[American Journal of Science, Vol. 311, May, 2011, P. 442–482, DOI 10.2475/05.2011.03]

SEDIMENT ROUTING SYSTEM EVOLUTION WITHIN A DIACHRONOUSLY UPLIFTING OROGEN: INSIGHTS FROM DETRITAL ZIRCON THERMOCHRONOLOGICAL ANALYSES FROM THE SOUTH-CENTRAL PYRENEES

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ABSTRACT. The Pyrenees represents an orogen that developed diachronously, from east to west, between the Late Cretaceous and Miocene. Here, we use detrital zircon fission-track thermochronological analyses and U-Pb geochronology, interpreted within the context of the thermal and tectono-sedimentary development of the orogen, to construct a 3-stage model for south-central Pyrenean sediment routing system evolution as follows: (1) *Late Cretaceous to Paleocene:* Oblique convergence and topographic growth initiates in the eastern Pyrenees. After erosion and removal of the "cover layer", south-central Pyrenean basins are supplied with zircons cooled during the Late Cretaceous (~78 Ma), with a fission-track lag time of *ca.* 15 Myr, that record early Pyrenean exhumation. The zircons are sourced from the eastern, not central, Pyrenees. Orogen-parallel sediment routing systems dominate; (2) *Early to Middle Eocene:* After a period of quiescence, plate convergence rates increase. Uplift of the central Pyrenees supplies the south-central Pyrenean basins with zircons sourced from the central Pyrenean cover layer. Out-of-sequence thrusting recycles the early foredeep deposits and their associated thermochronological signals. The sediment routing systems begin to transition from orogen-parallel to orogen-transverse states; (3) *Late Eocene to Miocene:* Uplift and exhumation of the western Pyrenees begins. Zircons exhumed and cooled during the Oligocene (~30 Ma) in response to duplex stacking in the central Axial Zone, reach the south-central Pyrenean wedge-top and foreland basins with a lag time of *ca.* 3 Myr. Orogen-transverse sediment routing systems become fully established. Our results extend the exhumational history of the Pyrenees beyond that shown from bedrock studies and reveal that significant topography existed in the Pyrenees in the Paleocene. Furthermore, our data demonstrate the successive change from orogen-parallel to orogen-transverse sediment dispersal along strike, coeval with diachronous mountain growth. This study has implications for understanding the evolution of synorogenic sediment routing systems, migrating depocenters and the redistribution of mass by surface processes that may drive any coupling with tectonics during oblique orogenic development.

Key words: Pyrenees, thermochronology, detrital zircon fission track, U-Pb zircon dating, orogenic evolution, sediment routing systems

INTRODUCTION

Advances in our understanding of fold-and-thrust belts that form critical-taper wedges in collisional mountain belts have highlighted the importance of coupling between tectonics and surface processes (Davis and others, 1983; Dahlen and others, 1984). Rather than simply passively responding to tectonics, surface processes have been shown to actively influence the geometry of an orogen through their ability to

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remove and redistribute mass (for example, Willett, 1999; Simpson, 2004, 2006; Stolar and others, 2007). Numerical modeling of this process has traditionally involved a simple cross-section through a two-dimensional orogenic wedge. But, because many real orogens exhibit some form of obliquity during collision, with sedimentary systems redistributing mass both perpendicular and parallel to orogen strike, more recent research has focused on adapting coupled models to three dimensions (Stolar and others, 2006). Diachronous orogenesis and topographic growth will have implications for the evolution of synorogenic sediment routing systems, including the spatial and temporal variation of source exhumation—here defined as the upward displacement of rock towards the surface, caused by tectonic or surficial denudation processes—and sediment supply, sediment transport and dispersal, and eventual deposition in relation to complexly evolving sedimentary basins. Understanding the complex evolution of sediment routing systems during orogenic development can aid our understanding of the redistribution of mass by surface processes that may drive the feedback with tectonics.

We investigate the Pyrenees, an orogen that formed during the oblique collision between the Iberian and European plates, resulting in diachronous orogenic evolution from east to west, between the Late Cretaceous and Miocene (Alonso-Zarza and others, 2002; Capote and others, 2002). We present new detrital thermochronological data that allow us to reconstruct the evolution of sediment routing systems over the entire orogenic lifespan. We define the lifetime of the Pyrenean orogen as the period of active contractional deformation, when the Iberian and European plates were moving toward one another. Today, the Pyrenees is in its post-orogenic phase and active convergence between the two plates has ceased (Alonso-Zarza and others, 2002; Capote and others, 2002).

In particular, we focus on the south-central Pyrenees (fig. 1). Here, the core of the mountain belt (the Axial Zone) is a complex south-vergent thrusted structure, dominantly composed of Hercynian basement rocks arranged in an antiformal stack (Séguret and Proust, 1968; Choukroune and ECORS Team, 1989; Muñoz, 1992). The mountain-belt core is flanked to the south by a south-vergent fold-and-thrust belt, which exhibits the geometric characteristics of a critically-tapered wedge. The Ebro Basin comprises the foredeep. The excellent exposure of syn-orogenic deposits in the south-central Pyrenees provides an ideal natural laboratory in which to reconstruct the sediment routing systems over the entire orogenic life span.

Our current understanding of Pyrenean development is mainly based on bedrock thermochronological studies (Morris and others, 1998; Fitzgerald and others, 1999; Maurel and others, 2002, 2004, 2008; Sinclair and others, 2005; Gibson and others, 2007; Jolivet and others, 2007), which constrain the thermal evolution of the Axial Zone. However, bedrock studies are limited to those rocks currently exposed at the surface and cannot be used to constrain early orogenesis because the overlying rock containing a record of earlier events has since been eroded and removed (Garver and others, 1999). The exhumation history for the Pyrenees is therefore only well constrained since the Eocene, meaning little is known about the early thermal evolution of the mountain belt. In this study, we use the detrital record because the sedimentary archive allows extension of the bedrock record back through time, thus detrital thermochronology provides a means for reconstructing the early history of orogenesis. Increasingly, it is recognized that basin sediments hold the key to unlocking the early stages of orogenic growth history (Brandon and Vance, 1992; Lonergan and Johnson, 1998; Garver and others, 1999; Ruhl and Hodges, 2005; Bernet and others, 2009). Even young orogens such as Taiwan require use of detrital samples to reconstruct their early stage exhumation (Kirstein and others, 2010).

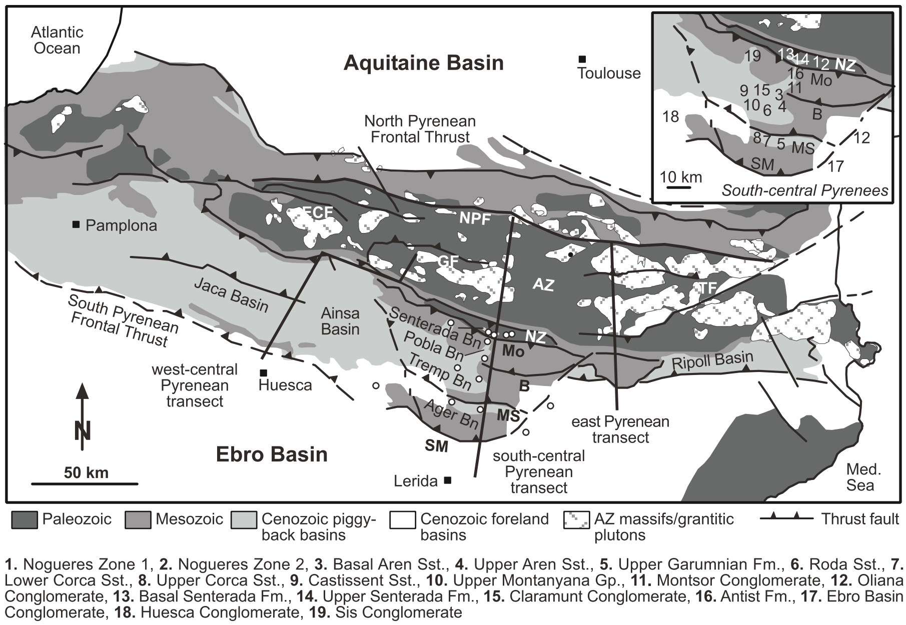


Fig. 1. Simplified structural and geological map of the Pyrenees. The Axial Zone (AZ) of the mountain belt lies between the north-vergent northern thrust belt and the south-vergent southern thrust-belt. The Ebro and Aquitaine basins comprise the pro- and retro-foreland basins respectively. Modified from Teixell (1996). The south-central Pyrenees form the focus of this study (inset box). Detrital sample locations are numbered and the corresponding names given. NPF—North Pyrenean Fault; AZ—Axial Zone; NZ—Nogueres Zone; TF—Tet fault; MF—Merens fault; ECF—Eaux Chaudes fault; M—Morerres backthrust; B—Boixols thrust; MS—Montsec thrust; SM—Sierras Marginales thrust. The west-central, south-central and east Pyrenean transect lines correspond to Figure 5.

The tectono-sedimentary evolution of the south-central Pyrenees is relatively well constrained (for example, Muñoz, 1992; Meigs and Burbank, 1997; Nijman, 1998; Sinclair and others, 2005), though in-depth provenance analyses using thermochronological data have not been carried out. We use U-Pb age dating of detrital zircons to fingerprint for source provenance, allowing connection between the depositional basin sink and source supply, and aiding the reconstruction of sediment routing systems.

In this study we aim, within the context of existing bedrock thermochronological and tectono-sedimentary data, to (1) use detrital zircon fission-track thermochronology from the south-central Pyrenees to reconstruct the exhumational history of the mountain belt, with particular focus on the early exhumation history; and (2) reconstruct the south-central Pyrenean sediment routing systems from source to sink using the provenance information recorded by detrital zircon fission-track and U-Pb age data. By integrating new detrital thermochronological analyses with geochronology we illustrate patterns of exhumation and deposition that may be typical of obliquely developing orogens.

METHODS AND APPROACH

We opt for the analysis of detrital zircon because this mineral is common to a wide range of lithologies, is resistant to weathering and abrasion, and because it contains trace amounts of uranium it can be dated by several isotopic methods. We sampled medium to coarse grained sandstone from key stratigraphic units, spanning the Upper Cretaceous to lower Miocene strata, within each wedge-top basin and the Ebro foreland basin of the south-central Pyrenees (fig. 1). Older foredeep deposits, currently buried beneath later sedimentary cover in the Ebro Basin, extend into the foreland fold-and-thrust belt where they are uplifted, well exposed and easily sampled.

We used zircon fission track analyses to define the long-term cooling rate of each sample and as a proxy for hinterland exhumation rate, because exhumation (displacement of rock relative to the surface) is also a cooling process. In active orogenic belts shortening and thrust faulting, which leads to crustal thickening, does not directly exhume rocks but instead creates the topography that orographically forces precipitation and erosion leading to the exhumation and cooling of rocks (Ring and others, 1999). Whilst erosion is the primary process driving exhumation, normal faulting can also play a role. Exhumation rates are calculated from the detrital zircon fission-track ages contained in those sedimentary rocks formed within basins associated with orogen development. Calculations of exhumation are based on the effective closure temperature for fission tracks in zircon, which records the time when zircons within exhuming rocks retain all of the fission tracks created by the natural decay of ^{238}U. These calculations only work if exhumation and cooling have been monotonic, but this is expected in an active orogen. Furthermore, the exhumation rates are predicated on the belief that fission-track ages of the detrital samples record exhumation in the hinterland, which may not be the case if samples have been subjected to extensive burial post-deposition and re-heating to levels sufficient to cause thermal resetting.

To reset the fission track clock (a self-repair process known as annealing), heating to 200 to 300 °C (for durations $>10^7$ yrs) is required (Brandon and others, 1998; Garver and others, 2005; Bernet and Garver, 2005), or higher temperatures if the zircons have only minor radiation damage (Tagami and others, 1998). Thus the minimum amount of heating by burial to cause resetting in the Pyrenees translates to minimum burial depths of 7 to 10 km for geothermal gradients between 25 to 30 °C/km based on present-day measurements (Zeyen and others, 1994). For this study the likelihood of resetting among the studied samples is low given that the sampled wedge-top basins in the south-central Pyrenees are not very thick and that samples were taken from depths much shallower than 6 km. Furthermore, post-deposition thermal resetting can easily be identified by adopting the minimum age approach, whereby unreset zircons will always record fission-track ages that are older than the deposition age of the sample (Brandon and others, 1998). Fission-track ages younger than the depositional ages indicate thermal resetting in the sedimentary basin.

The difference between the fission-track cooling age and depositional age of a detrital sample can be used to monitor the evolution of an orogen. This time lag approach, which assumes the time for erosion, transport and deposition is negligible (Brandon and Vance, 1992), has been successfully applied in a number of orogenic studies (for example, Bernet and Garver, 2005). Short lag times indicate rapid hinterland exhumation rates and long lag times indicate slow exhumation. The lag time approach is especially useful for monitoring the early stages of topographic growth, spanning the transition from erosion of sedimentary cover rocks—those rocks that do not record cooling associated with orogenesis—to exhumation of deeper basement rocks that do contain a record of orogen-related cooling. Once the cover layer has been removed, all rocks that are eroded afterwards will have shorter lag-times, with fission-track cooling ages that are diagnostic of deeper exhumation related to increased erosion rates. The increased erosion rates result from increases in relief associated with crustal thickening and topographic growth. These shorter time lags are often used to estimate exhumation rates but where there are marked changes in lag-time over periods of <5 Myrs the thermal field (and therefore depth to closure isotherm) will not have had sufficient time to adjust to a new steady-state (for example, Reiners and Brandon, 2006), which can make such calculations problematic.

The U-Pb (zircon) system is characterized by higher resistance to thermal overprinting (>700-900 °C for zircon; Mezger and Krogstad, 1997). U-Pb age dating of detrital zircons therefore mainly provides crystallization ages, recording the time at which zircons in the source lithology formed from melt. U-Pb (zircon) ages can thus be used to fingerprint sediment sources. This dating technique is also useful to help distinguish between zircon fission-track ages that record magmatic formation and those that record post-metamorphic cooling (Carter and Moss, 1999; Carter and Bristow, 2000). Although this method only strictly works for grains that are individually double dated, knowledge of the timing of periods of magmatic cooling, revealed by the U-Pb (zircon) ages, can still help to distinguish between fission-track ages that mark magmatic cooling compared to exhumation-induced cooling.

Zircons were extracted from crushed rock samples using conventional density separation methods, mounted in teflon (up to three mounts per sample), and polished and etched for variable periods of time (up to 48 hours) to optimize track revelation for zircons with different ages and variable uranium concentrations. The samples were irradiated with low-uranium muscovite external detectors (Hurford and Green, 1983) and Corning dosimeter glass CN-2 at the FRM II thermal neutron facility at the University of Munich in Germany. Fission-track densities were measured using an optical microscope at 1250× magnification with an oil objective. More than 50 to 100 grains were counted per sample, although in samples with low zircon yields fewer grains were analyzed. Ages (±1 s) were calibrated by the zeta method (Hurford and Green, 1983), using a zeta factor of 129 ± 5 (A. Whitchurch) determined by multiple analyses of zircon age standards (Tardree rhyolite, Buluk tuff, Fish Canyon tuff and Mount Dromedary banatite,) following the recommendations of Hurford (1990).

Detrital samples can be composed of mineral grains derived from entire hinterland drainage catchments. Different zircons within each detrital sample may therefore record a different fission-track age relating to the differential cooling of the catchment area source rocks. For each detrital sample between one and four fission-track component populations are identified (P1-P4). P1 relates to the most recent period of cooling experienced by that sample and P2, P3 and P4 relate to successively older periods of cooling. The fission-track grain age distributions were decomposed *via* binomial peak fitting (Galbraith and Green, 1990) into individual major age component populations using BinomFit (Brandon, 1992; Ehlers and others, 2005).

For the U-Pb (zircon) analyses, the detrital zircons were mounted in epoxy resin on a glass slide and polished. Data were produced on a New Wave Nd:YAG 213 nm laser ablation system, coupled to an Agilent 7500a quadrupole ICP-MS. Real-time data were processed using GLITTER 4.4 data reduction software. Repeated measurements of external zircon standard Plesovice (TIMS reference age 337.13±0.37 Ma) (Sláma and others, 2008) and NIST 612 silicate glass (Pearce and others, 1997) were used to correct for instrumental mass bias and depth-dependent inter-element fractionation of Pb, Th and U. Ages and probability density functions were calculated using Isoplot (Ludwig, 2003). Where possible, 120 zircons per sample were dated to ensure no fraction of the population comprising more than 0.05 of the total was missed at the 95 percent confidence level (Vermeesch, 2004). The $^{238}U/^{206}Pb$ ages are discussed here, with errors given at 2σ, because this ratio is generally more precise for younger ages (<1000 Ma) (Gehrels and others, 2006).

THE PYRENEAN OROGEN

Plate Tectonic Motions

The Pyrenees formed during collision of the Iberian and European plates between the Late Cretaceous and Miocene. Plate kinematic models, based on Atlantic magnetic anomalies, describe the relative motions of the Iberian, African and Eurasian plates (Srivastava and others, 1990a, 1990b; Roest and Srivastava, 1991; Roest and others, 1992; Srivastava and Roest, 1996; Torsvik and others, 2001; Rosenbaum and others, 2002). Reconstructions of plate motions show a mainly anticlockwise rotation of Iberia with respect to Europe (van der Voo, 1969; Galdeano and others, 1989).

Prior to ~84 Ma Iberia acted independently, moving laterally with respect to Africa and Europe and resulting in extension and transtension (Srivastava and others, 1990a; Roest and Srivastava, 1991). During the middle Cretaceous (~120-83 Ma), the Bay of Biscay opened and Iberia moved eastward with respect to the European plate (Rosenbaum and others, 2002), with motion accommodated by left-lateral strike-slip movement (Montigny and others, 1986; Costa and Maluski, 1988). Crustal thinning resulted in high temperature-low pressure (HT-LP) metamorphism in a narrow band adjacent to the North Pyrenean Fault (NPF) (Goldberg and Leyreloup, 1990).

At ~83 Ma, Iberia joined the African plate and relative plate motion changed to convergence (Rosenbaum and others, 2002), resulting in the inversion of the Mesozoic basins. Pyrenean uplift—here defined as the growth of topography—initiated in the east and propagated westward, as a result of the oblique partial subduction of the Iberian plate beneath the Eurasian plate (Choukroune and ECORS Team, 1989; Martín-Chivelet and others, 2002; Capote and others, 2002). Plate kinematic reconstructions indicate a period of tectonic quiescence during the Paleocene (~68-56 Ma), when Iberia stopped moving with respect to Europe (Rosenbaum and others, 2002). Iberia resumed motion during the Eocene (~55-46 Ma), marked by a short period of right lateral strike-slip motion (Soula and others, 1986). Convergence between Iberia and Europe continued until the Oligocene-Miocene (Rosenbaum and others, 2002; Capote and others, 2002). Compressional motion ceased during the middle to late Miocene (Alonso-Zarza and others, 2002) and since ~24 Ma, Iberia has been joined with the Eurasian plate (Capote and others, 2002).

During early compression (early Paleogene) there existed an east-west trending embayment that opened westward to the Bay of Biscay (Plaziat, 1981). Continued diachronous, east-to-west convergence and the progressive emergence of the Pyrenean Axial Zone during the Eocene separated a pro-foreland basin in the south (Ebro basin) from a retro-foreland basin in the north (Aquitaine basin) (Alonso-Zarza and others, 2002; Capote and others, 2002) (fig. 1).

In the eastern Pyrenees, convergence was replaced with extensional movements related to the opening of the Valencia Trough during the Oligocene (~28 Ma), with extension gradually migrating westward and replacing compression (Vergés and others, 2002).

Thermal Evolution of the Pyrenean Axial Zone

Existing thermochronological (bedrock apatite and zircon fission-track and zircon U-Pb) data are summarized. They are used to constrain the timing of events occurring in the Pyrenees and to provide a context within which to interpret our new thermochronological data.

Bedrock U-Pb (zircon) age data.—U-Pb dating of zircons from plutonic rocks within the Pyrenean Axial Zone provides crystallization ages and therefore, if concordant, dates the time of zircon growth (fig. 2A). Three major age components are evident. Firstly, the Axial Zone is dominated by rocks formed during the Carboniferous (~317-301 Ma) resulting from plutonism and volcanism associated with the Hercynian

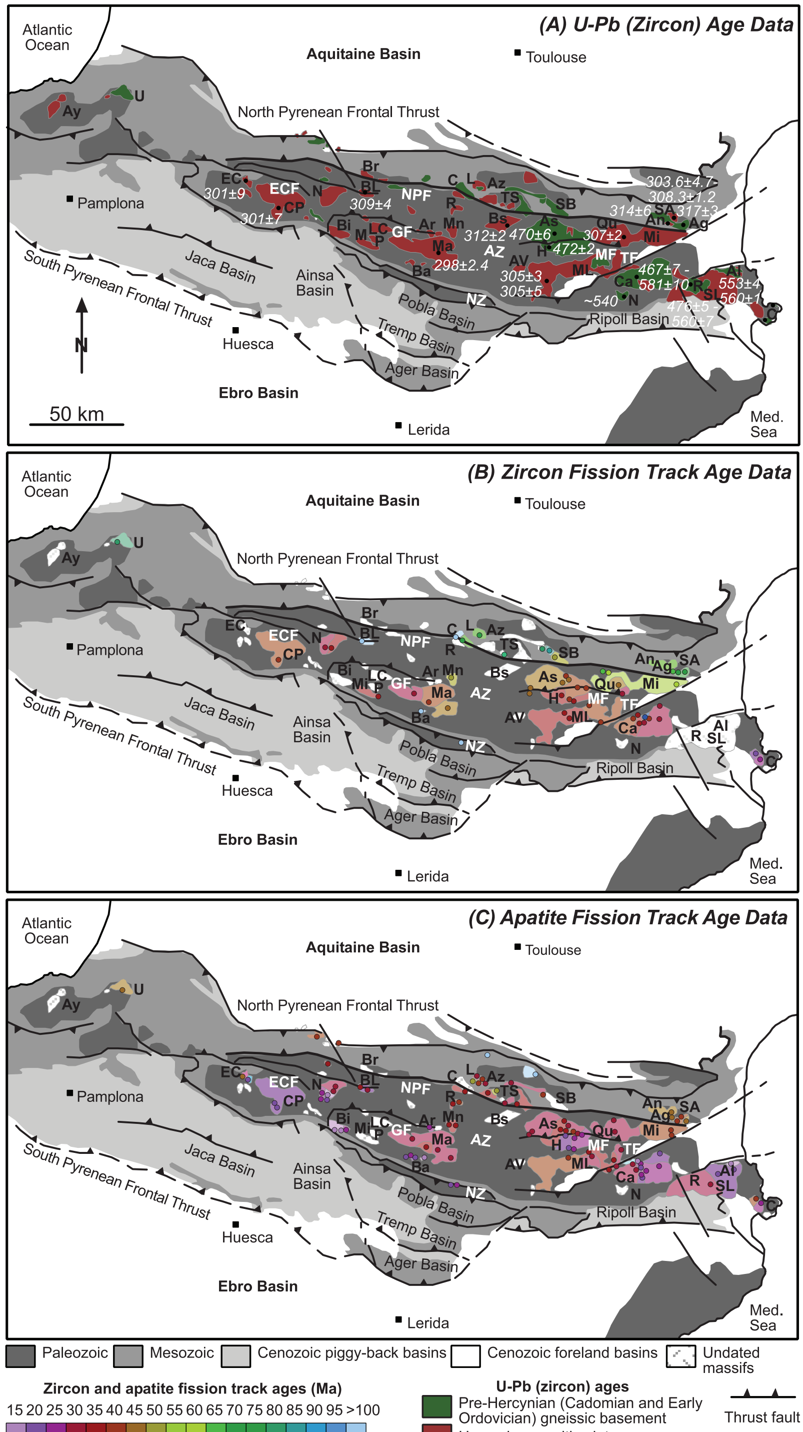


Fig. 2. Thermal evolution of the Pyrenean Axial Zone. (A) Bedrock U-Pb (zircon) age data (from Vitrac-Michard and Allegre, 1975; Respaut and Lancelot, 1983; Evans, ms, 1993; Romer and Soler, 1995; Paquette and others, 1997; Guerrot, 1998; Roberts and others, 2000; Deloule and others, 2002; Maurel and

(Variscan) Orogeny (Respaut and Lancelot, 1983; Evans, ms, 1993; Romer and Soler, 1995; Paquette and others, 1997; Guerrot, 1998, 2004; Roberts and others, 2000; Maurel and others, 2004; Olivier and others, 2004; Ternet and others, 2004; Gleizes and others, 2006; Olivier and others, 2008). The Hercynian rocks are distributed across the length and width of the Axial Zone (fig. 2A). Additionally, two significant pre-Hercynian periods of igneous activity have been identified: Ediacaran to Early Cambrian (580-540 Ma) magmatism and Early Ordovician (475-460 Ma) magmatism. Both periods represent the final stages of the Cadomian Orogeny and the transition to the Hercynian cycle (Vitrac-Michard and Allegre, 1975; Deloule and others, 2002; Cocherie and others, 2005; Castiñeiras and others, 2008; Denele and others, 2009). The Cadomian rocks are predominantly exposed in the eastern Axial Zone, but also outcrop north of the NPF. Importantly, plutonism associated with the Pyrenean Orogeny between the Late Cretaceous and Miocene is not recorded.

Bedrock zircon fission-track data.—Figure 2B indicates that zircon fission-track ages ranging from Cretaceous to Miocene are recorded in the Pyrenean Axial Zone. Early to Late Cretaceous cooling ages are interpreted as rift-induced periods of cooling, such as the opening of the Bay of Biscay (~120-83 Ma; Rosenbaum and others, 2002), and the associated HT-LP metamorphism (~98-87 Ma; Goldberg and Leyreloup, 1990). Because the U-Pb (zircon) data record no plutonism associated with the Pyrenean orogeny, and because this period is associated with tectonic convergence, fission-track ages ranging from the Late Cretaceous to Miocene are generally interpreted to represent erosion-induced exhumational cooling resulting from topographic growth during the Pyrenean orogeny (Sinclair and others, 2005; Maurel and others, 2008; Metcalf and others, 2009). However, late Oligocene to Miocene ages recorded in the extreme eastern Pyrenees (Cap de Creus) have been interpreted to represent normal fault-induced cooling because, at this time, the extreme eastern Pyrenees had undergone a transition to an extensional regime in association with the opening of the Gulf of Lyon (Maurel and others, 2004, 2008; Calvet and Gunnell, 2008; Gunnell and others, 2009).

Of the zircon fission-track ages that record Pyrenean exhumation, two cooling-age patterns are evident. Firstly, a younging trend from north to south across the Axial Zone is observed. For example, the Ursuya, Castillón, Lacourt, Querigut, Millas and Agly plutons in the northern Pyrenees (fig. 2B) each record cooling during the Late Cretaceous to Paleocene. Eocene cooling ages are recorded at Cauterets-Panticosa, Marimaña, Aston, Hospitalet and Mont Louis. Further south, late Eocene to Oligocene ages are recorded at Neouvielle, Maladeta and Canigou. The second pattern is a younging trend of Pyrenean exhumation from east to west across the Axial Zone. The majority of Paleocene cooling ages are observed in the eastern Pyrenees (for example, at the Agly, Querigut and Millas plutons). Paleocene cooling ages are rarely recorded in the central Pyrenees and further west. The exception is Ursuya, in the extreme western Pyrenees, where Late Cretaceous cooling ages are recorded. The late Oligo-

others, 2002, 2004, 2008; Olivier and others, 2004, 2008; Ternet and others, 2004; Cocherie and others, 2005; Gleizes and others, 2006; Castiñeiras and others, 2008; Denele and others, 2009). (B) Bedrock zircon fission-track age data (from Garwin, ms, 1985; Yelland, ms, 1991; Sinclair and others, 2005; Maurel and others, 2008). (C) Bedrock apatite fission-track age data (from Garwin, ms, 1985; Yelland, ms, 1991; Morris and others, 1998; Fitzgerald and others, 1999; Maurel and others, 2002, 2004, 2008; Sinclair and others, 2005; Gibson and others, 2007; Jovilet and others, 2007). North Pyrenean Massifs: U—Ursuya, Br—Barousse, C—Castillón, Az—Arize, TS—Trois Seigneurs, SB—Saint Barthelemy, As—Aston, H—Hospitalet, Ca—Canigou, N—Nuria, Ag—Agly, R—Roc de Frausa, Al—Alberes, C—Cap de Creus. Main granitic plutons: Ay—Aya, EC—Eaux Chaudes, CP—Cauterets-Panticosa, N—Neouvielle, Bi—Bielsa, BL—Borderes-Louron, Mi—Millares, P—Posets, LC—Lys-Caillaouas, Ba—Barruera, Ma—Maladeta, Ar—Arties, Mn—Marimaña, R—Riberot, L—Lacourt, Bs—Bassies, Av—Andorra, ML—Mont-Louis, Qu—Querigut, Mi—Millas, An—Ansignan, SA—St Arnac, SL—Saint Laurent.

cene to Miocene ages recorded in the extreme eastern Pyrenees (Cap de Creus) do not fit with the east-to-west younging trend. We suggest that this Pyrenean trend has been overprinted in the extreme east due to extension-related cooling and exhumation associated with the opening of the Gulf of Lyon (Maurel and others, 2004, 2008; Calvet and Gunnell, 2008; Gunnell and others, 2009).

Bedrock apatite fission-track data.—The bulk of published exhumation studies have used the apatite fission-track method because, owing to the lower closure temperature of this chronometer, it is more sensitive to small changes in erosion rate and depth of erosion. Figure 2C displays published bedrock apatite fission-track ages. They range from early Eocene to Miocene and are interpreted to represent cooling associated with erosion-induced exhumation relating to Pyrenean orogenic growth (Fitzgerald and others, 1999; Sinclair and others, 2005; Gibson and others, 2007; Jolivet and others, 2007; Maurel and others, 2008; Metcalf and others, 2009). Miocene ages recorded in the extreme eastern Pyrenees are again interpreted to relate to the opening of the Gulf of Lyon (Maurel and others, 2004, 2008; Calvet and Gunnell, 2008; Gunnell and others, 2009).

As with the zircon fission-track data, the apatite fission-track ages record a trend of southward-younging cooling ages across the Axial Zone. Those massifs in the north (Ursuya, Lacourt, Arize, Agly and Millas), many located north of the NPF, record cooling during the early Eocene. Farther south, Neouvielle, Maladeta, Marimaña, Riberot, Aston and Mont Louis all record cooling during the late Eocene to Oligocene. Massifs predominantly located at the southern margin of the Axial Zone (for example Cauterets-Panticosa, Bielsa, and Barruera) record late Oligocene to Miocene cooling. This southward-younging cooling age trend has been documented for individual north to south oriented transects across the western (Jolivet and others, 2007) and central Pyrenees (Fitzgerald and others, 1999; Sinclair and others, 2005; Gibson and others, 2007). Fitzgerald and others (1999) suggest that the variation in the exhumation pattern is controlled by the way in which contraction was accommodated in the Axial Zone. During the Eocene, thrusting was accommodated by inversion of extensional faults and thrust stacking during frontal propagation. During the Oligocene, crustal wedging and duplex formation caused rapid exhumation of the southern flank of the Axial Zone (Beaumont and others, 2000). Alternatively, Sinclair and others (2005) suggest that Pyrenean orogenic asymmetry is a simple consequence of the inherent tectonic growth of a doubly-vergent orogen.

The east to west younging trend observed in the zircon fission-track data is not clear in the apatite data, because several eastern massifs record younger, Miocene cooling (for example Canigou, Roc de Frausa and Alberes). Maurel and others (2004, 2008) suggest that late Oligocene (26-27 Ma) ages at Canigou result from the extensional reactivation of the Tet fault during opening of the Gulf of Lyon. The young cooling ages in the eastern Pyrenees therefore indicate the end of contraction here and the transition to an extensional regime. However, exhumation induced by erosion continued in the central Pyrenees at this time, as evidenced by young apatite fission-track ages recorded at the Bielsa and Barruera plutons and the Nogueres Zone (Sinclair and others, 2005; Gibson and others, 2007). Overall, the apatite data support interpretation of a general younging of erosion-induced cooling from east to west across the Pyrenean Axial Zone, as also recorded by the zircon fission-track data. The data imply diachronous topographic growth, from east to west, associated with the Pyrenean orogeny.

Tectono-Sedimentary Evolution of the Southern Pyrenees

Here we outline the tectono-sedimentary evolution of the southern Pyrenees as a framework within which to interpret the thermochronological data. Figure 3(A, B, C) provides a temporal and spatial reconstruction of the tectono-sedimentary evolution of

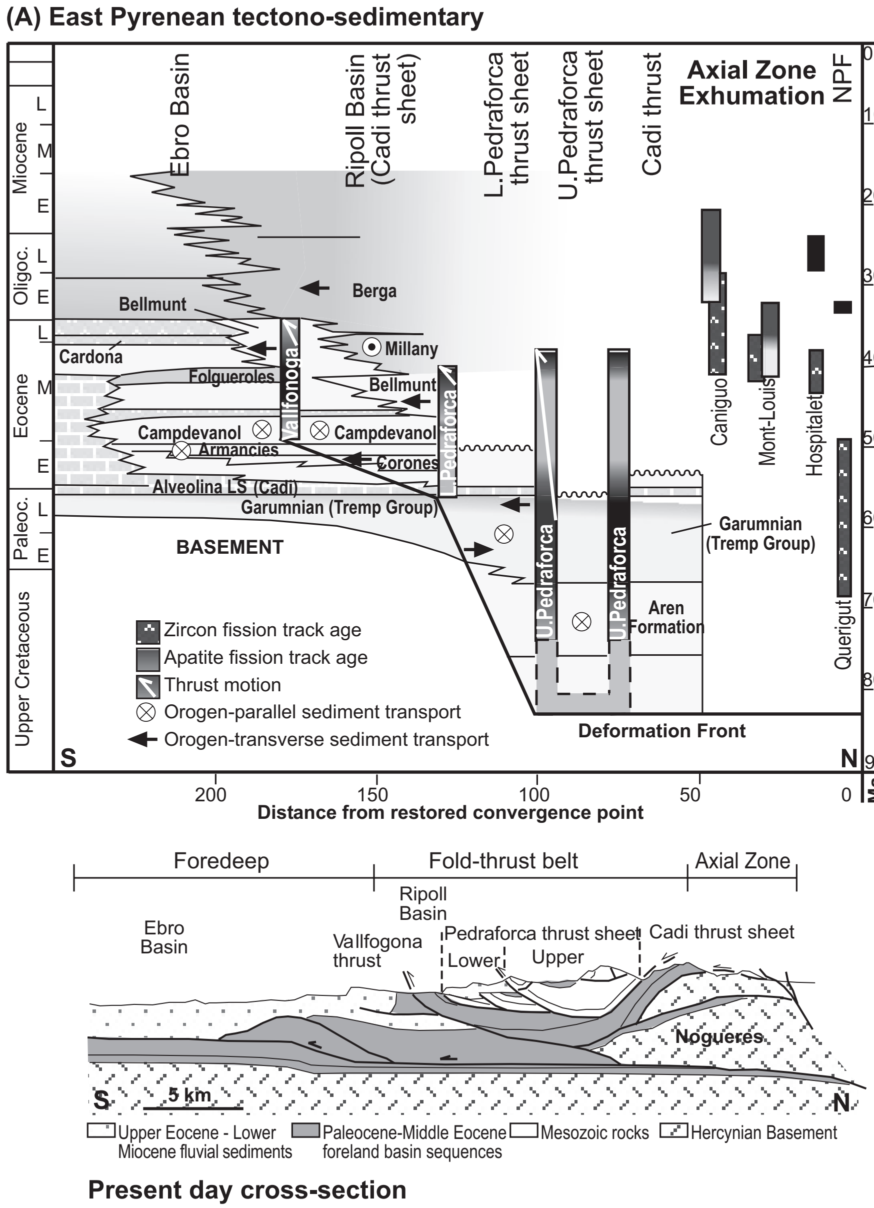


Fig. 3. Time-distance charts summarizing south Pyrenean tectono-sedimentary evolution, plus present-day geological cross-sections: (A) eastern transect, (B) central transect, (C) west-central transect. The time-distance charts illustrate the evolution of the sediment routing systems, fold-and-thrust belt development (darker colors indicate more rapid thrusting) and Axial Zone exhumation (darker colors indicate more rapid cooling) in three north-to-south oriented transects along orogenic strike (after Sinclair and others, 2005) (transects locations in Figure 1). Bedrock apatite and zircon fission-track data constraining timing of Axial Zone exhumation from Fitzgerald and others (1999); Maurel and others (2002, 2004, 2008); Sinclair and others (2005); Gibson and others (2007); Jovilet and others (2007). Thrust locations based upon restored cross-sections of Vergés (ms, 1993); Vergés and others (1995, 1998); Teixell (1996); Beaumont and others (2000) and Capote and others (2002). Timing of thrusting from Muñoz (1992); Vergés (ms, 1993); Teixell (1996); Meigs (1997); Meigs and Burbank (1997); Vergés and others (1995, 1998); Sinclair and others (2005) and references therein, verified through field analysis. Stratigraphy, biostratigraphic and magnetostratigraphic data from Alvaréz Sierra and others (1990); Burbank and others (1992); Hogan (ms, 1993); Mellere (1993); Hogan and Burbank (1996); Meigs and others (1996); Nijman (1998); Vergés and others (1995, 1998); Ardevol and others (2000); Beamud and others (2003) and Beamud and others (2011). Present day cross-sections from Vergés and others (1995); Teixell (1996); Beaumont and others (2000) and Capote and others (2002).

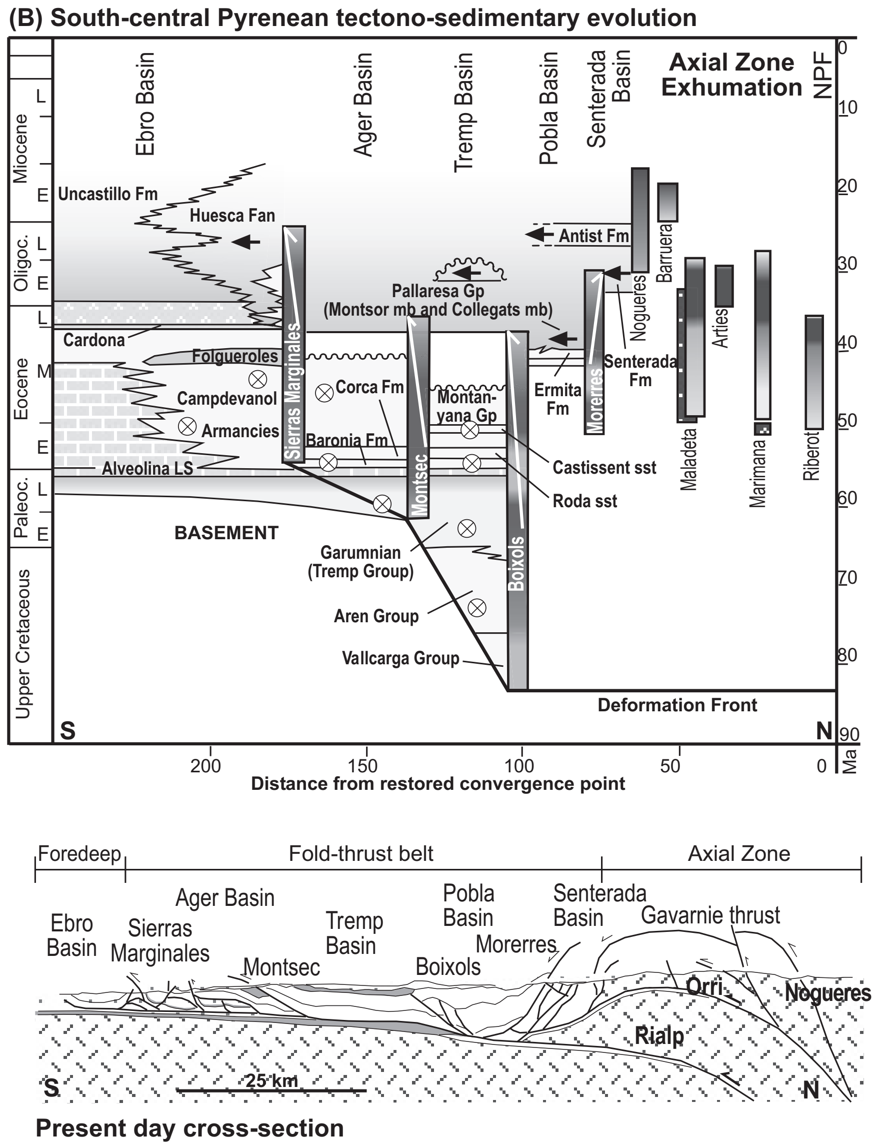


Fig. 3 (continued)

three north-south trending transects (eastern, central and west-central) for the southern Pyrenees. Each transect illustrates the cooling history of the Axial Zone based on existing apatite and zircon bedrock fission-track data. The Axial Zone is bounded to the north by the NPF, which is considered to be the axis of the collisional belt and presents the boundary between the Iberian and European plates (Choukroune and ECORS Team, 1989). The southern fold-and-thrust belt comprises dominantly south-vergent thrust sheets that have been transported southward on a basal detachment. Thrust sheets are composed mostly of Mesozoic limestone (Vergés and Muñoz, 1990). Each main thrust sheet is associated with a piggy-back (Ori and Friend, 1984) or

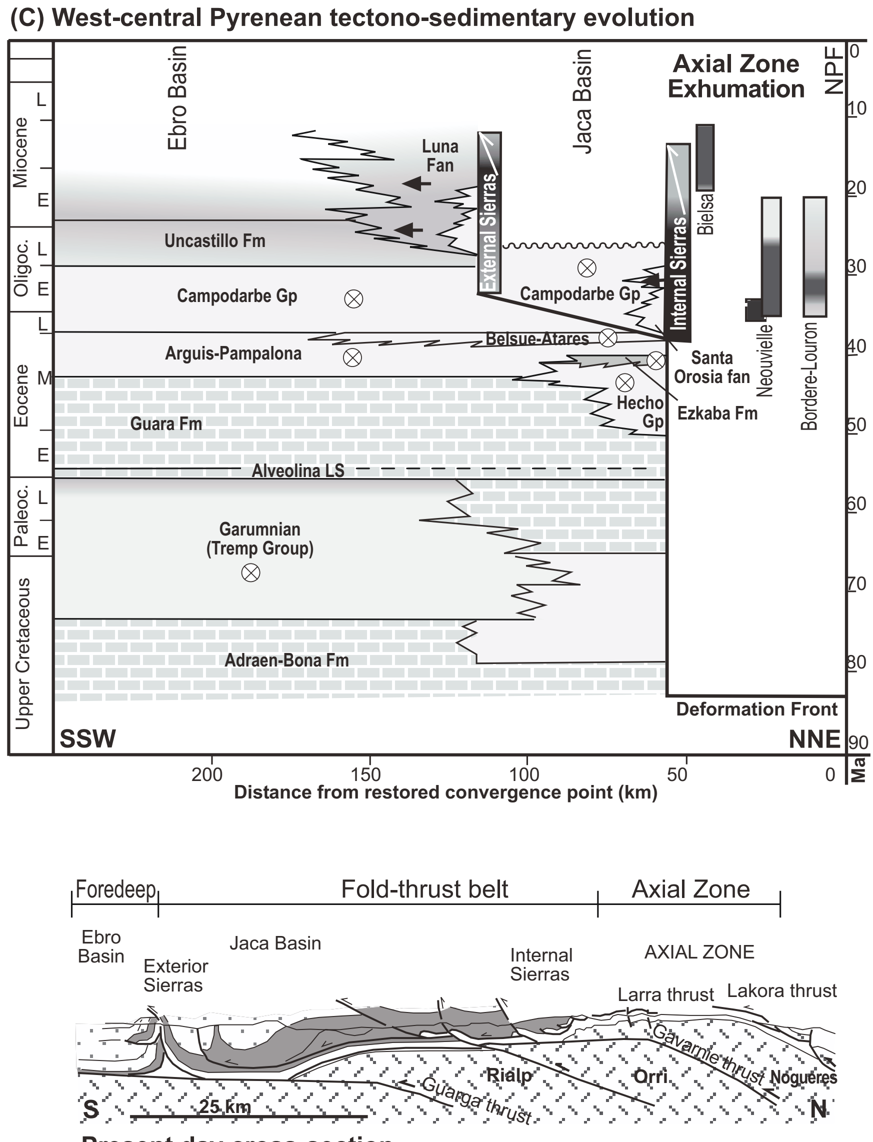


Fig. 3 (continued)

wedge-top basin (DeCelles and Giles, 1996) in its footwall that was active during thrust deformation. The chronology of thrust development is constrained through analysis of the deformation of well-dated stratigraphic units. The reconstructions are based on existing published data, and our own field analyses.

Eastern Pyrenean tectono-sedimentary development (fig. 3A).—In the eastern south Pyrenees, inversion of Mesozoic extensional basins resulted in southward emplacement of the Pedraforca thrust sheet during the Late Cretaceous (Burbank and others, 1992; Vergés, ms, 1993). The Garumnian Formation records deposition in an east-west trending trough connected to the Atlantic Ocean that formed in response to the inversion (Rosell and others, 2001). During the Maastrichtian, the depositional environment evolved from a quiet, muddy floodplain to a high-energy sandy braid-plain (Masriera and Ullastre, 1982; Oms and others, 2007) with a sediment source region to the south (Ebro Massif; Masriera and Ullastre, 1982) and east (Gulf of Lyon; Rosell and others, 2001). Just prior to the K-T boundary the provenance of the Garumnian Formation switched to the north; the upper Garumnian Formation exhibits south-southwesterly and westerly paleoflow, dispersing sediment toward the central and western Pyrenees. This transition of provenance is interpreted to represent the initiation of significant Pyrenean topography (Rosell and others, 2001).

After a period of relative tectonic quiescence during the Paleocene, shortening rates accelerated in the Eocene (Vergés, ms, 1993; Vergés and others, 1998), with thrusting of the Pedraforca and Cadi thrust sheets, out-of-sequence thrusting and development of the Vallfogona frontal thrust (Puigdefàbregas and others, 1986; Burbank and others, 1992; Vergés and others, 1998). The Ebro foredeep developed as underfilled and marine from ~55 to 37 Ma (Puigdefàbregas and Souquet, 1986; Puigdefàbregas and others, 1992; Vergés and others, 1995; Vergés and others, 1998). The marine deposits exhibit westerly paleoflow, toward the central and western Pyrenees (for example the Armancies and Campdevanol turbidites; Puigdefàbregas and others, 1986), with subordinate contributions from northerly derived, southward prograding deltaic sediments (for example, the Corones system; Burbank and others, 1992) and alluvial fan carbonate-conglomerates sourced from local thrust uplifts (for example, the Bellmunt conglomerates; Burbank and others, 1992).

Sediment dispersal transverse to orogen-strike occurs during the late Eocene to Oligocene. The granitic composition of the Millany conglomerates and Folgueroles turbidites indicates the significant contribution of Axial Zone derived material after ~42 Ma, associated with unroofing of the crystalline basement (Puigdefàbregas and others, 1986; Muñoz, 1992). The prograding alluvial fan deposits of the Millany Formation exhibit some easterly paleoflow associated with development of the Ripoll syncline and the separation of the eastern and central Pyrenees by the oblique boundary structure of the south-central Pyrenean unit (Puigdefàbregas and others, 1992; Burbank and others, 1992).

During the late Eocene (~37 Ma) uplift of the western Pyrenees closed connections with the Atlantic Ocean and the Ebro became an internally drained, intermontane basin. The Cardona evaporite horizon marks the end of marine deposition within the Ebro foredeep (Puigdefàbregas and Souquet, 1986; Puigdefàbregas and others, 1992; Vergés and others, 1995; Vergés and others, 1998). The Vallfogona frontal thrust continued to deform during deposition of the Berga conglomerates (Burbank and others, 1992). Contraction in the eastern Pyrenees halted during the middle Oligocene (Vergés, ms, 1993).

Bedrock zircon fission-track data indicate exhumation of the Querigot pluton during the Late Cretaceous and Paleocene. Exhumation progressed southward across the Axial Zone with time. Apatite fission-track data reveal relative rapid exhumation (~0.5-0.6 mm/yr of the Mont Louis pluton; Maurel and others, 2002) during the late Eocene to Oligocene contemporaneous with deposition of the Millany and Berga conglomerates. Exhumation continued into the Miocene at the Canigou Massif (~27-21 Ma; Maurel and others, 2002, 2008); however, these apatite fission-track ages have previously been interpreted to represent exhumation caused by normal faulting associated with the extensional opening of the Valencia Trough toward the east at this time (Maurel and others, 2002, 2004; Calvet and Gunnell, 2008; Gunnell and others, 2009).

Central Pyrenean tectono-sedimentary development (fig. 3B).—Thrusting within the south-central Pyrenean fold-and-thrust belt began during the Late Cretaceous with inversion of the Boixols fault (Puigdefàbregas and Souquet, 1986). Sediment was dispersed toward the west-north-west, with an open-connection to the Atlantic Ocean (Puigdefàbregas and Souquet, 1986; Rosell and others, 2001). The primary foredeep deposits (including the Aren shallow marine sandstones and Garumnian fluvial sandstones) were detached and carried piggy-back style as part of the Montsec and Sierras Marginales thrust sheets owing to the sequential migration of the thrust front during the Paleocene to early Eocene (Puigdefàbregas and Souquet, 1986; Muñoz, 1992; Beaumont and others, 2000).

The Tremp and Ager wedge-top basins initially developed under marine conditions (for example, the carbonate platform Alveolina limestones, and the deltaic/tidal Roda and Baronia systems), with south-southwestward progradation toward the open Atlantic Ocean (Mutti and others, 1985; López-Blanco and others, 2003). The depositional environment within the wedge-top basins shallowed during the middle Eocene, with deposition of the Corca and Castissent fluvial sandstones. The two systems exhibit some interconnection between the Ager and Tremp basins, with a dominant orogen-parallel transport direction, connecting to the Ainsa and marine Jaca basins in the west (Nijman and Puigdefàbregas, 1978; Nijman, 1998).

During the early Eocene to Oligocene, out-of-sequence thrusting, recorded by the re-activation of the Boixols thrust and Morerres backthrust, resulted in the development of the Pobla and Senterada basins. Fluvial and alluvial deposition within these basins records the transition between orogen-parallel and orogen-transverse sediment dispersal at this time. During the middle Eocene, the Pobla Basin developed as underfilled and lacustrine (Ermita Formation; Mellere, 1993). Prograding alluvial fan units (the Montsor and Senterada formations; Mellere, 1993) record the progressive northward expansion of drainage catchments during the late Eocene to Oligocene (Beamud and others, 2011), with the contribution of high grade metamorphic rocks and a variety of Paleozoic clasts derived from the Nogueres and Axial Zones of the Pyrenees. Although fed in their proximal reaches by orogen-transverse fans, the late Eocene to Oligocene fan systems in turn fed the orogen-parallel fluvial Escanilla system to the west (Bentham and others, 1992).

Deposition underwent a transition to fully transverse during the Oligocene, with deposition of the Antist Group (and equivalents), whose polymict clast lithologies, composed of diverse Paleozoic metamorphic rocks, Paleozoic and Mesozoic limestones, volcanic rocks, and Triassic sandstones, indicate a source in the Axial Zone. The orogen-transverse conglomerates are argued by some to have draped the entire fold-and-thrust belt (Coney and others, 1996), though today these deposits are preserved only as isolated remnants. The remnants include the Antist Formation within the Senterada and Pobla basins (Mellere, 1993; Beamud and others, 2003; Beamud and others, 2011), the Collegats Formation at the top of the Sis paleovalley fill (Vincent, 2001), the Claramunt conglomerates in the Tremp Basin, and the Oliana, Ebro Basin and Huesca fan conglomerate units exposed at the Sierras Marginales thrust front, within the Ebro Basin (Hirst and Nichols 1986; Burbank and others, 1992; Burbank and Vergés, 1994; Meigs and others, 1996; Meigs, 1997). Deposition of Axial Zone derived clasts within the Ebro Basin is observed in deposits aged between ~35 to 25 Ma (Hirst and Nichols, 1986; Álvarez Sierra and others, 1990; Burbank and others, 1992; Burbank and Vergés, 1994; Meigs and others, 1996; Meigs, 1997; Arenas and others, 2001; Yuste and others, 2004) indicating the full transition to orogen-transverse sediment dispersal in the south-central Pyrenees during this time. Thrust front propagation into the Ebro foredeep halted at 29.5 Ma, but the thrust wedge continued to deform internally during the late Oligocene, until 24.7 Ma (Meigs and others, 1996).

Apatite and zircon fission-track data from the central Pyrenean massifs indicate relative thermal and tectonic stability during the early Eocene (55-50 Ma; Fitzgerald and others, 1999; Sinclair and others, 2005). Zircon fission-track data indicate the onset of exhumation of deep-seated rocks within the central Pyrenees during the early to middle Eocene, with cooling ages of 49.7 ± 3.1 Ma and 49.3 ± 2.6 Ma recorded at the Marimaña and Maladeta plutons (Sinclair and others, 2005).

During the late Eocene to Oligocene, the pattern of exhumation became markedly asymmetric, as evidenced by the apatite fission-track data, with denudation progressively focused toward the southern flank of the Axial Zone. From north to south, the Riberot pluton records a period of rapid exhumation between ~44 to 36 Ma (Fitzgerald and others, 1999), the Marimaña pluton at ~35 to 30 Ma (Sinclair and others, 2005), Arties at ~32 to 29 Ma (Gibson and others, 2007), and Maladeta at ~35 to 32 Ma (Fitzgerald and others, 1999; Sinclair and others, 2005).

During the late Oligocene to early Miocene the Nogueres Zone cooled (~30-24 Ma; Sinclair and others, 2005; Gibson and others, 2007), after which exhumation stepped back into the Axial Zone with cooling of the Barruera massif at ~21 to 19 Ma (Sinclair and others, 2005; Gibson and others, 2007). Zircon fission-track ages from the Barruera pluton (104.0 ± 7.0 Ma; Sinclair and others, 2005) and Nogueres Zone (159.0 ± 33.0 Ma; Sinclair and others, 2005) record periods of cooling prior to the onset of active collision and the Pyrenean orogen. That is, they do not record Pyrenean-aged cooling. The lack of Pyrenean-aged zircon fission-track data from these plutons implies that the late Eocene to Oligocene period of exhumation caused rocks from shallow levels to be brought to the surface, but was too short-lived or too slow to exhume deeper-seated rocks from below the zircon fission-track closure depth (Sinclair and others, 2005).

West-central Pyrenean tectono-sedimentary development (fig. 3C).—Inversion of extensional structures was also initiated during the Late Cretaceous in the western-central Pyrenees, on the Lakora Thrust, north of the presently exposed Axial Zone (Puigdefàbregas and others, 1992; Teixell, 1996). Development of the west-central Pyrenean fold-and-thrust belt did not occur until the middle to late Eocene. Prior to fold-and-thrust belt development, an east-west oriented foredeep, the Jaca Basin, developed. The northern Jaca Basin filled with turbiditic deposits of the lower to middle Eocene Hecho Group supplied from the central Pyrenees (Mutti, 1984), whilst a carbonate platform developed at the southern basin margin (Puigdefàbregas and Souquet, 1986). Overlying the Hecho Group, deposits of the Ezkaba Formation represent a granite-rich turbidite system fed from the Pyrenean Axial Zone farther east (Payros and others, 1997).

The Gavarnie thrust initiated in the late Eocene (Puigdefàbregas, 1975; Teixell, 1996) and the Internal Sierras uplifted as a complex imbricated thrust system. During the early Oligocene, continued development of the Gavernie thrust caused the erosional recycling of the Hecho Group into the terrestrial foreland basin Campodarbe deposits. However, overall the Campodarbe Formation depositional system was still dominated by axial fluvial deposition with westerly paleotransport (Puigdefàbregas, 1975; Turner, 1992; Hogan, ms, 1993).

The Guarga thrust initiated during the early Oligocene (Puigdefàbregas and Soler, 1973; Pocovi and others, 1990; Hogan, ms, 1993; Teixell, 1996), creating the External Sierras. The Jaca Basin was transported as a piggyback basin, southward over the Ebro Basin. During the late Oligocene, the Jaca basin-fill, including deposits of the Campodarbe Formation, was reworked into alluvial fan-type deposits of the Uncastillo Formation, Huesca and Luna fan systems (Puigdefàbregas, 1975; Hirst and Nichols, 1986; Hogan, ms, 1993; Arenas and others, 2001). Minor contributions from the Internal Sierras and Axial Zone are also recorded in the alluvial fan deposits (Nichols, 1987, 1989; Turner, 1992; Arenas and others, 2001). In the west-central Pyrenees deformation of the youngest frontal structures occurred during sedimentation of the lower Miocene conglomerates (the Luna fan system) (Nichols, 1987; Arenas and others, 2001).

Southward translation of the Gavarnie thrust sheet was contemporaneous with Axial Zone antiformal stack exhumation during the Oligocene to Miocene, as indicated by the bedrock apatite fission-track ages from the Bordere-Louron and Neouville massifs, which record exhumation between ~35 to 22 Ma (Jolivet and others, 2007). Exhumation continued until the middle Miocene on the southern-most Bielsa massif (Jolivet and others, 2007).

Summary of the south-Pyrenean tectono-sedimentary evolution.—Comparison of the three south-Pyrenean transects indicates the progressive east-to-west cooling of the Axial Zone rocks, with exhumation initiated during the Late Cretaceous in the eastern Pyrenees and the late Eocene to Oligocene in the western Pyrenees. The sediment routing systems are also shown to develop from dominantly orogen-parallel to orogen-transverse sequentially along orogen strike. Orogen-transverse sediment dispersal is established during the middle Eocene in the eastern Pyrenees, during the late Eocene to Oligocene in the central Pyrenees and during the late Oligocene in the western Pyrenees. Furthermore, frontal thrust propagation is shown to halt sequentially along orogen-strike, occurring during the late Eocene to Oligocene in the eastern Pyrenees, the late Oligocene in the central Pyrenees and the Miocene in the western Pyrenees.

DETRITAL ZIRCON DATA

Detrital Zircon U-Pb Age Data

U-Pb (zircon) age data from all Pyrenean detrital samples are presented in Appendix A and data from key stratigraphic units are summarized in figure 4. No U-Pb (zircon) age data younger than ~200 Ma were recorded in any of the detrital samples.

U-Pb (zircon) age data from the base of the Maastrichtian Aren sandstone exhibit a broad range of ages, with component populations at 584 Ma and 448 Ma. A minor peak at 288 Ma is also observed. The upper Aren sandstone, deposited later in the Maastrichtian, is dominated by a component population of 480 Ma.

The Paleocene Garumnian Formation and lower Eocene Roda and Castissent sandstones are all dominated by component peaks of ~300 Ma. The upper Eocene Upper Montanyana sandstone yielded few zircons, hence data are few, but also exhibits a component peak of ~300 Ma, with additional peaks at 468 Ma and 504 Ma.

The Antist, Claramunt, Ebro Basin and Huesca fan conglomerates, all deposited between the late Eocene and the late Oligocene, each exhibit a broad spectrum of U-Pb (zircon) ages, with ages spanning the range ~280 M to >1000 Ma.

Detrital Zircon Fission-Track Age Data

Our new detrital zircon fission-track grain age data are presented Appendix B. Figure 5 and table 1A represent a summary of all of the zircon fission-track grain ages, taken from every detrital sample, deconvolved into component peaks (P1, P2, P3) that are Late Cretaceous in age or younger. This provides a simple method for visualizing the dominant periods of erosion-induced exhumational cooling associated with the Pyrenean orogeny, as recorded by all of our detrital samples. The grouped data record three dominant age components of ~77.5 Ma, ~50.9 Ma and ~30.5 Ma.

Figure 6 illustrates the youngest component peaks from individual samples plotted against the depositional age of that sample in a lag-time plot. The lag time is defined as the difference between the youngest (P1) zircon fission-track age and the depositional age of that sample (Garver and others, 1999). Lag-time analysis of the detrital zircon fission-track data from the south-central Pyrenees is assessed within the

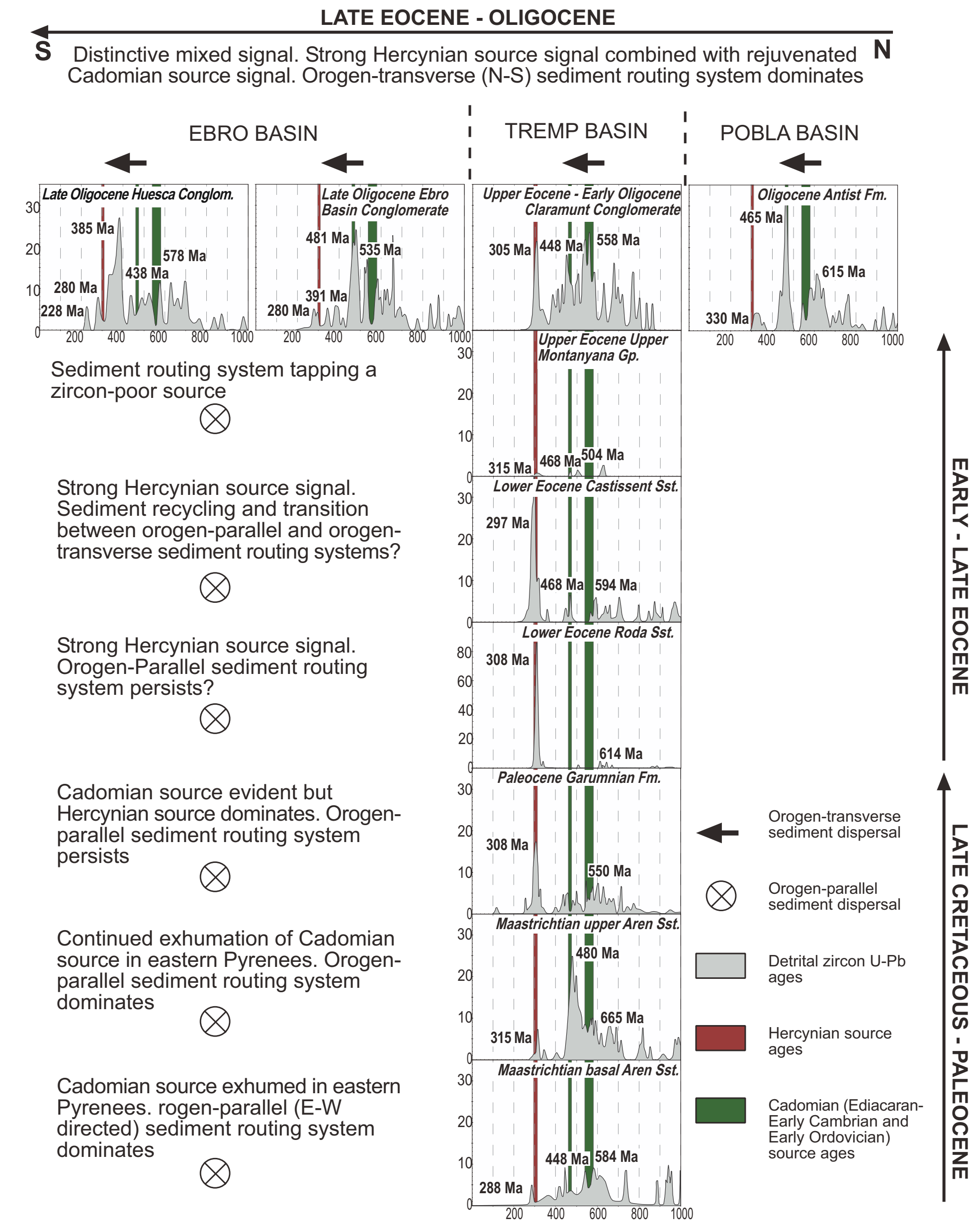


Fig. 4. Detrital zircon U-Pb age data from the south-central Pyrenees. Detrital zircon U-Pb dates, plotted as cumulative probability diagrams using Isoplot (Ludwig, 2003), provide information on the crystallization age of the zircons and therefore act as a fingerprint for provenance. Vertical sampling through the Tremp basin stratigraphy allows tracking of the temporal variation in the provenance signal and sediment routing system evolution. Transverse sampling (approximately one time line) from north to south within adjacent wedge-top basins and the foredeep allows correlation of sediment routing systems downstream.

context of the reconstructed sediment routing systems, with those samples taken from deposits of the orogen-parallel drainage systems distinguished from those taken from the orogen-transverse drainage systems. The data record long lag times during Late

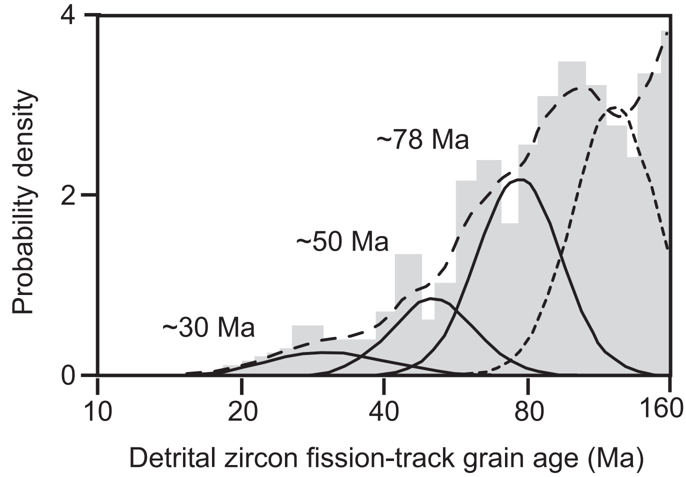


Fig. 5. Summary probability-density plot with best-fit component populations. The detrital zircon fission-track grain ages from all Pyrenean samples analysed during this study are summarized. Grain age components are deconvolved into best-fit component populations using BinomFit (Brandon, 1992; Ehlers and others, 2005). Only those component populations recording Pyrenean-aged cooling are shown here. The details of the component population ages are given in table 1A.

Cretaceous deposition of the Aren sandstone, decreasing through the Paleocene. A short lag-time of *ca.* 15 Myr is recorded in the sandstone deposits of the upper Garumnian Formation. During the early to middle Eocene, lag times significantly increased to *ca.* 50 to 70 Myr, before decreasing again during the late Eocene to Oligocene. Lag times reached a minimum of *ca.* 3 Myr during deposition of the Senterada Formation in the early Oligocene. Finally, lag times sharply increased again during the late Oligocene, with the Antist Formation recording lag times of *ca.* 100 Myr between ~27 to 24 Ma.

detrital zircon interpretation

Detrital Zircon U-Pb Dating as a Fingerprint for Provenance

To better constrain the sediment source regions for the depositional systems, the detrital zircon U-Pb age data are compared to the bedrock zircon U-Pb ages in the Pyrenean Axial Zone (fig. 2A).

Table 1A

Detrital zircon data from south-central Pyreanean samples grouped and summarized according to the best fit component populations shown in figure 5

Sample	Nt	Binomial Component Population Fit Ages (Ma)		
		P1	P2	P3
All detrital grains	842	30.5 (-2.9 / +3.2) Nf = 1.6 % W = 0.27	50.9 (-4.9 / +5.5) Nf = 4.2 % W = 0.20	77.5 (-6.5 / +7.1) Nf = 11.0 % W = 0.20

Table 1B

Summary of the detrital zircon fission-track grain ages for individual samples

Sample (Depositional Age)	Nt	Binomial Component Population Fit Ages (Ma)			
		P1	P2	P3	P4
Nogueres Zone 1 (255.9 Ma + 5.25 / - 5.25)	35	323.6 (-19.9 / +21.2)			
Nogueres Zone 2 (240.5 Ma + 5.5 / - 5.5)	40	262.3 (-22.3 / +24.3)	382.1 (-30.8 / +33.5)		
Aren Fm. (Tremp Basin) (73.0 Ma + 2.0 / - 2.0)	21	134.8 (-14.9 / +16.7)	326.8 (-21.2 / +22.6)		
Garumnian Fm. (Ager Basin) (57.25 Ma + 1.65 / - 1.65)	75	72.3 (-7.6 / +8.5)	134.7 (-10.8 / +11.7)	298.5 (-16.6 / +17.5)	
Lower Corca Fm. (Ager Basin) (52.5 Ma + 0.8 / - 0.8)	75	122.2 (-9.1 / +9.9)	255.8 (-16.9 / +18.1)	401.5 (-29.1 / +31.3)	
Upper Corca Fm. (Ager Basin) (49.25 Ma + 2.05 / - 2.05)	73	99.3 (-7.6 / +8.2)	248.3 (-17.6 / +18.9)	414.1 (-33.4 / +36.2)	
Montsor Conglomerate (Pobla Basin) (37.0 Ma + 3.2 / - 3.2)	85	51.5 (-6.0 / +6.7)	76.7 (_5.3 / +5.7)	127.7 (-8.1 / +8.6)	288.6 (-13.9 / +14.6)
Lower Senterada Fm. (Senterada Basin) (30.0 Ma + 2.0 / - 3.0)	95	30.0 (-2.4 / +2.7)	239.3 (-11.7 / +12.3)		
Upper Senterada Fm. (Senterada Basin) (27.0 Ma + 5.0 / - 0)	92	41.5 (-3.9 / +4.3)	166.8 (-13.3 / +14.5)	294.7 (-16.6 \ +17.6)	
Claramunt Conglomerates (Tremp Basin) (29.0 Ma + 4.9 / - 0.6)	74	70.7 (-5.3 / +5.7)	100.8 (-5.6 / +5.9)		
Antist Fm. (Pobla Basin) (25.5 Ma + 1.5 / - 1.5)	56	128.6 (-27.4 / +34.7)	195.1 (-48.5 / +64.2)	287.3 (-19.6 / +21.0)	
Oliana Conglomerate (Ebro Basin) (35.15 Ma + 1.15 / - 1.15)	100	57.1 (-3.3 / +3.5)	186.8 (-9.1 / +9.6)	355.3 (-21.9 / +23.3)	
Ebro Basin Conglomerate (Ebro Basin) (26.3 Ma + 1.65 / - 1.65)	68	51.8 (-4.5 / +5.0)	95.2 (-7.5 / +8.2)	239.4 (-7.5 / +8.2)	
Sis Conglomerate (Sis Paleovalley) (36.9 Ma + 3.1 / - 3.1)	28	111.8 (-10.7 / +11.8)	267.5 (-15.6 / +16.5)		

The individual grain age data are deconvolved into age component populations using Binomfit (Brandon, 1992; Ehlers and others, 2005).

Nt = total number of grains counted; Nf = calculated percentage of grains in a specific component population or fraction; W = estimated relative standard deviation for a component population, expressed in percentage of component population age; uncertainties cited at ±1σ.

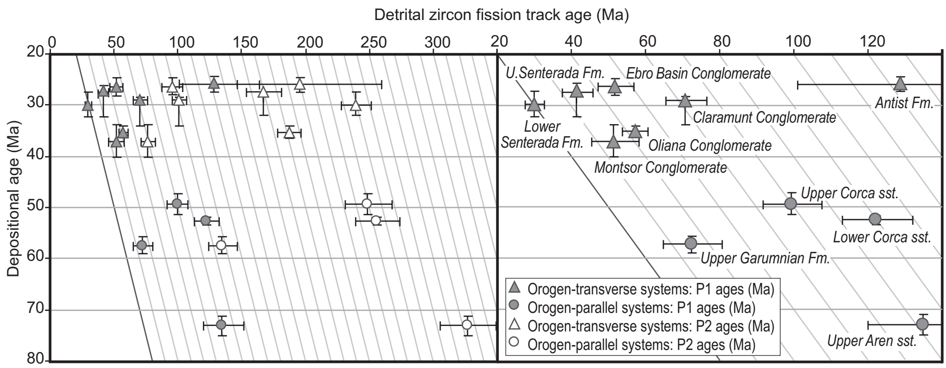


Fig. 6. Lag-time plot for the south-central Pyrenees. (A) Lag-time plot summarizing the zircon fission-track cooling ages obtained from detrital samples from the south-central Pyrenees. The zircon fission-track cooling age data from individual samples are plotted against the depositional age of each sample. Individual fission-track ages represent those component population ages (P1 and P2) derived through the deconvolution of up to 100 individual grain ages from each sample. P1 corresponds to the youngest cooling age obtained. The lag-time is the difference between the cooling age and the depositional age of the detrital sample zircons. Short lag-times correspond to periods of rapid exhumation and long lag-times correspond to slow exhumation. Lag-time contours in 10 Myr intervals. (B) Lag-time plot focusing on the P1 ages only. Individual sample names are given corresponding to table 1B.

No U-Pb (zircon) ages younger than 200 Ma were recorded in any of the detrital samples, supporting claims that the Pyrenean orogeny was not associated with any granitic plutonism (Choukroune and ECORS Team, 1989). Only late Neogene to Quaternary volcanism associated with extension in the eastern Pyrenees is known (Arana and others, 1983; Martí and others, 1992; Gunnell and others, 2008).

U-Pb (zircon) age data from the Maastrichtian Aren sandstones exhibit a broad range of ages. We suggest that the youngest ~300 Ma aged zircons formed during plutonism associated with the Hercynian orogeny. Component populations at ~448 Ma and ~584 Ma in the basal Aren sandstone are interpreted as Ordovician and Ediacaran ages, indicative of zircons crystallized during Cadomian magmatism (Castiñerias and others, 2008). The Cadomian signal is continued and is amplified in the slightly younger deposits of the upper Aren sandstone. A dominant component population of ~480 Ma in the upper Aren sandstones fits well with the Early Ordovician timing of plutonism reported by Castiñeiras and others (2008). Plutons formed during the Cadomian orogeny outcrop in the eastern and central Pyrenees (fig. 2A). However, those in the central Pyrenees are found north of the NPF and the axis of the collisional belt. Thus, plutons north of this region were likely exhumed in catchments draining toward the northern retro-foredeep, rather than toward the south-central Pyrenees. We therefore suggest that the eastern Pyrenees represents the source for the Maastrichtian Aren sandstones.

The Garumnian Formation contains zircons with Cadomian crystallization ages also, which we suggest implies a continued eastern source for the sediment routing system during the Paleocene. A strong Hercynian (~308 Ma) signal dominates the age distribution of the Garumnian Formation. Because Hercynian age plutons are distributed throughout the Axial Zone it is difficult to speculate further on a precise source.

The lower Eocene Roda sandstone U-Pb (zircon) age signal is very distinctive because it comprises almost entirely Hercynian-aged zircons. The Cadomian signal observed in older depositional units (Garumnian and Aren) is absent. The Roda sandstone sample is thus possibly derived from a "point" source draining an individual pluton that cooled at ~308 Ma. The Roda depositional system dispersed sediments from east to west, parallel to the strike of the orogen, in a tidal and deltaic setting, confined by individual thrusts and their sidewall ramps (López-Blanco and others, 2003).

The lower Eocene Castissent sandstone exhibits a detrital zircon U-Pb age signal that is similar to that of the Garumnian and Aren formations. It records a strong Hercynian age component and minor Cadomian age components. During the Eocene, out-of-sequence thrusting of the Boixols thrust and backthrusting on the Morerres thrust was initiated in the south-central Pyrenees (fig. 3B). This period of out-of-sequence thrusting is marked by a significant unconformity north of the Boixols thrust, where middle Eocene conglomerate deposits within the Pobla Basin are observed to directly overly Mesozoic carbonates. We suggest that the Aren and Garumnian formation primary foredeep deposits were recycled into younger deposits of the wedge-top basins, causing rejuvenation of the Cadomian signal. The Castissent Formation was therefore probably sourced within the south-central Pyrenees.

The upper Eocene Upper Montanyana sandstone was deposited in the Tremp Basin. The basin was bounded by the Boixols and Montsec thrusts, both of which were active during deposition of the Upper Montanyana sandstones (fig. 3B). Both thrust sheets are composed of Mesozoic limestones and present a zircon-poor source to sediment routing systems draining the local uplifts, which we suggest is the reason for the lack of zircons in the Upper Montanyana sandstone deposit.

Conglomerates deposited within the Pobla, Tremp and Ebro basins between the late Eocene and late Oligocene exhibit a distinctive pattern of mixed U-Pb (zircon) ages. Samples from each basin record mixed ages with a strong Hercynian component and rejuvenation of the Cadomian signal. The mixed signal is typical of multiple recycling of sediments. We suggest that these conglomerates represent the redistribution by alluvial fans of sediment sourced in the Nogueres and Axial zones southward toward the Ebro Basin foredeep (Hirst and Nichols, 1986; Mellere, 1993; Meigs and others, 1996). We propose that a mixed U-Pb (zircon) age signal is characteristic of the transverse distribution of sediment, sourced from the exhuming Axial Zone and distributed perpendicular to orogen strike, across the fold-and-thrust belt in the final stages of Pyrenean orogenesis.

Thermo-Tectonic Evolution of the Pyrenees from the Detrital Zircon Fission-Track Record

Our interpretations of the detrital zircon fission-track grain age data are based on the following assumptions: 1) none of the detrital zircon fission-track grain age component peaks are younger than the depositional age of the sedimentary rock samples. We therefore conclude that none of the samples have experienced thermal resetting in the sedimentary basins after deposition, either by burial or by localized reheating associated with fault motion; 2) U-Pb (zircon) ages $<$200 Ma were not recorded. Thus, any detrital zircon fission-track ages younger than 200 Ma are interpreted to represent periods of cooling through normal fault- or erosion-induced exhumation, rather than cooling after plutonism or zircon crystallization; 3) because the Pyrenees were in compression between the Late Cretaceous and Oligocene, detrital zircon fission-track grain ages are interpreted to represent cooling through erosion-induced exhumation, rather than normal-fault induced exhumation; 4) because the south-central Pyrenean fold-and-thrust belt is composed of limestone-dominated thrust sheets that bound the wedge-top and foredeep basins, there is no local source for the detrital zircons. All detrital zircon fission-track grain ages are thus interpreted to reflect exhumation in the Axial Zone hinterland, rather than exhumation of individual thrust sheets.

The oldest component population recorded by all of the detrital samples (fig. 5) is 77.5 ($-$6.5/$+$7.1) Ma, and records significant cooling during the Late Cretaceous. We interpret the component population to represent exhumation-induced cooling through the zircon effective closure temperature in response to the growth of the Pyrenean orogen during the Late Cretaceous. The component population age obtained corroborates Late Cretaceous to Paleocene detrital apatite fission-track cooling ages from wedge-top basins of the south-central Pyrenees (Beamud and others, 2011) and independent reports of the onset of Pyrenean contraction as during the Santonian/Campanian (~83 Ma) (Puigdefàbregas and Souquet, 1986; Capote and others, 2002; Rosenbaum and others, 2002).

Lag times are also observed to decrease through the Late Cretaceous, with a short lag time of *ca.* 15 Myr recorded in the Paleocene (fig. 6). A comparable, *ca.* 11 Myr lag time is also recorded in detrital zircon fission-track ages of the slightly younger Ypresian (lower Eocene) strata taken from the northern retro-foreland basin (Shoemaker, ms, 2000). Our Paleocene lag-time data require relatively rapid exhumation rates in the range ~0.5 to 0.8 mm/yr (if at thermal-steady-state, with a zircon fission-track closure temperature of 240 °C and a geothermal gradient of 20-30 °C/km), and by implication require significant relief to drive erosion of deep-seated rocks. Hence, sufficient topography must have existed in the Pyrenees during the Late Cretaceous to Paleocene to act as sources for sediment dispersed both northwards and southwards into retro- and pro-foreland basins. However, reconstructed cross-sections (Beaumont and others, 2000) and bedrock fission-track data (Fitzgerald and others, 1999; Sinclair and others, 2005) from the central Pyrenees indicate that high topography did not exist in the central sector of the Pyrenees at this time. The lag-time plot therefore cannot be interpreted in terms of the central Pyrenean evolution alone. We suggest that the decreasing lag times between the Late Cretaceous and Paleocene record accelerated exhumation of the eastern, not central, Pyrenees. This interpretation is supported by the regional bedrock zircon fission-track data (fig. 2A), the U-Pb (zircon) source fingerprints (fig. 4) and tectono-sedimentary reconstructions (fig. 5). We suggest that the "cover layer" was removed from the eastern Pyrenees during the Late Cretaceous, in association with increasing exhumation rates and sediment discharge to the forelands. Sediments recording exhumation through the zircon closure temperature in the eastern Pyrenean hinterland were eventually deposited in basins in the south-central Pyrenees, as part of the Garumnian Formation, during the Paleocene.

The detrital zircon fission-track ages from all of the south-central Pyrenean samples show a second component population age of 50.9 (−4.9/+5.5) Ma (fig. 5). Similar Eocene cooling ages are recorded in detrital apatites found in south-central Pyrenean wedge top basins (Beamud and others, 2011). This indicates that exhumation-induced cooling of Axial Zone rocks occurred at ~50 Ma, and implies growth of the Pyrenean Axial Zone topography at this time. One would expect lag times to be relatively short at this time, yet figure 6 indicates that lag times, as recorded by the Lower and Upper Corca Sandstones, increased significantly to *ca.* 50 to 70 Myr during the early to middle Eocene. One or a combination of the following scenarios can explain these observations.

Rosenbaum and others (2002) report a 10 to 15 million year period in the Paleocene during which Iberia stopped moving with respect to Europe. Convergence ceased only temporarily, and may have caused a marked decrease in shortening across the Pyrenean chain, before resuming in the early Eocene, between ~55 to 46 Ma. The ~50 Ma component population age recorded by all of the Pyrenean detrital samples may therefore record the exhumational response to the resumption of convergence between Iberia and Europe. Because the zircon fission-track closure temperature is high and the fission track clock is set at considerable depth in the hinterland, Axial Zone rocks recording the lull and recommencement of convergence during the Paleocene will have required *ca.* 10 Myr to be exhumed to the surface once convergence had resumed. The sedimentary archive should record an increase in sediment discharge to the neighboring basins well before the minimum in thermochronological lag time. This is a predictable feature of the lag-time model. We would therefore expect the fission-track signal recording the Paleocene lull in convergence to appear in the sedimentary detrital archive during the Eocene. The long lag times and corresponding slow exhumation rates recorded by the lower Eocene Corca Formation sandstones (at ~52-50 Ma) support this prediction and may therefore reflect the decreased shortening rates. A similar record of long lag times (*ca.* 80 Myr) is observed in the detrital zircon fission-track grain ages of Bartonian aged (middle Eocene, ~40 Ma) sedimentary rocks in the northern retro-foreland basin (Shoemaker, ms, 2000), indicating that long lag times may have persisted for some significant time after the deceleration of convergence. That long lag times are recorded in both the pro- and retro-foreland basin sedimentary rocks supports interpretation of an Axial Zone control and lends weight to the hypothesis of much-reduced tectonic shortening during the Paleocene.

The increase in lag times up stratigraphic section could also result from the diachronous development of the orogen and the sediment routing systems. Because of the gradual east to west development of the Pyrenees, significant topography was not generated in the central Pyrenees until the early Eocene. The progressive westward topographic growth of the orogen may have caused reorganization of the sediment routing systems as the central Pyrenean hinterland, rather than the eastern, became the primary source region supplying the south-central Pyrenees with sediment. Within the central Pyrenees there may still have been a cover layer consisting of rocks with non- or partially-reset grains that contain no record of Pyrenean-aged cooling. The Corca sandstones may therefore record erosion of the central Pyrenean cover layer, prior to exhumation to the surface of those zircons exhumed from below their effective closure temperature in response to early Eocene growth of the central Pyrenean topography.

Alternatively, reconstructions of the temporal and spatial evolution of the south-central Pyrenees reveal early to middle Eocene out-of-sequence thrusting on the Boixols thrust and Morerres backthrust (fig. 3B). Out-of-sequence thrusting may have caused recycling of the Aren and Garumnian formations as they were uplifted during formation of the Pobla and Senterada wedge-top basins, recycling the Aren and Garumnian formation zircon fission-track signal back into the deposits of the Corca Formation. Rejuvenation of the U-Pb (zircon) Cadomian signal during the early Eocene (fig. 4) and the absence of any Pyrenean-aged sedimentary units older than middle Eocene within the Pobla Basin, north of the Boixols thrust support this interpretation.

Overall, we suggest that the early to middle Eocene marks the beginning of significant sediment routing system reorganization in the south-central Pyrenees, with sediment dispersal systems starting to transition from orogen-parallel to orogen-transverse dispersal. The bedrock fission-track data indicate that, with the onset of central Pyrenean uplift, exhumation in the eastern Pyrenees did not halt, but continued through the Eocene. The eastern Pyrenees should therefore be associated with a Corca Formation age-equivalent sediment pile derived from and deposited within the eastern Pyrenees. The time-distance chart for the eastern Pyrenees indicates that this is the case (fig. 3A). Deposition of the Bellmunt Conglomerates in orogen-transverse dispersal systems in the south-eastern Pyrenees occurs contemporaneous with deposition of the upper Corca sandstones in the south-central Pyrenees.

The youngest component population from all of the detrital zircon fission-track grain ages is observed at 30.5 (−2.9/+3.2) Ma. We suggest that the most recent component population records exhumation associated with late Eocene to Oligocene Axial Zone stacking and duplex formation (Fitzgerald and others, 1999; Beaumont and others, 2000). This last period of Pyrenean exhumation is well documented in the bedrock apatite fission-track data (Fitzgerald and others, 1999; Sinclair and others, 2005; Gibson and others, 2007; Jolivet and others, 2007), and is also recorded in the detrital zircon fission-track grain ages of sediments from the modern day Ariege River in the northern Pyrenees and Segre River in the southern Pyrenees (Shoemaker, ms, 2000) and detrital apatites of the south-central Pyrenean wedge top basins (Beamud and others, 2011).

Lag times are observed to decrease during the late Eocene to Oligocene (fig. 6). Minimum lag times of *ca.* 3 Myr are recorded by the early Oligocene Lower Senterada Formation, corresponding to exhumation rates of ~3 to 4 mm/yr. The exact exhumation rates are sensitive to the precise values of depositional and fission-track ages for the Senterada Formation, but are comparable to those reported for the central Pyrenean hinterland, at the Maladeta Massif (2-4 mm/yr between 35-32 Ma, Fitzgerald and others, 1999; 1-1.5 mm/yr between 31-29 Ma, Gibson and others, 2007).

The period of accelerated exhumation during the early Oligocene was short-lived. The late Oligocene Antist Formation records increasing lag times, up to *ca.* 100 Myr, between ~27 to 24 Ma. The increase in lag times up stratigraphic section implies that catchments expanded, tapping back into the surrounding Axial Zone cover layer, as evidenced by clast lithologies (Mellere, 1993), and supplying the younger Antist Group with zircons that were not reset during the final stage of Pyrenean contraction. Bedrock apatite fission-track data indicate that exhumation continued in the central Pyrenean Axial Zone until ~20 Ma (Barruera Massif; Sinclair and others, 2005). However, a lack of late Eocene- to Oligocene-aged detrital zircon fission-track grain ages found in the Oligocene sedimentary units analyzed here suggest that exhumation after ~30 Ma was shallow and generally did not exhume zircons from the zircon closure depth.

Overall, the new detrital zircon fission-track cooling ages presented here provide an extension of the exhumational history of the Pyrenees that has so far not been reconstructed using *in situ* bedrock thermochronological sampling. Whereas the bedrock data provide information on exhumational periods since the Eocene only, the detrital data from retro- and pro-foreland basins suggest that exhumation occurred during the Late Cretaceous to Paleocene from a Pyrenean wedge source during the early stages of compression. Rapid exhumation could only take place if there was substantial relief to drive erosion implying that the nascent Pyrenean mountain belt was already a topographic feature during the early stages of compression.

DIACHRONOUS OROGENIC EVOLUTION

3-Stage Model of Pyrenean Thermo-Tectono-Sedimentary Evolution

The new detrital zircon thermochronological analyses can be combined with the existing published literature into a 3-stage model to describe the thermo-tectono-sedimentary evolution of the southern Pyrenees:

Stage 1: Late Cretaceous to Paleocene (fig. 7A).—Pyrenean shortening was initiated in the Late Cretaceous (~83 Ma) with the inversion of Mesozoic extensional faults, including reactivation of the Boixols fault. The anticlockwise rotation of Iberia with respect to Europe resulted in diachronous orogenic growth and the building of topography in the eastern Pyrenees. The paleo-Bay of Biscay formed the main sedimentary basin. Thus, sediment transport from the newly rising Pyrenean orogen was dominantly toward the west, parallel to the strike of the orogen. Topographic growth associated with shortening in the eastern Pyrenees resulted in the exhumation of rocks from the zircon closure depth during the Campanian (~78 Ma). Exhumation rates in the eastern Pyrenees increased from the Campanian to Paleocene, to ~0.5 to 0.8 mm/yr. The orogen-parallel sediment dispersal systems supplied a south-central Pyrenean foredeep basin, including the Aren and Garumnian formations, with detrital

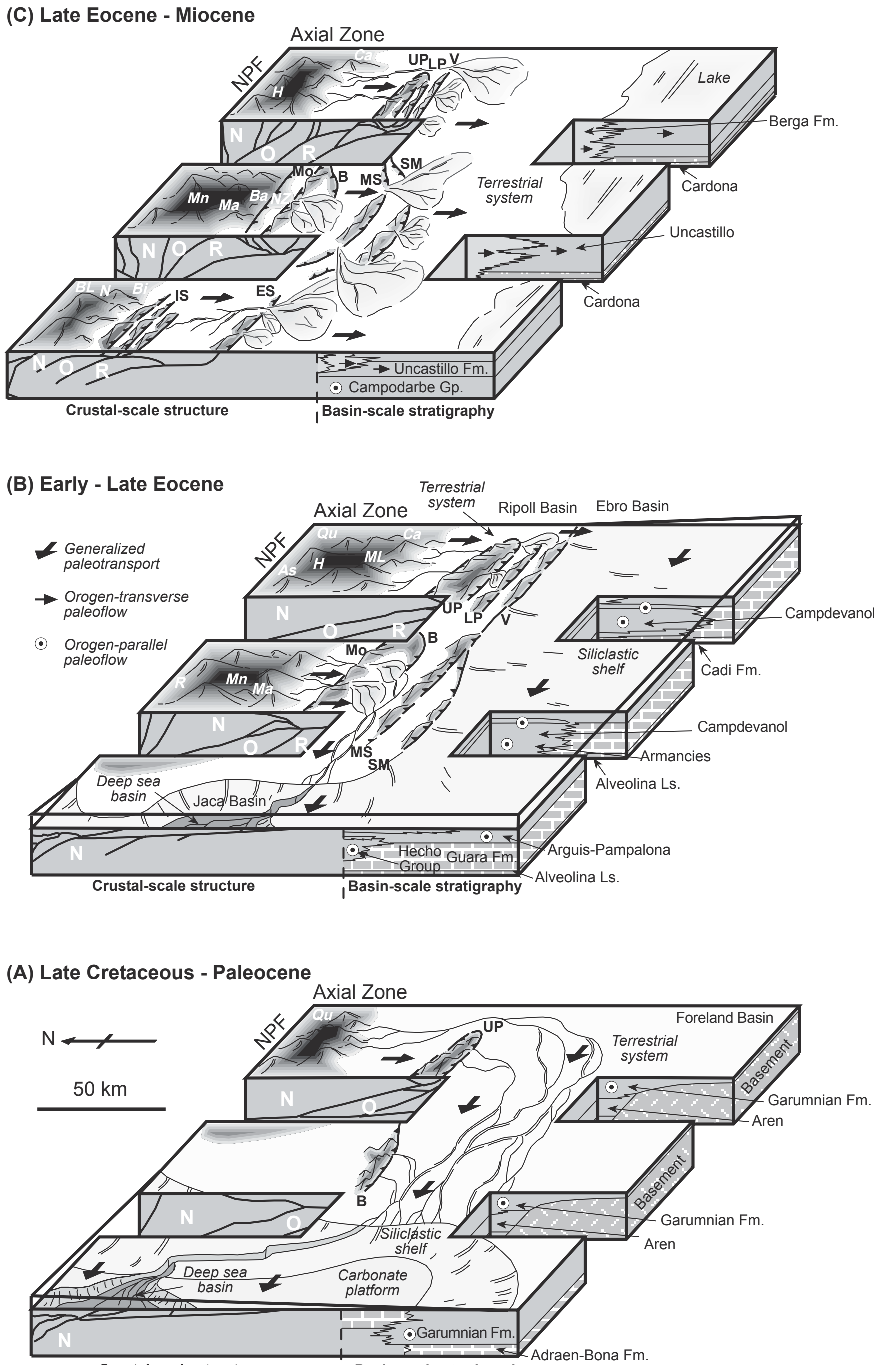


Fig. 7. 3-stage model of south Pyrenean tectono-sedimentary evolution. The south Pyrenean sediment routing systems exhibit the progressive transition from orogen-parallel to orogen-transverse dispersal, contemporaneous with east-to-west diachronous orogenic development. NPF—North Pyrenean Fault. Major fold-and-thrust belt units: UP—Upper Pedraforca thrust sheet, LP—Lower Pedraforca thrust sheet, V—Vallfogona thrust, Mo—Morerres backthrust, B—Boixols thrust sheet, MS—Montsec thrust sheet, SM—Sierras Marginales thrust sheet, IS—Internal Sierras, ES—External Sierras. Exhuming Axial Zone massifs/Plutons: Qu—Querigut, Ca—Canigou, H—Hospitalet, Mn—Marimaña, Ma—Maladeta, Ba—Barruera, NZ—Nogueres Zone, BL—Borderes-Louron, N—Neouvielle, B—Bielsa. Axial Zone antiformal stack sheets: N—Nogueres, O—Orri, R—Rialp.

zircons derived from Cadomian and Hercynian plutons in the eastern Pyrenees. After removal of the "cover layer" in the eastern Pyrenees, exhumation of previously deep-seated basement rocks in the eastern Pyrenees during the Paleocene supplied the south-central Pyrenean basins with zircons whose fission-track ages recorded the primary stages of Pyrenean compression. The lag time between cooling below the zircon fission-track closure temperature and deposition in the sedimentary basins was *ca.* 15 Myr.

Stage 2: Early to middle Eocene (fig. 7B).—After a 10 to 15 Myr period of tectonic quiescence (~68-55 Ma; Rosenbaum and others, 2002), the compressional regime was rejuvenated. Diachronous, gradual east to west development of the Pyrenees resulted in the formation of high topography in the central Pyrenees. The south Pyrenean frontal thrust rapidly propagated and the foredeep deposits were carried piggyback style southward on the Boixols, Montsec and Sierras Marginales thrust sheets. Two separate foreland basins were well established at this time; the Ebro foredeep formed the pro-wedge depocenter and the Aquitaine foredeep formed the retro-wedge depocenter. This period represents a transitional time between the orogen-parallel and orogen-transverse sediment dispersal systems. The exhumational response to the newly formed central Pyrenean topography is recorded in the zircon fission-track signal at ~50 Ma. Prior to exhumation of those zircons buried at depths beneath the zircon closure temperature, the "cover layer" of the central Pyrenees was removed and an influx of un-reset or partially reset zircons was supplied to the sedimentary basins. Furthermore, out-of-sequence thrusting resulted in the cannibalization and recycling of the Late Cretaceous to Paleocene foredeep deposits and their associated thermochronological signal, within the fold-and-thrust belt. Zircons recording a fission-track age indicative of the ~50 Ma rejuvenation in exhumation did not reach the sedimentary basins until the late Eocene (~37 Ma), implying a lag-time of ~13 Myr.

Stage 3: late Eocene to Miocene (fig. 7C).—Thrust stacking and duplex formation within the south-central Pyrenean Axial Zone during the late Eocene to Oligocene (Muñoz, 1992; Beaumont and others, 2000) were associated with a rapid, north to southward migrating wave of Axial Zone exhumation, evidenced by bedrock fission-track studies recording rapid exhumation ~35 to 20 Ma. In response to thrust stacking and the rapid growth of topography in the central Pyrenees, zircons were rapidly exhumed from below the zircon fission-track closure temperature at ~30 Ma and deposited in neighboring wedge-top basins within *ca.* 3 Myr, hence exhumation rates were ~3 to 4 mm/yr. Continued diachronous development of the Pyrenean topography resulted in the uplift of the western Pyrenees and the Iberian Range. The Ebro basin became a closed intermontane basin at ~37 Ma (Burbank and others, 1992; Vergés and Burbank, 1996). The sediment routing systems of the south-central Pyrenees transitioned to orogen-transverse, becoming fully established in the Oligocene and dispersing Nogueres Zone and Axial Zone derived clasts across the width of the fold-and-thrust belt. Long-distance transfer of Axial Zone detritus out of the orogenic wedge and into the Ebro foredeep is evidenced by distinctive clast lithologies observed in alluvial and fluvial deposits at the fold-and-thrust front at ~42 Ma (eastern Pyrenees), ~35 to 24 Ma (central Pyrenees) and ~30 Ma (west-central Pyrenees). The gradual, east-west shift in the delivery of Axial Zone clasts to the foredeep occurred in response to the diachronous uplift of the orogen and the gradual along-strike reorganization of sediment routing systems from orogen-parallel to orogen-transverse. Detrital zircon U-Pb age data imply that the transverse sediment dispersal systems are associated with a distinctive signature, composed of mixed ages that are representative of mixed provenance from the stacked Axial Zone source units. At ~29 Ma propagation of the south-central Pyrenean thrust front halted (Meigs, 1997). Internal contractional deformation continued until ~24 Ma (Meigs, 1997). The cessation of internal deformation was coincident with the joining of Iberia with the Eurasian plate at ~24 Ma (Capote and others, 2002). The bedrock fission-track studies indicate continued exhumation of the central Pyrenean Axial Zone until at least ~20 Ma (Sinclair and others, 2005).

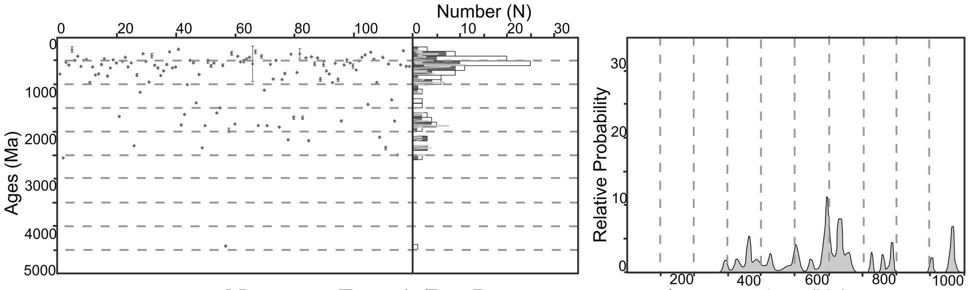
Data from the Pyrenees indicate that the main sedimentary basins evolved during orogenesis in response to oblique convergence. During the early stages of compression, the obliquity of the system resulted in one main depositional basin located at the paleo-Bay of Biscay. Sediment was delivered to this depocenter in a direction parallel to the east-west strike of the orogen. With time, diachronous crustal thickening and east-to-west topographic growth caused loading of the lithospheric crust. Loading resulted in flexure and the formation of the Ebro and Aquitaine flexural foredeep basins to the south and north of the orogen respectively. Initially, sediment continued to be guided longitudinally along troughs defined by underlying thrust-related culminations. Later, sediment routing systems re-organized and sediment was delivered transversely to the foredeeps, burying the underlying tectonic structures of the wedge-top zone.

CONCLUSIONS

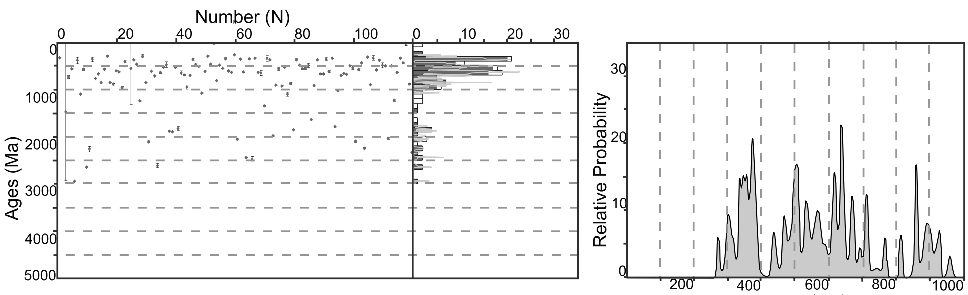
The Pyrenees represents an orogen that closed diachronously from east to west between the Late Cretaceous and Miocene. The excellent exposure afforded by the region has resulted in an abundance of studies that constrain the chronology of deformation, the sedimentary evolution of the wedge-top and foreland basins, and the thermal evolution of the Axial Zone hinterland. However, the link between source and sink has not been comprehensively investigated. Detrital zircon thermochronological analyses, interpreted within the context of the tectono-sedimentary evolution of the Pyrenees, address this gap in our understanding and allow links to be drawn between the discharge of sediment from the source, sediment dispersal and deposition in relation to the complexly evolving depositional basins associated with a diachronously uplifting orogen. Through use of the detrital archive we are able to extend the thermal record back to the early stages of orogenesis. The data indicate the successive transition from orogen-parallel to orogen-transverse sediment routing systems along strike, coeval with diachronous orogenic development, that are summarized by a three-stage model of Pyrenean evolution: (1) A period of exhumation of deep-seated rocks, coupled with the onset of compression and uplift in the eastern Pyrenees during the Late Cretaceous to Paleocene, is associated with dominantly orogen-parallel sediment dispersal; (2) with uplift of the central Pyrenees during the Eocene, the sediment routing systems underwent a transition from orogen-parallel to predominantly transverse. The basins were supplied with erosional material that represents "cover layer" rocks from the central Pyrenees and recycled foredeep deposits; (3) the establishment of fully transverse sediment dispersal occurred during the Oligocene. The western Pyrenees uplifted and the wedge-top and foreland basins were supplied with rapidly exhumed zircons, cooled during the final stages of orogenesis. Knowledge of the three-dimensional, oblique development of orogens such as the Pyrenees is required to understand the redistribution of mass by surface processes that may drive feedbacks with tectonics.

Appendix A

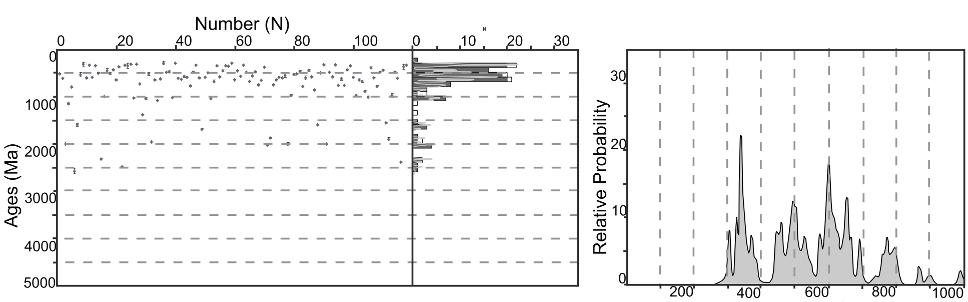
Detrital Zircon U-Pb Age Data



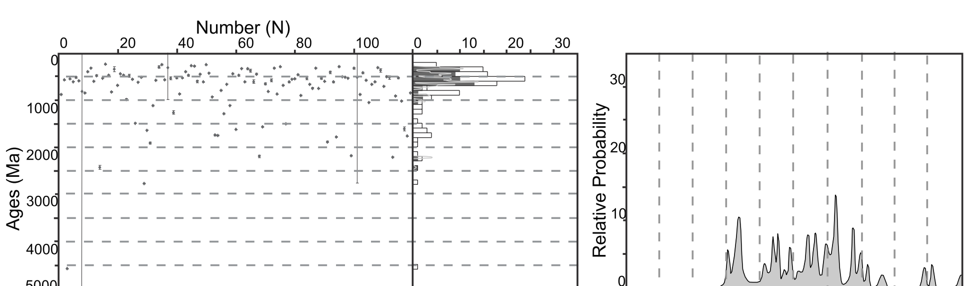
Nogueres Zone 1 (Pre-Pyrenean orogeny)
Depositional age: 255.9 Ma (+ 5.25 / - 5.25)



Lower Senterada Formation (Senterada Basin)
Depositional age: 30.0 Ma (+ 2.0 / - 3.0)



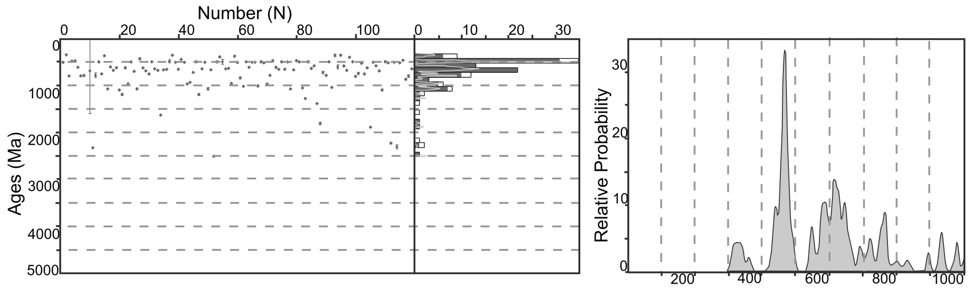
Upper Senterada Formation (Senterada Basin)
Depositional age: 27.0 Ma (+ 5.0 / - 0.0)



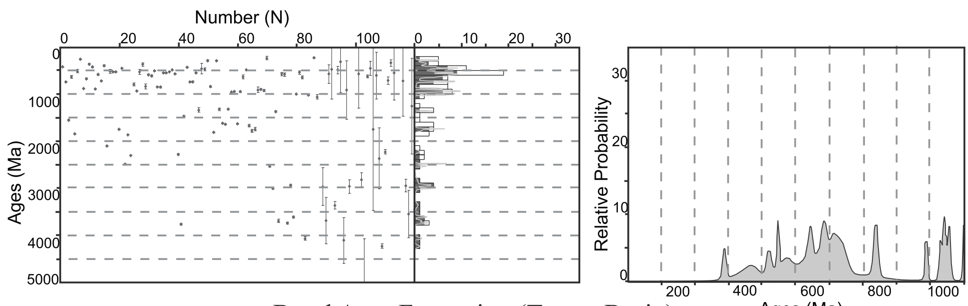
Montsor Conglomerate (Pobla Basin)
Depositional age: 37.0 Ma (+ 3.2 / - 3.2)

Appendix A

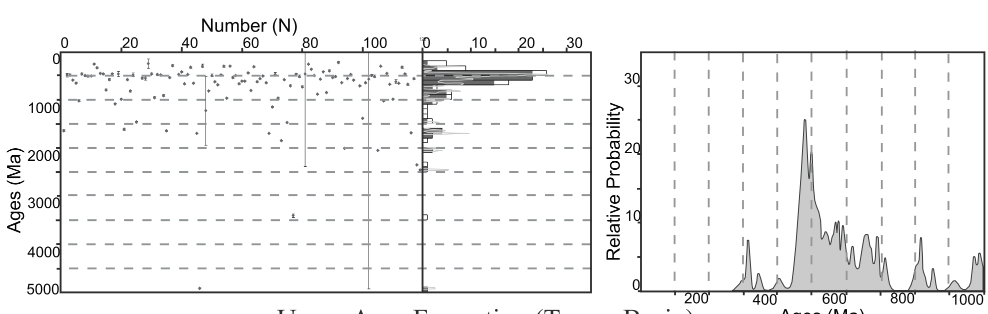
(Continued)



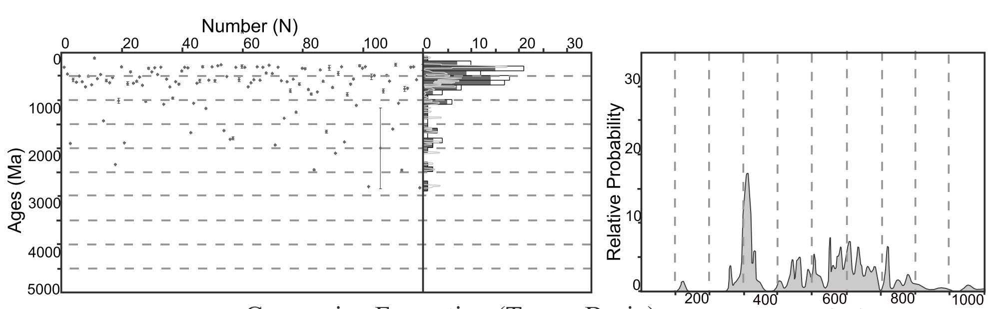
Antist Formation (Pobla Basin)
Depositional age: 25.5 Ma (+ 1.5 / - 1.5)



Basal Aren Formation (Tremp Basin)
Depositional age: 73.0 Ma (+ 2.0 / - 2.0)



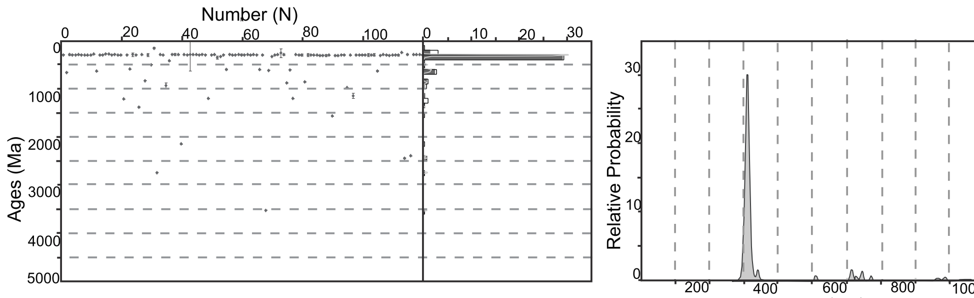
Upper Aren Formation (Tremp Basin)
Depositional age: 73.0 Ma (+ 2.0 / - 2.0)



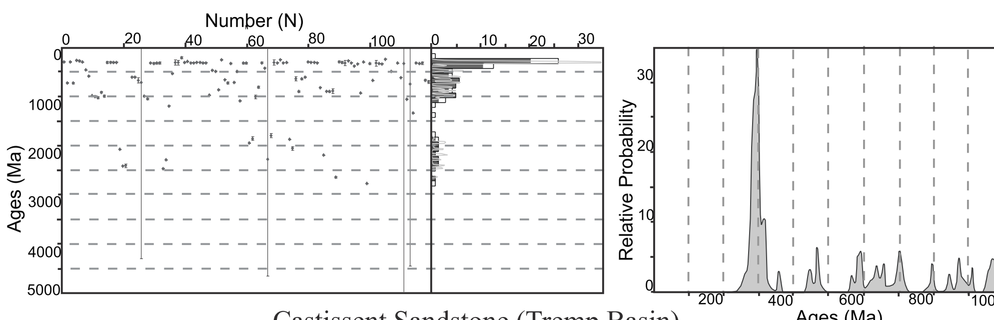
Garumnian Formation (Tremp Basin)
Depositional age: 57.25 Ma (+ 1.65 / - 1.65)

Appendix A

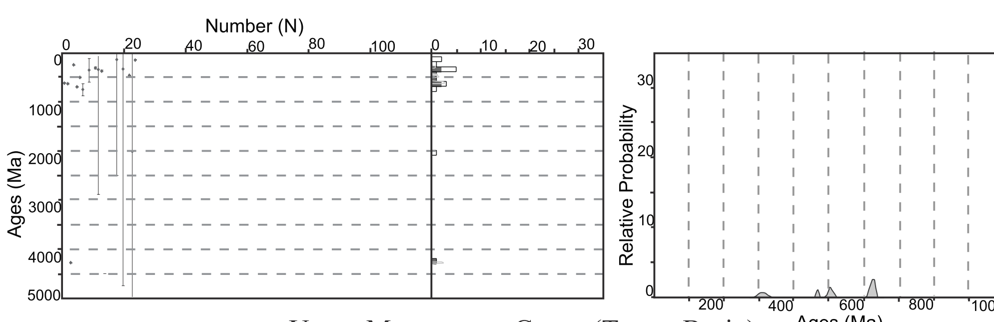
(Continued)



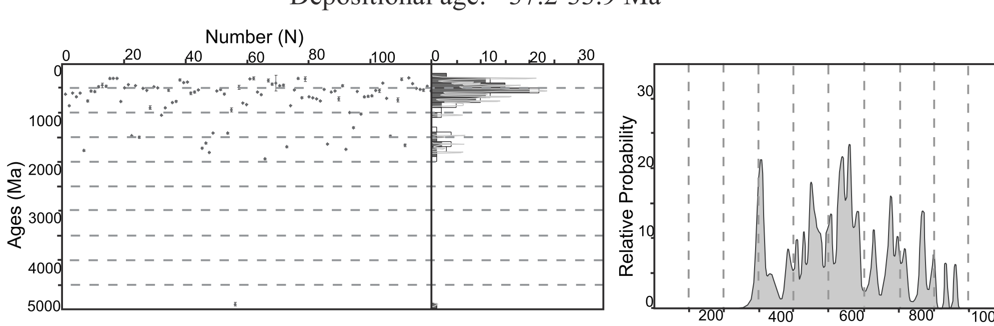
Roda Sandstone (Tremp Basin)
Depositional age: ~55.8-48.6 Ma



Castissent Sandstone (Tremp Basin)
Depositional age: ~55.8-48.6 Ma



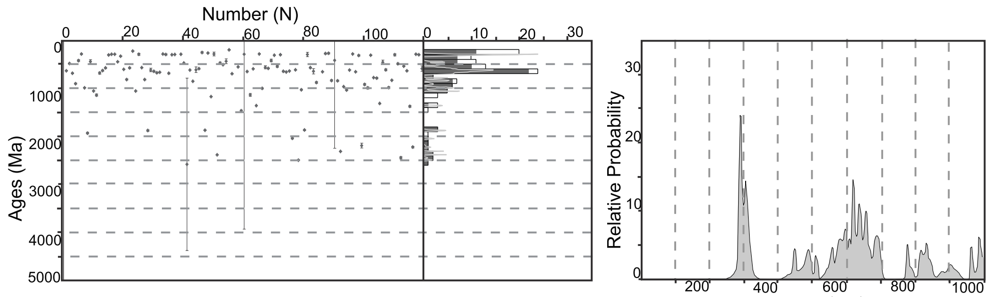
Upper Montanyana Group (Tremp Basin)
Depositional age: ~37.2-33.9 Ma



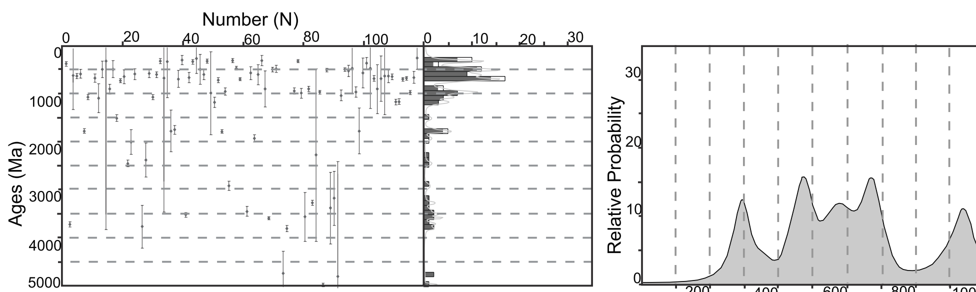
Campodarbe Conglomerates (Tremp Basin)
Depositional age: ~37.2-23.0 Ma

Appendix A

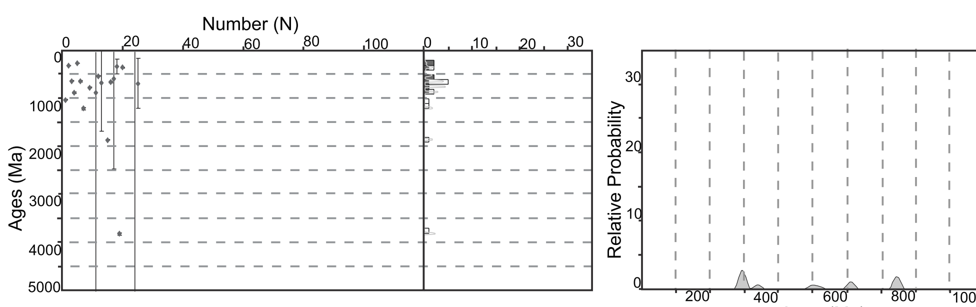
(Continued)



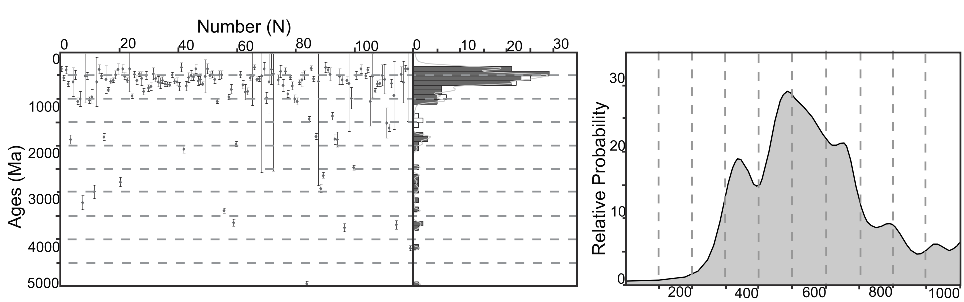
Lower Corca Formation (Ager Basin)
Depositional age: 52.5 Ma (+ 0.8 / - 0.8)



Upper Corca Formation (Ager Basin)
Depositional age: 49.25 Ma (+ 2.05 / - 2.05)



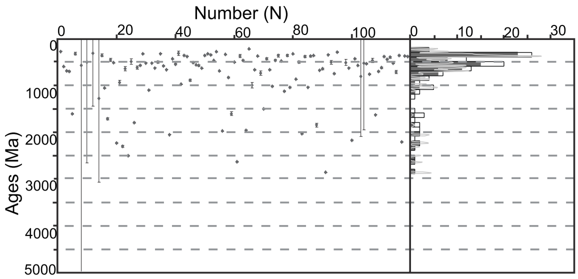
Camarasa Sandstone (Ebro Basin)
Depositional age: ~55.8-33.9 Ma

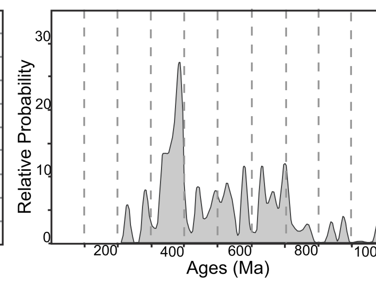


Oliana Conglomerates (Ebro Basin)
Depositional age: 35.15 Ma (+ 1.15 / - 1.15)

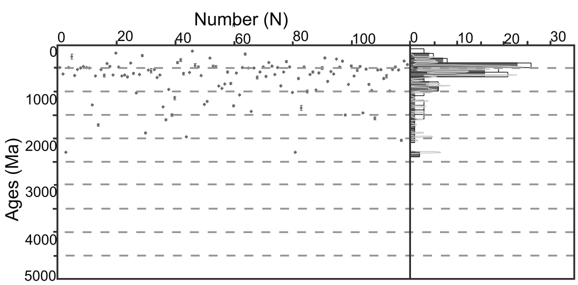
Appendix A

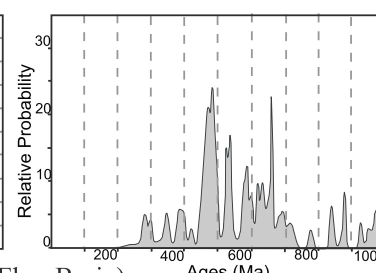
(Continued)



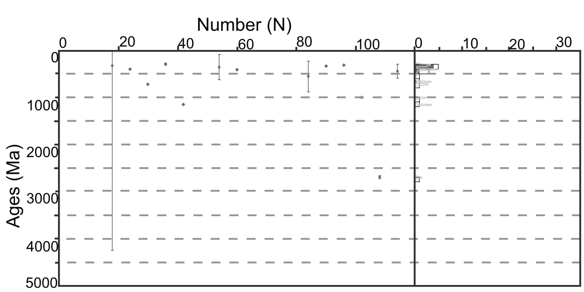


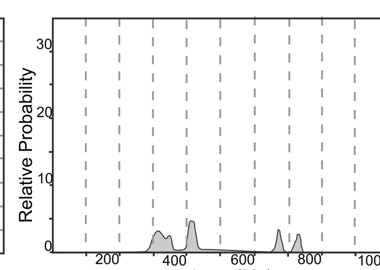
Huesca Fan (Ebro Basin)
Depositional age: ~37.2-23.0 Ma





Ebro Basin Conglomerate (Ebro Basin)
Depositional age: 26.3 Ma (+ 1.65 / - 1.65)

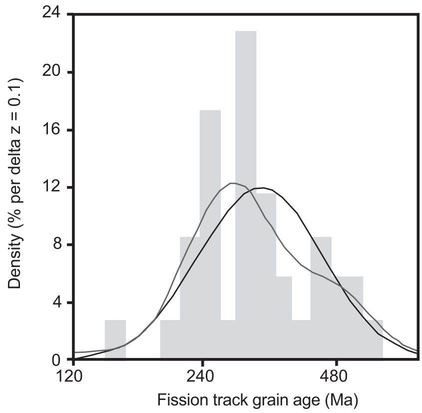




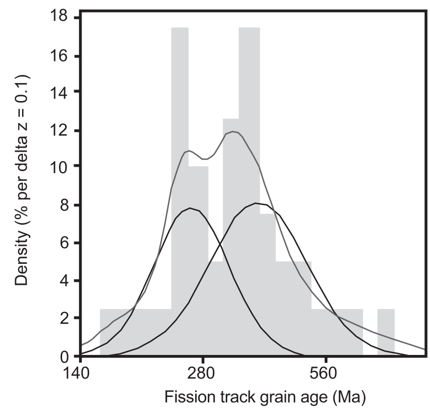
Sis Conglomerate (Sis Paleovalley)
Depositional age: 36.9 Ma (+ 3.1 / - 3.1)

Appendix B

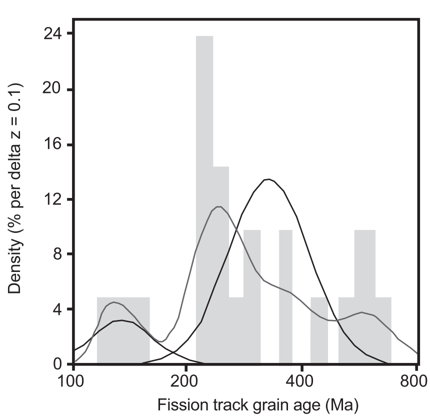
Detrital Zircon Fission Track Grain Age Data



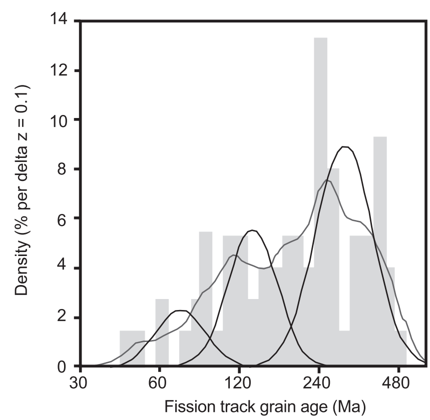
Nogueres Zone 1 (Pre-Pyrenean orogeny)
Depositional age: (255.9 Ma + 5.25 / - 5.25)



Nogueres Zone 2 (Pre-Pyrenean orogeny)
Depositional age: (240.5 Ma + 5.5 / - 5.5)



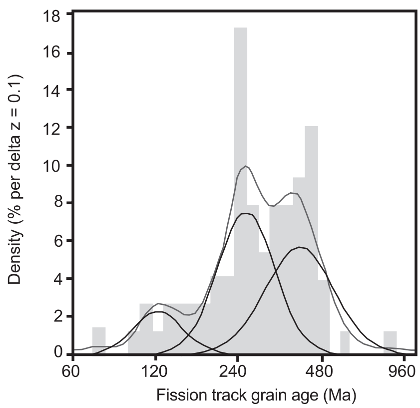
Aren Formation (Tremp Basin)
Depositional age: (73.0 Ma + 2.0 / - 2.0)



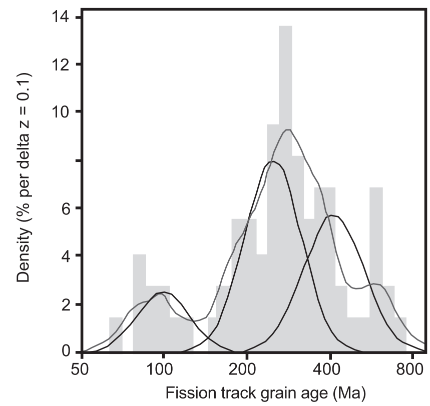
Garumnian Formation (Ager Basin)
Depositional age: (57.25 Ma + 1.65 / - 1.65)

Appendix B

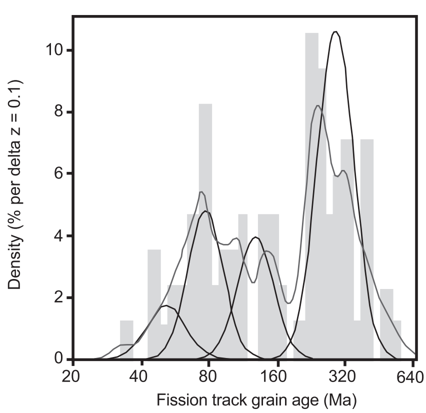
(Continued)



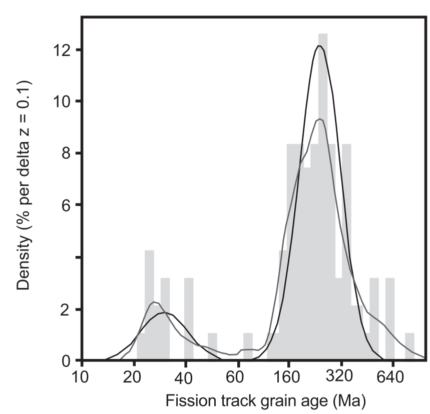
Lower Corca Formation (Ager Basin)
Depositional age: (52.5 Ma + 0.8 / - 0.8)



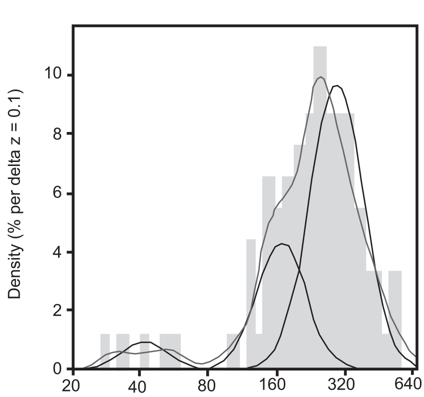
Upper Corca Formation (Ager Basin)
Depositional age: (49.25 Ma + 2.05 / - 2.05)



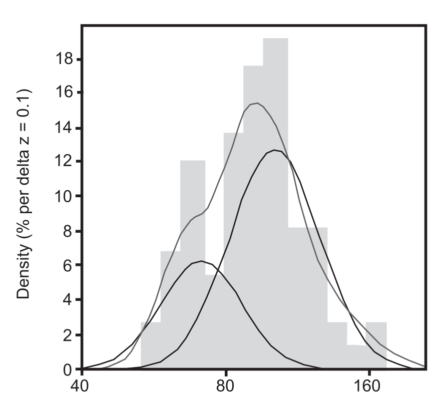
Montsor Conglomerate (Pobla Basin)
Depositional age: (37.0 Ma + 3.2 / - 3.2)



Lower Senterada Formation (Senterada Basin)
Depositional age: (30.0 Ma + 2.0 / - 3.0)



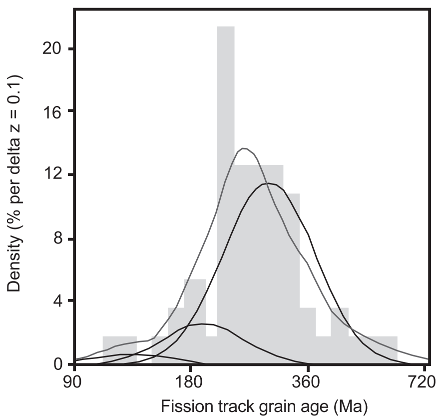
Upper Senterada Formation (Senterada Basin)
Depositional age: (27.0 Ma + 5.0 / - 0.0)



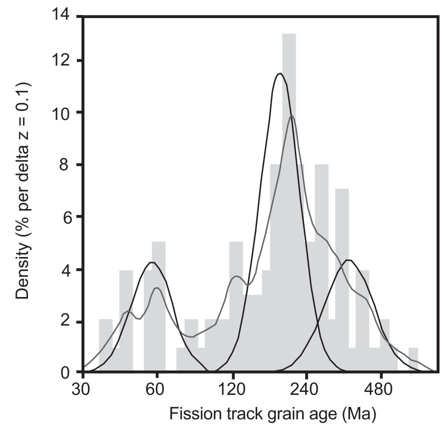
Claramunt Conglomerates (Tremp Basin)
Depositional age: (29.0 Ma + 4.9 / - 0.6)

Appendix B

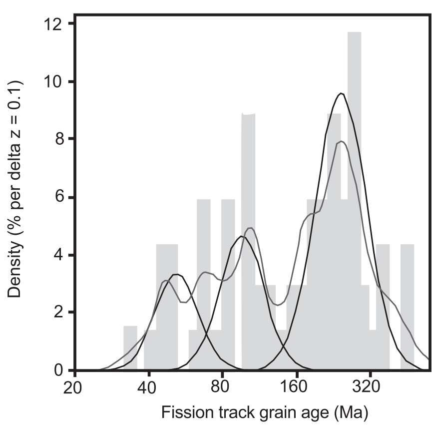
(Continued)



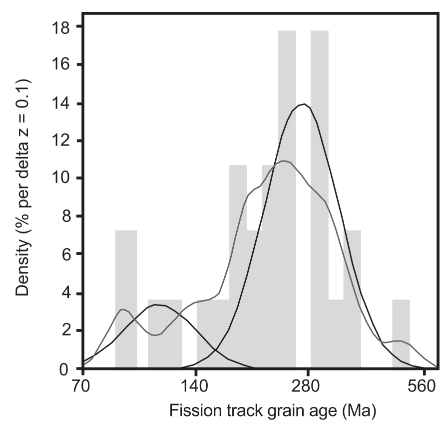
Antist Formation (Pobla Basin)
Depositional age: (25.5 Ma + 1.5 / - 1.5)



Oliana Conglomerates (Ebro Basin)
Depositional age: (35.15 Ma + 1.15 / - 1.15)



Ebro Basin Conglomerate (Ebro Basin)
Depositional age: (26.3 Ma + 1.65 / - 1.65)



Sis Conglomerate (Sis Paleovalley)
Depositional age: (36.9 Ma + 3.1 / - 3.1)

acknowledgments

We are very grateful for the financial support of Statoil for a generic research program on sediment routing systems. Stephanie Brichau provided invaluable instructions in the lab. We have benefited greatly from discussions with Jaume Vergés, Cai Puigdefabregas, Sébastien Castelltort, Guy Simpson and Fritz Schlunegger. Journal reviewers Matthias Bernet and one anonymous reviewer are thanked for their comments.

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