C. R. Geoscience 348 (2016) 236–245

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Tectonics, Tectonophysics

Tectonic control on sediment sources in the Jaca basin (Middle and Upper Eocene of the South-Central Pyrenees)

Marta Roigé [a,*], David Gómez-Gras [a], Eduard Remacha [a], Raquel Daza [b], Salvador Boya [a]

[a] Départament de Geologia, Universitat Autònoma de Barcelona, Bellaterra, Spain
[b] Departamento de Geología, Museo Nacional de Ciencias Naturales-CSIC, Madrid, Spain

ARTICLE INFO

Article history:
Received 1st October 2015
Accepted after revision 14 October 2015
Available online 22 January 2016

Handled by Yves Lagabrielle

Keywords:
Sediment sources
Pyrenees
Jaca basin
Sandstone petrography
Eocene

ABSTRACT

The Eocene clastic systems of the Jaca foreland Basin (southern Pyrenees) allow us to identify changes in sediment composition through time. We provide new data on sediment composition and sources of the northern Jaca basin, whose stratigraphic evolution from Middle Lutetian deep-marine to Priabonian alluvial systems record a main reorganization in the active Pyrenean prowedge. Petrological analysis shows that the Banastón and the Lower Jaca turbidite systems (Middle–Upper Lutetian) were fed from an eastern source, which dominated during the sedimentation of the Hecho Group turbidites. In contrast, the upper part of the Jaca turbidite systems (Lutetian–Bartonian transition) records an increase in the number of subvolcanic rock and hybrid-sandstone fragments (intrabasinal and extrabasinal grains) being the first system clearly fed from the north. This change is interpreted as associated with an uplifting of the Eaux-Chaudes/Lakora thrust sheet in the northern Axial Zone. The Middle Bartonian Sabiñánigo sandstone derives from eastern and northeastern source areas. In contrast, the overlying Late Bartonian–Early Priabonian Atarés delta records sediment input from the east. The Santa Orosia alluvial system records a new distinct compositional change, with a very high content of hybrid-sandstone clasts from the Hecho Group, again from a northern provenance. Such cannibalized clasts were sourced from newly emerged areas of the hinterland, associated with the basement-involved Gavarnie thrust activity in the Axial Zone.

© 2015 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

1. Introduction

Sand petrography is a robust tool to investigate sediment provenance and to reconstruct the geotectonic setting that controls the infilling of a basin. Provenance of sandstones in foreland basins has been widely investigated as it provides valuable information about the erosional history of the fold-and-thrust belt (Graham et al., 1986).

The Ainsa–Jaca basin (Fig. 1) has been an important target in terms of basinal sediment investigation, mainly focused on the deep-marine clastic systems, known as Hecho Group turbidites. Well-known stratigraphic and facies models (Mutti et al., 1985, 1988; Remacha and Fernández, 2003, among others) have been extracted from these turbidites and have been used as analogues for other deep-marine systems. However, the large amount of research concerning the sedimentological and tectonic evolution of the Ainsa–Jaca basin (Beaumont et al., 2000; Mutti et al., 1985, among others) contrasts with the little published research with regard to sediment composition and provenance.

---

* Corresponding author.
E-mail address: Marta.Roige@uab.cat (M. Roigé).

http://dx.doi.org/10.1016/j.crte.2015.10.005
1631-0713/© 2015 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

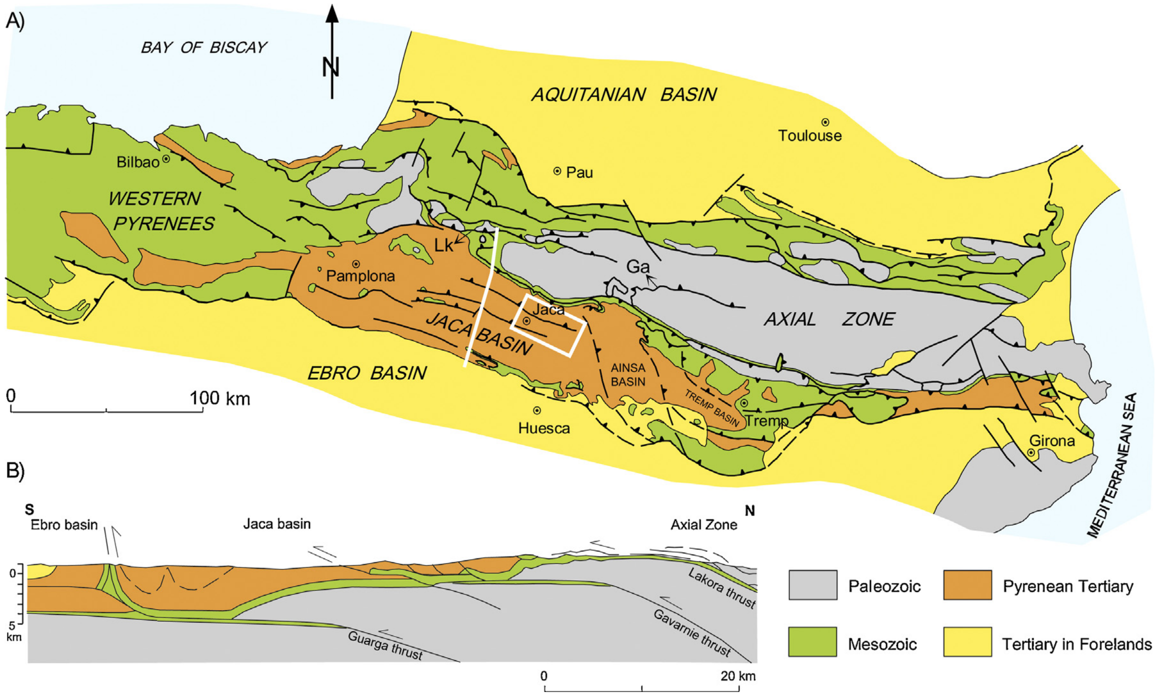

Fig. 1. (A) Simplified geological map of the Pyrenees (redrawn from Teixell, 1996), showing the location of the study area (white frame). The white line indicates section in Fig. 1B. Lk: Lakora thrust; Ga: Gavarnie thrust. (B) Cross-section of the South Pyrenean thrust belt showing the structure of the Jaca basin (simplified from Teixell, 1998).

Provenance studies carried out in the Ainsa and Jaca basins have been mainly focused on the Hecho Group turbidites (Caja et al., 2010; Fontana et al., 1989; Gupta and Pickering, 2008). Little sandstone petrography analyses have been carried out in both Ainsa and Jaca basins for the sedimentary succession that represents the abandonment of deep-marine conditions to generalized continental environments, especially in the Jaca basin. The main research regarding to provenance of fluvial and alluvial systems has been carried out in the Bartonian–Priabonian Escanilla System (Michael, 2013), located in the Ainsa basin, and in the Middle Eocene–Oligocene deposits of the Sis palaeovalley (Vincent, 2001), in the Tremp–Graus basin, mainly using data from gravel-sized clasts and heavy mineral signatures. No detailed provenance studies are available for the slope/coastal and non-marine environments (Middle Eocene to Early Oligocene) of the Jaca basin.

The present paper provides new data on the provenance of the eastern Jaca basin, whose stratigraphic evolution from deep-marine (Middle Lutetian) to alluvial environments (Priabonian) records main palaeogeographic reorganization in the active Pyrenean prowedge. A revision of sandstone compositions of the upper Hecho Group has been performed in order to link sediment composition shifts with the geotectonic setting of the basin.

2. Geological and stratigraphic framework

The Pyrenean orogen is a fold-and-thrust belt that resulted from the collision between the Iberian and the European plates from Late Cretaceous to Miocene times. The Pyrenean convergence was accommodated by the development of an upper crustal doubly-vergent orogenic prism and the subduction of the Iberian lower crust under the European plate (Beaumont et al., 2000; Muñoz, 1992; Teixell, 1998; Teixell et al., 2016). The Pyrenean orogen is flanked by the Ebro and Aquitanian foreland basins to the south and the north, respectively (Fig. 1A). The southern side of the Pyrenean orogen consists of a basement-involved thrust stack formed by three main imbricate thrust sheets known as Lakora–Eaux-Chaudes, Gavarnie, and Guarga thrusts (Fig. 1B). This thrust stack includes a Palaeozoic basement characterized by the occurrence of granitoids and metamorphic rocks (Axial Zone), and a cover imbricate thrust system with preorogenic Mesozoic rocks and synorogenic assemblage of Late Santonian to Early Miocene clastic and carbonate rocks (Fig. 1B). These synorogenic rocks constitute the South Pyrenean basin, which during Early and Middle Eocene times concentrated fluvio-deltaic sedimentation in the east (Tremp-Graus and Ager basins, Fig. 1A) passing to the west to coastal/slope to deep-marine sedimentation (Ainsa and Jaca basins). These fluvio-deltaic systems were fed from the Palaeozoic basement (Axial Zone) and from the Mesozoic rocks that constituted the South-Central Pyrenean Unit (Séguret, 1972).

Thrust activity, and associated flexural subsidence, highly controlled the Jaca basin infill. It firstly consists of turbidites (Lower–Middle Eocene flysch, Hecho Group) and coastal, non-marine deposits (Upper Eocene–Lower Oligocene molasse) during the overfilled stage (Barnolas and Teixell, 1994; Labaume et al., 1985; Mutti et al., 1988;

Puigdefàbregas, 1975; Teixell, 1996). The 3800 m-thick analysed sedimentary succession crops out in the northern Jaca basin (Fig. 1A). The lower part of the section is located in the footwall of the Oturia thrust (north of Jaca town; Fig. 2), while the upper part is located in the northern limb of the Yebra de Basa anticline (Fig. 2).

The succession starts with the Banastón turbidite systems (Lutetian according to Labaume et al., 1985; Oms et al., 2003) from the upper Hecho Group (Fig. 3), that are built up by a succession of sandstones and mudstones including carbonate megaturbidites (labelled as MT-5, MT-6 and MT-7 by Labaume et al., 1987). They correspond to turbiditic sheet-like lobes, changing into basin plain facies more to the west (Remacha and Fernández, 2003; Remacha et al., 2005). As for the preceding turbiditic systems (i.e. Cotefablo and Broto of the Lower Hecho Group), the Banastón system was fed by a single entry point located in the southeastern end of the foredeep (Remacha et al., 1998b), mainly sourced from erosion of the eastern Pyrenees (Caja et al., 2010; Puigdefàbregas et al., 1992; Teixell, 1998). This first unit is overlain by the Jaca turbidite systems (Fig. 2; Fig. 3) subdivided into the Jaca-1 to Jaca-4 depositional sequences (Remacha and Picart, 1991; Remacha et al., 2003). Turbidites of Jaca-1 to Jaca-3 are representative of the deep-marine stage, whereas the occurrence of channelized turbidites in the Jaca-4 sequence (the Rapitán system of Remacha et al., 1995) depicts a landward stepping trend leading to a molassic stage (Remacha et al., 2005). This facies change is also coincident with a shift of the direction of the palaeocurrents with transport direction from the north (Remacha and Picart, 1991). The Rapitán system (Lutetian–Bartonian transition) evolves further up to the Larrés Marls (Fig. 2; Fig. 3), which represent the delta slope sediments (Puigdefàbregas, 1975) of the platform deposits of the Sabiñánigo Sandstone delta (Middle Bartonian). The Sabiñánigo Sandstone shows a wide variety of facies that are mainly associated with outer shelf and delta front environments, with palaeocurrents from the east and southeast, and in the upper part from the north (Remacha and Picart, 1991; Oms and Remacha, 1992) The upper part of the Sabiñánigo Sandstone (Figs. 2 and 3) is mostly transgressive, passing upward into the Atarés delta and the Santa Orosia alluvial fan (Figs. 2 and 3). The Atarés delta (Priabonian according to Hogan and Burbank, 1996) shows a cyclic delta front stacking pattern that ends up with marked alluvial influence. The palaeocurrents indicate sediment transport from the east and the southeast (Oms and Remacha, 1992; Oms, 1994). The overlying Santa Orosia fan (Priabonian) is the first important irruption of conglomeratic facies alternating with red-coloured palaeosoils, with palaeocurrents from the north and the northeast (Puigdefàbregas, 1975). The lower part of the fan is characterised by marine influence (Oms and Remacha, 1992), while in the upper part continental facies are found (Fig. 3). Therefore, the continental Santa Orosia fan belongs to the Campodarbe formation in the sense of Puigdefàbregas (1975), and marks the establishment of generalized terrestrial environments in much of the Jaca basin. The continentalization of the basin is evidenced by the subsequent irruption of other alluvial fans such as the Peña Oroel and the Canciás fans (Fig. 2). The analysed stratigraphic section ends with the overlying Canciás alluvial fan that shows thick conglomeratic levels, interrupted by lacustrine limestone beds and yellow-to-grey shales.

3. Samples and methods

A total of 103 sandstones and conglomerates samples were collected and examined in thin sections under the

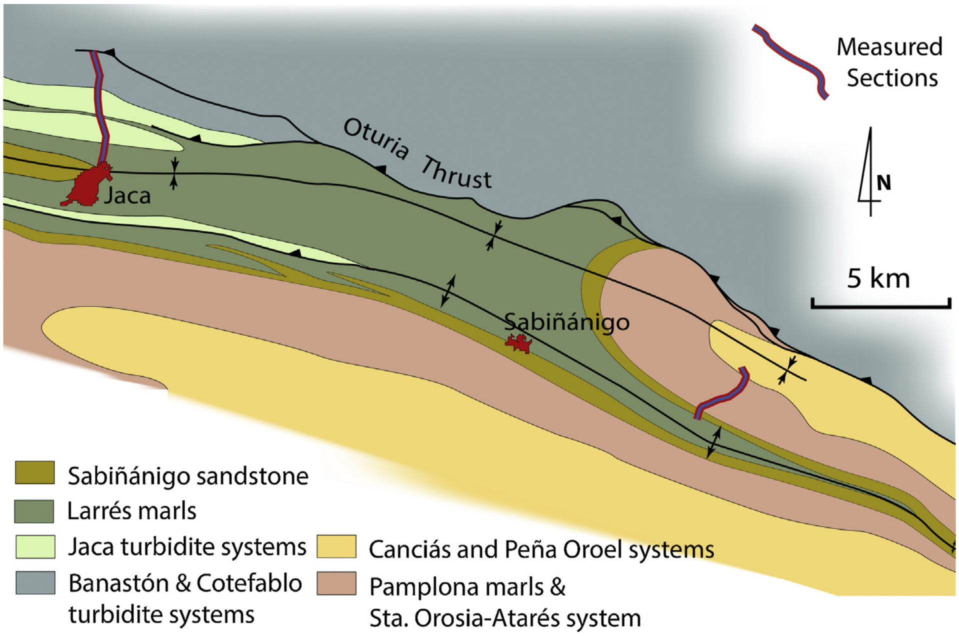

Fig. 2. Geological map of the Jaca area modified from Remacha et al. (1998a). Red lines: location of the two measured sections that build up the stratigraphic section represented in Fig. 3.

polarizing microscope. Sixty-five representative samples were selected for a detailed quantitative study based on point counting analysis in order to establish the detrital modes. Textural features as size and sorting were set for all the samples following the criteria of Beard and Weyl (1973) that allow us to establish the degree of sorting depending on each grain size using thin section comparators. All thin sections were stained using Na-cobaltinitrite (Chayes, 1952) for accurate identification of feldspar and alizarine red-S staining was applied for distinction of carbonate composition, such as dolomite and calcite.

Quantification of detrital modes was performed by petrographic analysis of thin sections using the Gazzi–Dickinson point counting method (Dickinson, 1970; Gazzi, 1966; Zuffa, 1985). Grain size effects are minimized, as crystals and other sand size (> 0.0625 mm) grains that occur in larger rock fragments are classified by the type of crystal below the cross-hair (Ingersoll et al., 1984), as well as the type of rock fragment. The distance between two counting points was larger than the coarsest grain fraction in all the samples (Van der Plas and Tobi, 1965). A total of 500 points were counted for each thin section (following Dryden, 1931) and fifty-six petrographic classes were considered, referring to framework grains (forty-five classes), matrix, cement and porosity (twenty one classes). Framework grains were grouped into the four main categories defined by Zuffa (1980): non-carbonate extrabasinal (NCE), non-carbonate intrabasinal (NCI), carbonate extrabasinal (CE) and carbonate intrabasinal (CI).

Quantification of the main clast lithologies in the conglomeratic levels of the Santa Orosia and Canciás alluvial systems were performed on outcrops. Four sampling locations were established for the Santa Orosia conglomerates, and one for the Canciás system. Clast counting was set at the same conglomerate bed whose matrix had been sampled for sandstone petrography. Procedure for clast counting was done following the method of Howard (1993) consisting in counting four closely spaced subsets of 100 clasts each, obtaining a total of 400 clasts for each studied sampling location.

A composite stratigraphic section was constructed across all the studied systems (Fig. 2), where all the samples are situated (Fig. 3).

4. Results

All the samples are grain supported with a very low matrix ratio (less than 1% in most sandstone). Turbidite sandstones show angular to subangular grains with low sphericity and sorting ranges from poorly to well sorted, depending on the grain size. Grains from deltaic and alluvial samples are subrounded to angular and show a highly variable sphericity. Samples from deltas are very well to well sorted, while sorting of alluvial fan samples ranges from moderately to well sorted.

Ternary diagrams (Fig. 3) are used in order to classify and identify the main compositional changes of the studied systems. The modal composition of sandstones is here represented according to the criteria of Zuffa (1980) (NCE–CE–CI) and Dickinson et al. (1983) (QFL). Supplementary diagrams have been used according to the most distinctive components of each sedimentary system. For deep-marine environments, a ternary diagram comparing the main lithic grains (F + PRF: feldspar and plutonic rock fragments; SndSilt + VRF: sandstone rock fragments and volcanic rock fragments; MRF: metamorphic rock fragments) allow us to identify compositional trends. Transitional to continental environments were represented in a triangular diagram comparing hybrid-sandstone fragments (hybrid sand), plutonic and volcanic fragments (PRF + VRF) and metamorphic fragments (MRF). The term “hybrid-sandstone fragments” is here used in the sense of Zuffa (1980), and is referred to those sandstone fragments that contain intrabasinal and extrabasinal grains.

A first-order compositional classification has been obtained for all the studied samples by representing the relative content on NCE, CE and CI components.

4.1. *Modal sandstone composition: turbiditic systems*

4.1.1. *Banastón turbidites*

The Banastón turbiditic system shows similar proportion of carbonate and NCE grains and an increase in the number of carbonate intrabasinal grains from base to top (Fig. 3A). Quartz is the most represented siliciclastic component, and shows angular to subrounded shapes (Fig. 3B). Mono and polycrystalline quartz with evaporitic inclusions (halite and anhydrite) is frequent. Some quartz grains show inherited overgrowths.

K-feldspars appear as orthoclase and microcline, commonly unweathered to slightly weathered. Plagioclases appear in lower proportions at the base of the system, always partially to totally replaced by illite or kaolinite. Plagioclases to K-feldspars ratio (P/K) is < 1, excepting the uppermost samples exhibiting a ratio close to 1.

Among the lithic fragments, the low-grade metamorphic ones show a decreasing trend towards the upper part of the system. Subvolcanic fragments with common ophitic texture are weakly represented, but increase upward. Silicified limestones and radiolarite fragments appear in low proportions ($<1\%$) in all the samples.

Bioclastic limestone rock fragments appear widely as grainstones, wackestones–packstones and mudstones fragments. Most common bioclasts are alveolinids, nummullitids, and milliolids. Late Cretaceous *phitonellid* tests are also present in some wackestone–packstone fragments, and in most of the samples. Sporadic *microcodium* grains are also present. Single grain dolomite and dolostone fragments reach the highest proportions at the base of this turbiditic system. Intrabasinal grains are mainly foraminifera and red algae. Miliolids appear widely in the uppermost samples.

The Banastón turbiditic system shows an upward increase in carbonate intrabasinal components, with a mean value of $NCE_{43}CE_{45}CI_{12}$. Although the CI content increases, it not surpasses the CE content in any case (Fig. 3A). Samples from the base of this system can be classified as calclithites, while at the uppermost part the main petrofacies are hybrid arenites, characterized by the occurrence of intra- and extrabasinal grains. Regarding to the quartz/feldspar/lithics content, the mean value for this system is $Q_{47}F_{24}L_{29}$. The standard QFL diagram (Fig. 3B)

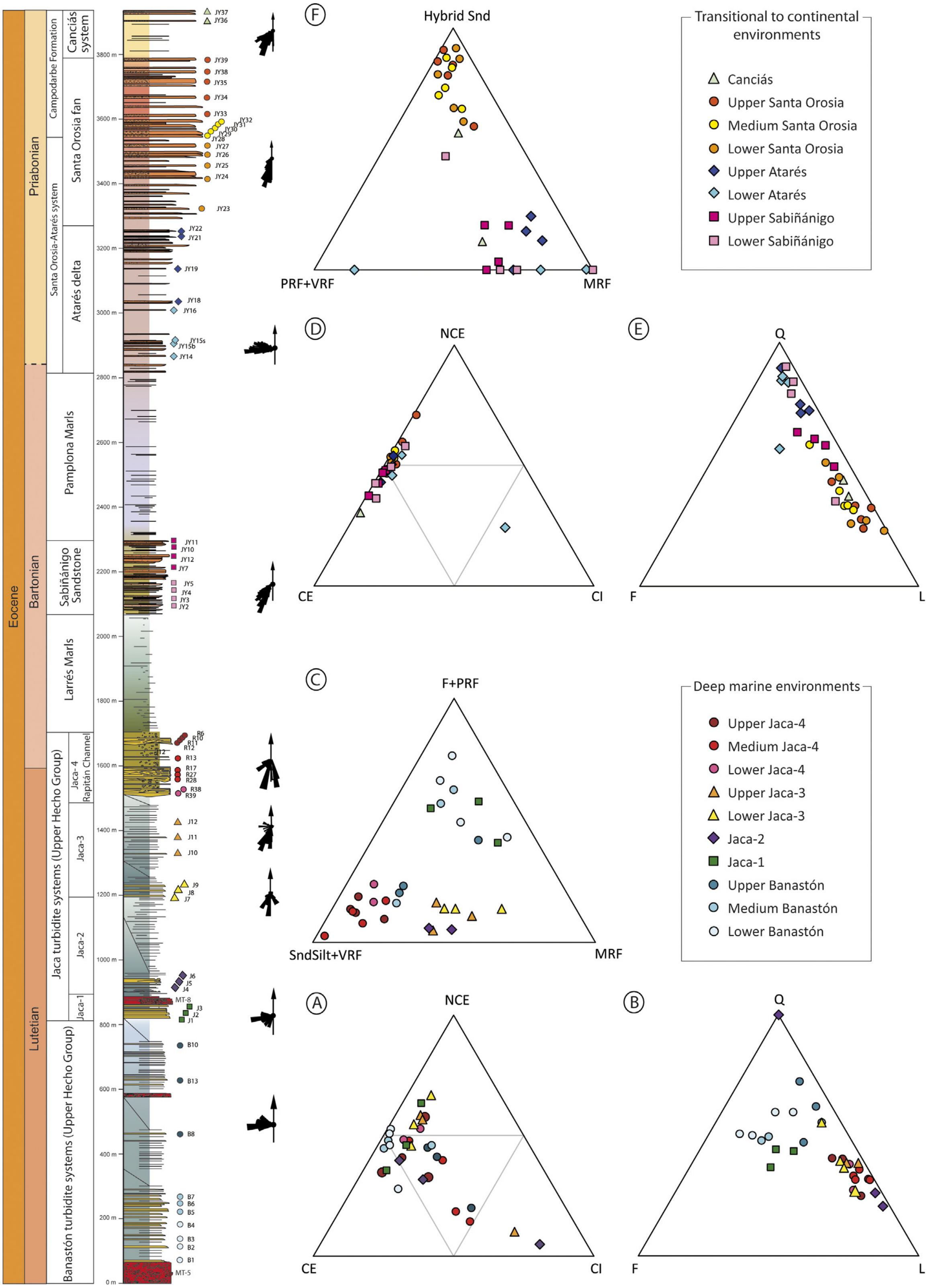

Fig. 3. Sandstone composition plots for the clastic systems of the studied section (see location in Fig. 2) with stratigraphic position of the analysed samples and general paleocurrent directions (extracted from Oms, 1994; Oms and Remacha, 1992; Remacha and Fernández, 2003, Remacha and Picart, 1991). Compositional ternary diagrams for deep-marine environments of the Jaca basin: (A) first-order compositional plot (Zuffa, 1980) where NCE:

shows a clear decrease in feldspar, together with an increase of quartz grains.

4.1.2. Jaca turbidites

The Jaca turbidites exhibit a similar evolution compared to the Banastón system (Fig. 3A and C). The proportion of extrabasinal grains is higher than that of intrabasinal ones in most of the samples. However, there are more carbonate intrabasinal grains than in the Banastón system, increasing from the base to the top. Single quartz grains appear in low proportions, and show angular to subrounded shape. Mono- and polycrystalline quartz with evaporitic inclusions is usual. K-feldspars appear as orthoclase and microcline, commonly unweathered to slightly weathered. Plagioclase is found in lower proportions at the base of the system, partially replaced by illite or kaolinite. The P/K ratio is > 1, except in samples from the base (Jaca-1), which show higher amounts of K-feldspar, with a P/K ratio close to 1/3. Lithic grains allow us to discriminate between the systems forming the Jaca turbidites. The proportion of plutonic fragments is higher in Jaca-1, whereas the highest amount of low-to-medium-grade metamorphic fragments appears in the Jaca-2 and Jaca-3 systems (Fig. 3C). The Rapitán system (Jaca-4) records an important compositional change, shown by the increase in the number of subvolcanic and sandstone fragments, some of them being hybrid arenites (Fig. 3C). Most of these subvolcanic fragments show an ophitic texture developed from medium to coarse plagioclase crystals.

CE components are made of bioclastic limestones, similar to those of the Banastón turbidites. *Microcodium* grains are not present. As for the Banastón system, single dolomite grains and dolostone fragments reach the highest proportion at the base of the Jaca turbiditic system, while the uppermost samples (Jaca-4) show a lower proportion. Intrabasinal grains reach important amounts ($> 50\%$) in some arenites from the Jaca-2 and Jaca-3.

The Jaca turbiditic system shows an increasing trend of carbonate intrabasinal components (Fig. 3A). The mean value for this system is $NCE_{41}CE_{38}CI_{21}$. Samples from the base can be classified as lithic sandstones, although in the uppermost section, the main petrofacies are hybrid arenites (Jaca 4). The standard QFL diagram (Fig. 3B) shows a clear decreasing trend of the feldspar content, together with an increase in the number of quartz grains. The mean compositional value for this system is $Q_{31}F_{10}L_{59}$.

4.2. Modal sandstone composition: deltaic and alluvial systems

4.2.1. Sabiñánigo Sandstone

The Sabiñánigo Sandstone delta is the first system that shows a dominance of CE grains versus non-carbonate grains (Fig. 3D), with $NCE_{45}CE_{53}CI_2$ as the mean composition. According to these proportions, samples can be classified as calclithites. The mean QFL composition for this system is $Q_{58}F_7L_{35}$. The standard QFL diagram (Fig. 3E) depicts a clear trend, with an increase in lithic fragments towards the top of the Sabiñánigo Sandstone.

Single quartz grains appear in relatively high proportions at the base of the delta. Mono- and polycrystalline quartz with evaporitic inclusions are usually present, as seen in the former systems.

K-Feldspar occurs in low proportions ($< 10\%$) as orthoclase and microcline, unto slightly weathered. Plagioclase is partially replaced by illite or kaolinite. The P/K ratio is <1, with a P/K ratio close to 1/3 for most of the samples. Lithic grains are mainly: (a) siliciclastic sandstone and hybrid sandstone, (b) shale and schist fragments, (c) plutonic fragments and (d) subvolcanic fragments. An upward decrease in the content of plutonic fragments can be observed towards the top, as well as an increase in the number of lithic grains. Hybrid siltstone and sandstone fragments are rare (1–9%) in the samples from the uppermost part of the delta and absent in most of the samples of the lower part.

Limestones (mainly mudstones) appear in high proportions all along the system. Only some samples from the top show a greater variety of limestones such as grainstone or packstone fragments. One of the key components of the Sabiñánigo Sandstone is detrital dolomite. Dolomite and dolostone fragments appear in considerable proportions (10–20%) in almost all samples, contrasting with the lower proportion of these components in the Rapitán turbidites. Planktonic foraminifera and bivalve fragments are the most common intrabasinal component of this deltaic system.

4.2.2. Atarés delta

This deltaic system shows similar content of non-carbonate versus CE grains (Fig. 3D). Despite some facies show exceptionally high bioclastic content associated with the transgressive part of mouthbars, the mean composition for this system is $NCE_{46}CE_{44}CI_{10}$. Samples from the base of this system can be classified as lithoarenites and calclithites. In terms of siliciclastic components, the mean composition is $Q_{73}F_7L_{20}$. As shown in the standard QFL diagram (Fig. 3E), the lower part of this delta exhibits higher amounts of quartz grains, while the uppermost part records an increase in the lithic components.

Plagioclase and K-feldspar are also present ($< 10\%$), displaying various degrees of alteration. The P/K ratio is always < 1, close to 1/3 in most of the samples.

The Atarés delta, together with the Sabiñánigo Sandstone, shows the highest amount of metamorphic fragments of the studied section (up to 10%). Siliciclastic sandstone and siltstone rock fragments are quite common.

The limestone population is highly homogenous, consisting of mudstone fragments. As for the Sabiñánigo

---

non-carbonate extrabasinal grains; CE: carbonate extrabasinal; and CI: carbonate intrabasinal, (B) QFL compositional plot (Dickinson et al., 1983) with Q: quartz; F: feldspar; and L: lithic grains, and (C) compositional plot of lithic grains where F + PRF, feldspar and plutonic fragments; SndSilt + VRF, sandstone and volcanic fragments; and MRF: metamorphic fragments. Compositional ternary diagrams for transitional to continental environments of the Jaca basin: (D) first-order compositional plot (Zuffa, 1980) where NCE: non-carbonate extrabasinal grains; CE: carbonate extrabasinal; and CI: carbonate intrabasinal, (E) QFL compositional plot (Dickinson et al., 1983) with Q: quartz; F: feldspar; and L: lithic grains, and (F) compositional plot of lithic grains where hybrid sand, hybrid-sandstone fragments; PRF + VRF, plutonic and volcanic fragments; and MRF: metamorphic fragments.

Sandstone, the Atarés delta shows distinctive high concentrations of detrital dolomite grains and dolostone fragments.

Intrabasinal grains are mainly bioclasts such as benthic foraminifera, bivalves, and echinoderms. Glauconite is quite common, being mainly concentrated in the transgressive facies of delta front deposits.

4.2.3. *Santa Orosia fan*

Lithoarenites are the most representative petrofacies for the first alluvial system of the stratigraphic section, with a mean of $NCE_{52}CE_{46}CI_2$ (Fig. 3D).

The proportion of lithic grains reaches the highest ratios (Fig. 3E), as shown by a $Q_{33}F_7L_{60}$Mean. Quartz grains appear rounded to subangular. Plagioclase and K-feldspar display several degrees of weathering. The P/K ratio is < 1 for most of the samples.

The most distinctive characteristic of this system is the large proportion (up to 40%) of hybrid siltstone and sandstone fragments (Fig. 3F). The high input of these components increases towards the top of this system and denotes an important change in the lithologies cropping out in the source area.

The Santa Orosia fan displays an increase in plutonic fragments from base to top. Compared to the Sabiñánigo Sandstone and Atarés delta, this system shows a higher influence of plutonic source areas. Subvolcanic fragments appear in low proportions along all the system, occasionally concentrated in some conglomeratic levels. Metamorphic fragments are mainly schists. Silicilastic red sandstones also occur in most of the samples. Limestones are the second most common component (30 to 50%) and appear as mudstone, bioclastic grainstone/packstone and crystalline limestone fragments. Compared with the former deltas, the lack of dolomite grains and dolostone fragments also points to an important source change. Chert and silicified limestone rock fragments are quite common.

4.2.4. *Canciás fan*

The sandstone composition of this alluvial system is similar to that from the Santa Orosia fan. As shown in the NCE–CE–CI diagram (Fig. 3D, E), the main difference lies in a higher concentration of CE grains, being calclithites the most representative petrofacies with a mean $NCE_{37}CE_{62}CI_1$. The QFL content displays a mean for this system of $Q_{38}F_6L_{56}$. Fine lithic grains are less abundant, mainly due to the decrease in the hybrid sandstone versus CE fragments. Metamorphic grains are more abundant than in the former alluvial fan, being schists the most representative. The new occurrence of detrital dolomite grains and dolostone fragments, together with the increase in the content of limestone fragments (55 to 70%), is the most characteristic feature of this system. Silicified limestones are also widely represented.

4.3. *Modal composition of pebbles (conglomerates)*

The Santa Orosia and Canciás alluvial systems are composed of thick (up to 30 m) conglomerate levels. The sandy matrix of these beds has been sampled for conventional petrographic analysis (see description above). Some of these conglomerate levels have been selected for point counting of gravel sized components that constitute the framework structure, allowing a comparison of compositional modes between the matrix and framework clasts of the same conglomerate bed.

The Santa Orosia conglomerates are mainly clast-supported and show a sorting that ranges from moderate to poor. The size of the clasts varies from 5 to 15 cm, occasionally reaching up to 30 cm. The matrix grain size ranges from medium to very coarse sand, and commonly shows a fining-upwards pattern. The textural features of the Canciás conglomerates show some changes with respect to the Santa Orosia system, consisting in a decrease in the mean clast size (about 8 cm) and an increase in the matrix proportion.

In the Santa Orosia system, clasts are extrabasinal and dominated by hybrid sandstones (65–85%) that range from very fine to very coarse sand sizes. Some of these clasts show a wide variety of sedimentary structures as cross lamination or gradations. The rest of siliciclastic clasts are subordinate and appear scattered as green subvolcanic, quartz, and granitoid clasts. Some pebbles of metamorphic clast-rich breccia can also be found.

Proportion of carbonate clasts ranges from 10 to 30% with a wide variety of limestones. In the conglomerate bodies, grey mudstone clasts are the most abundant, although black mudstone, grey packstones and grainstones are also common. Bioclasts such as nummullites, alveolines or rudists occur within limestone clasts. Orange and white mudstone-wackestone clasts are less abundant. Limestone clasts with flint concretions are also present (Fig. 4). The coarsest pebbles correspond to hybrid sandstones and in some cases to limestones. The main trend that can be identified in the Santa Orosia fan is an increase of hybrid sandstone and plutonic clasts and a

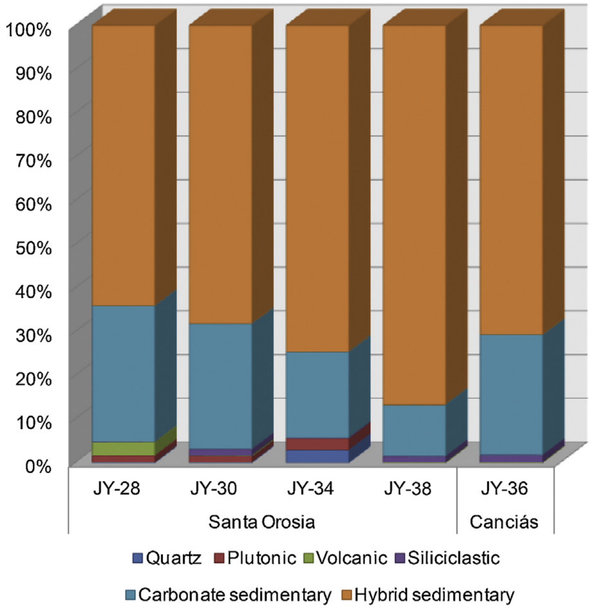

Fig. 4. Compositional diagram of the main clast lithologies in the Santa Orosia and Canciás alluvial fans. Note the increasing content of hybrid sedimentary clasts toward the top of the Santa Orosia fan.

decrease in limestone clasts, from the base to the top of the system. In contrast, the Canciás fan shows a decrease in hybrid-sandstone fragments and higher contents of limestone clasts (Fig. 4).

5. Discussion

Although detrital grains of the sedimentary systems of the Jaca basin can be sourced from a wide variety of rocks, some characteristic features allow us to recognize their most likely provenances. The quartz content decreases from base to top along the entire turbiditic succession (Banastón and Jaca systems) and transitional marine to alluvial environments (Sabiñánigo Sandstone to Canciás fan). Its origin can be diverse, as it appears in a wide kind of varieties. Well-rounded quartz indicates recycling from terrigenous grains of the lowstand wedge prograding complex deltas (Fontana et al., 1989) or from Cretaceous or Palaeocene sandstone formations. The presence of inherited quartz overgrowths in detrital quartz grains represents the cementing of grains from a previous sedimentary cycle (Sanderson, 1984). This kind of detrital quartz suggests recycling of Palaeozoic (Carboniferous or Permian–Triassic rocks) or Upper Cretaceous (Marboré sandstone) rocks, that crop out in the western part of the Pyrenees (north of the Jaca and Ainsa basins). Fine-grained polycrystalline quartz can be associated with medium/high grade metamorphic rocks such as schists and quartzites from the Palaeozoic basement. In contrast, some euhedral quartz grains with abundant evaporitic inclusions (halite and anhydrite) derive from the Triassic Keuper facies (Marfil, 1970).

K-feldspar and plagioclase are attributed to the crystalline rocks from the Palaeozoic basement such as granitoids or metamorphic rocks. Lithic clasts like shales, schists, plutonic and radiolarite fragments are also indicative of a contribution from the Palaeozoic basement.

Hybrid sandstone and siltstone rock fragments are interpreted as mainly supplied from erosion from the Hecho Group turbidites, as they present both intrabasinal and extrabasinal components and appear to widely suggest a large source area containing this kind of petrofacies. Features such as lamination and gradation found in sandstone pebbles support also the attribution to a turbiditic source area.

Subvolcanic rock fragments are associated with erosion from Triassic tholeiitic dolerites (ophites), cropping out in Keuper materials that even can be part of diapiric structures such as the Naval or Tolva diapirs, located in the South-Central Pyrenean Unit (Séguret, 1972). The provenance of subvolcanic fragments is also interpreted as fed from the North Pyrenean zone, where Triassic dolerites are widely found.

The bioclast content of the terrigenous grains indicates the presence of Cretaceous and Palaeocene/Eocene limestones in the source area. *Microcodium* grains are attributed to the erosion of Palaeocene limestones of the South-Central Pyrenean Unit. Some wackestones fragments with *pithonellid* tests occur in Cenomanian limestones, while dolostone and dolomitized limestones clasts are interpreted as supplied from the Palaeocene carbonate materials. Some dolostone fragments with sucrosic texture are associated with erosion from Jurassic dolostones involved in the main thrust sheets of the South-Central Pyrenean Unit. Single dolomite grains are related to weathering of both dolostone formations.

The changes observed in the petrofacies of the studied sedimentary systems of the Jaca basin indicate variations in source areas during the sedimentation of the last turbidites of the Hecho Group and the overlying deltas and conglomeratic fans.

Calclithites are the most representative petrofacies for the lower part of Banastón turbidites, although the increasing trend on intrabasinal components towards the upper part indicates a transition to hybrid arenites. Our results are in accordance with those of Fontana et al. (1989) for the Banastón system located in the hanging wall of the Oturia thrust (Fig. 2)). The increase of carbonate intrabasinal components to the uppermost part of each turbiditic system has been associated with episodes of carbonate platform development evidencing abatement in siliciclastic input related to reduced tectonic activity (Caja et al., 2010; Fontana et al., 1989).

Our petrographical results for the Banastón and Jaca turbiditic systems differ significantly from those obtained by Gupta and Pickering (2008) in the Jaca basin. This difference is due to their poor recognition of CE grains, feldspar varieties (K-feldspar vs. plagioclase) and some lithic grains such as shales, schists and volcanic fragments in the Banastón and Jaca turbidites.

Palaeocurrent analysis for the Banastón turbidites indicates a sediment supply coming from the east (Remacha and Fernández, 2003), consistent with the sediment composition. High proportions of terrigenous carbonate grains indicate a major contribution from Mesozoic and Palaeocene platforms from the South-Central Pyrenean Unit. The high amounts of feldspar and plutonic fragments are indicative of the exhumation of Palaeozoic granitoids. The Jaca-1 turbidites show a composition similar to that of the former system, with similar paleocurrent directions (Fig. 3). In contrast, an important change is recorded in the Jaca-4 system (Rapitán turbidites), evidenced by a variation in composition, facies and palaeocurrent directions that point to a new sediment routing system coming from the north (Remacha et al., 1995). This change is shown by an increase of sandstone and subvolcanic rock fragments together with higher P/K ratios (Fig. 3C). The change is interpreted as the result of a new tectonic pulse that caused the emergence of new source areas to the north. This tectonic pulse is represented by the activity of the Lakora–Eaux-Chaudes, whose age (Early–Middle Eocene) is consistent with the depositional age of the Rapitán turbidites (Jolivet et al., 2007; Labaume et al., 1985; Meresse, 2010; Oms et al., 2003; Teixell, 1996; Teixell et al., 2016). The fragments of Triassic subvolcanic rocks (ophites) currently cropping out in the leading edge of the Lakora thrust sheet (e.g., Bedous area) are among the most distinctive grains of the Rapitán system. Thus, the first record of a northern source area in the Jaca basin can be attributed to the uplift of new terrains that created a strongly emergent, northern thrust margin of the basin during the deposition of the upper Hecho Group turbidites.

P/K ratios for the Banastón turbidites obtained in this work are consistent with those obtained by Fontana et al., 1989 for the Banastón System in the Fiscal area (eastern Jaca basin). The increase in the P/K ratio in Jaca-4 turbidites is interpreted as related to the creation of new emerged areas, where fresher rocks were exhumed. In contrast, Banastón and Jaca-1 turbidites were derived from relatively more mature source areas that supplied higher amounts of K-feldspar. Thus, the change in the nature of source rocks and its residence/exposure time due to their distinct tectonic evolution is here interpreted as the main cause of the P/K ratio changes, and not as the degree of chemical weathering due to climate characteristics.

As for the former turbiditic systems, compositional ternary diagrams allow us to discriminate between the first deltaic systems of the basin (Fig. 3F). The Sabiñánigo Sandstone and Atarés deltas are characterized by the high amounts of carbonatic extrabasinal fragments and detrital monocrystalline dolomite grains. These kinds of grains can be attributed to the erosion of the Mesozoic cover rocks of the South-Central Pyrenean Unit, indicating supply of eastern source areas. Nonetheless, the presence of hybrid-sandstone fragments in the Sabiñánigo Sandstone is interpreted as early erosion of the turbiditic basin, indicating a contribution of a northeastern source area. Paleocurrent directions support this interpretation for both the Sabiñánigo and Atarés deltas (Remacha and Picart, 1991). The Atarés delta exhibits higher proportions of metamorphic rock fragments than the Sabiñánigo Sandstone, which shows significant contributions of plutonic and subvolcanic rock fragments.

The overlying alluvial systems of Santa Orosia and Canciás are characterized by a northern input, evidenced by palaeocurrents and facies architecture (Puigdefàbregas, 1975). This input is recorded through the high amounts of hybrid-sandstone rock fragments (Fig. 3F), sourced from the turbidite sandstones of the Hecho Group that originally overlaid the uplifting Axial Zone. This sharp petrological change implies the contribution of Hecho Group turbidites as part of a new source area and points to a major paleogeographic reorganization, here interpreted as generated by the onset of the basement-involved Gavarnie thrust (Roigé et al., 2013). The activity of the Gavarnie thrust has been set to the Late Eocene–Early Oligocene according to structural data from Teixell (1996) and thermochronological data from Jolivet et al. (2009) and Meresse (2010), who obtained exhumation ages around 37–28 Ma. According to these data, the emplacement of the Gavarnie thrust was contemporaneous with the Santa Orosia fan, dated as Priabonian (Canudo and Molina, 1988; Hogan and Burbank, 1996).

The involvement of recycled turbidites of the Hecho Group increases from the base to the top of the Santa Orosia fan. In contrast, the Canciás fan records a minor contribution of this recycling as well as an increase on limestone and dolostone rock fragments that indicates major contributions of Palaeocene/Eocene carbonates that are interpreted as indicative of erosion of deeper levels in the source area (Fig. 4).

6. Conclusions

Sandstone compositions allow us to link the main paleogeographic changes that controlled the infill of the Jaca basin during the transition from deep-marine to terrestrial environments (Middle Lutetian to Priabonian). The petrological analysis shows that the most representative petrofacies of the Banastón turbidite systems (Middle Lutetian) are calclithites and hybrid arenites, whereas in the youngest turbidites (Lutetian to Bartonian transition) of the Jaca Basin are lithic arenites and hybrid arenites. The proportion of carbonate intrabasinal components depicts a similar increasing upwards trend in each turbiditic system. The Banastón and the lower Jaca turbidite systems were fed from an eastern source, which dominated during most of the sedimentation of the Hecho Group in the Jaca Basin. In contrast, the upper part of the Jaca turbidite Systems (Rapitán turbidites) records a change in the source area, being the first depositional system clearly fed from the north. The content increase of subvolcanic rock and sandstone fragments is the main feature associated with the shift of sediment input from the north. This change is interpreted as the result of a new tectonic pulse associated with the Eaux-Chaudes/Lakora thrusts that acted at the northern margin of the foreland basin during sedimentation of the Jaca turbidites.

The petrofacies of the Sabiñánigo Sandstone and Atarés deltas and of the overlying Santa Orosia alluvial systems are mainly calclithites and lithic arenites. The provenance of the Sabiñánigo Sandstone sediments is interpreted from both eastern and northeastern source areas, this last source predominating in the upper part. In contrast, the overlying Atarés delta complex records only sediment input from the east, characterized by a higher proportion of metamorphic fragments and single dolomite grains. Moreover, the Santa Orosia and Canciás alluvial systems, sited in the uppermost part of the studied section, record an important compositional change evidenced by the high content of recycled hybrid sandstones, which are absent from the former Atarés delta. These hybrid sandstones were sourced from the turbidites of the Hecho Group, which originally overlaid the uplifting Axial Zone. This recycling is interpreted as related to the onset of the basement-involved Gavarnie thrust during Priabonian times.

The change of the eastern source for the northern source acted as a major control during the continentalization of the basin. This shift in source location was gradual, and reflects a competition between the east-derived and north-derived systems that constitute the infill of the Jaca basin, highly controlled by the thrust activity of the Pyrenean prowedge.

Acknowledgements

This paper is a contribution to the project CGL2014-54180-P, financed by the Ministerio de Economía y Competitividad of Spain. M. Roigé and S. Boya acknowledge support from the Universitat Autònoma de Barcelona (PIF grant). We are very grateful to the reviewers P. Labaume and F. Christophoul, and to the editor Y. Lagabrielle for their helpful comments to improve the manuscript. We are indebted to A. Teixell for discussion in the field that has contributed to the development of this work. We would like to thank Conwy Valley Systems

Limited to provide us PETROG$^{\mathrm{TM}}$ software for the compositional data acquisition.

References

Barnolas, A., Teixell, A., 1994. Platform sedimentation and collapse in a carbonate-dominated margin of a foreland basin (Jaca basin, Eocene, southern Pyrenees). Geology 22 (12), 1107–1110.

Beard, D.C., Weyl, P.K., 1973. Influence of texture on porosity and permeability of unconsolidated sand. AAPG Bull. 57, 349–369.

Beaumont, C., Muñoz, J.A., Hamilton, J., Fullsack, P., 2000. Factors controlling the Alpine evolution of the central Pyrenees inferred from a comparison of observations and geodynamical models. J. Geophys. Res. 105 (B4), 8121–8145.

Caja, M.A., Marfil, R., Garcia, D., Remacha, E., Morad, S., Mansurbeg, H., Amorisi, A., Martínez-Calvo, C., Lahoz-Beltrá, R., 2010. Provenance of siliciclastic and hybrid turbiditic arenites of the Eocene Hecho Group, Spanish Pyrenees: implications for the tectonic evolution of a foreland basin. Basin Res. 22, 157–180.

Canudo, J.I., Molina, E., 1988. Biocronología de foraminíferos planctónicos de la secuencia deposicional de Jaca (Pirineo Aragonés): Eoceno medio y superior. In: II Cong. Geol. Esp. SGE, Granada 1, 273–276.

Chayes, F., 1952. The finer-grained calcalkaline granites of New England. J. Geol. 207–254.

Dickinson, W., 1970. Interpreting detrital modes of graywacke and arkose. J. Sediment. Petrol. 40, 695–707.

Dickinson, W.R., Beard, L.S., Breankenridge, J.L., Erjavec, R.C., Ferguson, K.F., Inman, R.A., Knepp, F.A., Linberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geol. Soc. Am. Bull. 94, 222–235.

Dryden Jr., A.L., 1931. Accuracy in percentage representation of heavy mineral frequencies. Proc. Natl. Acad. Sci. USA 17 (5), 233–238.

Fontana, D., Zuffa, G.G., Garzanti, E., 1989. The interaction of eustacy and tectonism from provenance studies of the Eocene Hecho Group Turbidite Complex (South-Central Pyrenees, Spain). Basin Res. 2, 223–237.

Gazzi, P., 1966. Le arenarie del flysh sopracretaceo dell'Apenino modenese; correlazioni con il flysh Monghidoro. Miner. Petrol. Acta 12, 69–97.

Graham, S.A., Tolson, R.B., Decelles, P.G., Ingersoll, R.V., Bargan, E., Caldwell, M., Cavazza, W., Edwards, D.P., Follo, M.F., Handschy, J.F., Lemke, L., Moxon, I., Rice, R., Smith, G.A., White, J., 1986. Provenance modelling as a technique for analysing source terrane evolution and controls on foreland sedimentation. Spec. Publ. Int. Assoc. Sediment. 8, 425–436.

Gupta, K.D., Pickering, K.T., 2008. Petrography and temporal changes in petrofacies of deep-marine Ainsa-Jaca basin sandstone systems, Early and Middle Eocene, Spanish Pyrenees. Sedimentology 55 (4), 1083–1114.

Hogan, P.J., Burbank, D., 1996. Evolution of the Jaca piggyback basin and emergence of the External Sierra, southern Pyrenees. In: Friend, P.F., Dabrio, J.C. (Eds.), Tertiary Basins of Spain: the Stratigraphic Record of Crustal Kinematics. Cambridge University Press, Cambridge, pp. 153–160.

Howard, J.L., 1993. The statistics of counting in rudites: a review, with examples from the Upper Palaeogene of southern California, USA. Sedimentology 40, 157–174.

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., Sores, S.W., 1984. The effects of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method. J. Sediment. Petrol. 54, 103–116.

Jolivet, J., Labaume, P., Monié, P., Brunel, M., Arnaud, N., Campani, M., 2007. Thermochronology constraints for the propagation sequence of the South Pyrenean basement thrust system (France-Spain). Tectonics 26, 1–17.

Labaume, P., Seguret, M., Seyve, C., 1985. Evolution of a turbiditic foreland basin and analogy with an accretionary prism: example of the Eocene South-Pyrenean basin. Tectonics 4, 661–685.

Labaume, P., Mutti, E., Seguret, M., 1987. Megaturbidites: a depositional model from the Eocene of the SW-Pyrenean Foreland Basin, Spain. Geo-Mar. Lett. 7 (2), 91–101.

Marfil, R., 1970. Estudio petrogenético del Keuper en el sector meridional de la Cordillera Ibérica. Estud. Geol. 2, 113–163.

Meresse, F., 2010. Dynamique d'un prisme orogénique intracontinental : évolution thermochronologique (traces de fission sur apatite) et tectonique de la Zone Axiale et des piémonts des Pyrénées centro-occidentales. Univ. Montpellier-2 (Doctoral dissertation, PhD thesis).

Michael, N.A., 2013. Functioning of an ancient sediment routing system, the Escanilla Formation, South-central Pyrenees. Imperial College London (Doctoral dissertation, PhD thesis).

Muñoz, J.A., 1992. Evolution of a continental collision belt: ECORS-Pyrenes crustal balanced cross section. In: McClay, K.R. (Ed.), Thrust Tectonics. Chapman and Hall, New York, pp. 235–246.

Mutti, E., Seguret, M., Sgavetti, M., 1988. Sedimentation and Deformation in the Tertiary Sequences of the southern Pyrénées. Field Trip 7 Guidebook: AAPG, Mediterranean Basins Conference, Nice, France. Special Publication of the Institute of Geology of the University of Parma, 169 p.

Mutti, E., Remacha, E., Sgavetti, M., Rosell, J., Valloni, R., Zamorano, M., 1985. Stratigraphy and facies characteristics of the Eocene Hecho group turbidite systems, South-Central Pyrenees. In: IAS 6th European regional meeting, Lleida, Field Trip 12 Guidebook, pp. 519–576.

Oms, O., 1994. Estratigrafía del fan-delta de Santa Orosia. Universidad Autónoma de Barcelona (Tesis de Licenciatura).

Oms, O., Remacha, E., 1992. Relación entre el abanico deltaico de Santa Orosia y la tectónica sinsedimentaria (Eoceno medio y superior de la cuenca de Jaca, provincia de Huesca). III Congreso geológico de España y VIII Congreso Latinoamericano de Geología. Universidad de Salamanca, Simposios175–178.

Oms, O., Dinarès-Turell, J., Remacha, E., 2003. Magnetic stratigraphy from deep clastic turbidites: An example from the Eocene Hecho Group (southern Pyrenees). Stud. Geophys. Geod. 47, 275–288.

Puigdefàbregas, C., 1975. La sedimentación molásica en la cuenca de Jaca. Pirineos 104, 1–188.

Puigdefàbregas, C., Muñoz, J.A., Vergés, J., 1992. Thrusting and foreland basin evolution in the southern Pyrénées. In: McClay, K.R. (Ed.), Thrust Tectonics. Chapman & Hall, London, pp. 247–254.

Remacha, E., Picart, J., 1991. El complejo turbidítico de Jaca y el delta de la arenisca de Sabiñánigo. 116 p. In: Libro Guía Excursión n° 8, I Cong. Esp. del Terciario, Vic.

Remacha, E., Fernández, L.P., 2003. High-resolution correlation patterns in the turbidite systems of the Hecho Group (South-Central Pyrenees, Spain). Mar. Petrol. Geol. 20, 711–726.

Remacha, E., Oms, O., Coello, J., 1995. The Rapitán turbidite channel and its related eastern levee-ovebank deposits, Eocene Hecho group, South-Central Pyrenees, Spain. In: Pickering, K.T., Hiscott, R.N., Kenyon, N.H., Ricci Lucchi, F., Smith, R.D.A. (Eds.), Atlas of Deep Water Environments: Architectural Style in Turbidite Systems. Chapman & Hall, London, pp. 145–149.

Remacha, E., Fernández, L.P., Maestro, E., 1998a. Relationships between lobes and basin plain elements in the Hecho turbidite basin (Eocene, South-central Pyrenees, Spain): International Association of Sedimentologists. In: 15th Internat. Sedimentological Congress, Alicante, Spain, Abstracts, pp. 655–657.

Remacha, E., Fernández, L.P., Maestro, E., 2005. The transition between sheet-like lobes and basin plain turbidites in the Hecho Group (South-central Pyrenees, Spain). J. Sediment. Res. 75, 798–819.

Remacha, E., Fernández, L.P., Maestro, E., Oms, O., Estrada, R., Teixell, A., 1998b. The Upper Hecho Group turbidites and their vertical evolution to deltas (Eocene, South-central Pyrenees): International Association of Sedimentologists. In: 15th International Sedimentological Congress, Alicante, Spain, Field Trip Guidebook, pp. 1–25.

Roigé, M., Gómez-Gras, D., Remacha, E., 2013. Procedencia de las areniscas y conglomerados de la sucesión estratigráfica del flanco sur del sinclinal de Santa Orosia (Bartoniense y Priaboniense inferior de la cuenca de Jaca). Geogaceta 53, 93–96.

Sanderson, D., 1984. Recognition and significance of inherited quartz overgrowths in quartz arenites. J. Sediment. Petrol. 54 (2), 473–486.

Séguret, M., 1972. Etude tectonique des nappes et séries décollées de la partie centrale du versant sud des Pyrenées. Univ. Montpellier, 155 p, Doctoral thesis.

Teixell, A., 1996. The Ansó transect of the southern Pyrenees: basement and cover thrust geometries. J. Geol. Soc. London 153, 301–310.

Teixell, A., 1998. Crustal structure and orogenic material budget in the West-Central Pyrenees. Tectonics 17 (3), 395–406.

Teixell, A., Labaume, P., Lagabrielle, Y., 2016. The crustal evolution of the West-Central Pyrenees revisited: inferences from a new kinematic scenario. C. R. Geoscience [this issue].

Van der Plas, L., Tobi, A.C., 1965. A chart for judging the reliability of point counting results. Am. J. Sci. 263 (1), 87–90.

Vincent, S.J., 2001. The Sis palaeovalley: a record of proximal fluvial sedimentation and drainage basin development in response to Pyrenean mountain building. Sedimentology 48 (6), 1235–1276.

Zuffa, G., 1980. Hybrid arenites: their composition and classification. J. Sediment. Petrol. 50, 21–29.

Zuffa, G., 1985. Optical analyses of arenites: influence of methodology on compositional results. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Boston, pp. 165–189.