therefore, highlight the importance of integrating different provenance techniques in geological settings with complex provenance evolution and cannibalization or recycling of earlier basinal deposits, such as proximal foreland basins.

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Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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