PROVENANCE CONSTRAINTS ON THE TREMP FORMATION PALEOGEOGRAPHY (SOUTHERN PYRENEES): EBRO MASSIF *VS* PYRENEES SOURCES

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Abstract

A detailed petrological study has been carried out for the end-Cretaceous clastic sediments of the southern Pyrenees. Provenance results indicate that the Maastrichtian systems from both Àger and Vallcebre synclines show compositional features that mainly consist on a high proportion of single and polycrystalline quartz grains, feldspar and plutonic fragments. In contrast, the sandstone systems of the Tremp syncline exhibit minor contributions of igneous source areas and higher amounts of carbonatic components. These results reveal that the Tremp basin had a source area interpreted as situated to the North, in the uplifting Pyrenees. The fact that this basin does not show a high plutonic source signal indicates that the Àger and Vallcebre basins had been fed from a distinct source area located to the South, here interpreted as the Ebro Massif. In this way, the above mentioned differences might imply that the Montsec High acted as a barrier, avoiding a southern influence in the Tremp basin.

Keywords: provenance; sediment routing; petrography; Southern Pyrenees; Maastrichtian; foreland basin; Tremp Formation.

1. Introduction

Sand petrography is a powerful tool to investigate sediment provenance and to reconstruct paleogeographic basin evolution. Provenance of clastic deposits in foreland basins has been widely investigated as it provides valuable information about the erosional history of the fold-and-thrust belt that supplies the detritus (Graham *et al.*, 1986).

Petrological studies have been widely applied in the Eocene basins of the Pyrenean mountain belt, but few works have been carried out in the Maastrichtian part of the Tremp Formation (Mey et al., 1968). Although a detailed sedimentological and chronostratigraphic framework have been achieved for these end-Cretaceous marine-to-continental unit during the last decade, few is known about the nature and provenance of the clastic components that mainly feature the environments of the Tremp Formation. Most of the authors argued an East origin (Sardinia massifs) for the South Pyrenean sedimentary supply due to its East-West orientation (Ullastre and Masriera, 1982), but a possible influence of the southern Ebro Massif is not well documented. Also, differences in provenance between the Àger, Vallcebre and Tremp basins, as well as possible changes in source areas linked to facies shifts, remain unclear.

The present paper provides new data regarding to the provenance of the clastic systems during the early stages of the South Pyrenean foreland basin, contributing to reconstruct a more detailed paleogeographic evolution and to better characterise its sediment routing systems. This paleogeographic reconstruction will frame a reference continental record for the Maastrichtian in Eurasia.

2. Geological and stratigraphic framework

The Pyrenees (Fig. 1) are a fold and thrust belt that developed foreland basins both in its Southern and Northern sides of the orogen. The South Pyrenean foreland basin was active from the Late Cretaceous until the Oligocene, had an East-West orientation and was connected to the Atlantic ocean. During the Maastrichtian and Paleocene this basin was partially filled with terrestrial sediments which are known as the Tremp Formation (Mey *et al.*, 1968). The Tremp Formation is found in several thrust sheets (Fig. 1): Bóixols-Sant Corneli, Montsec, Serres Marginals, Pedraforca and Cadí (Rosell et al, 2001).

These thrusts have a displacement of tens of kilometers and are reactivated from growth structures that were active during the basin infill from the Late Cretaceous to Eocene times. Sinsedimentary thrusting lead to the partitioning of the foreland into sub-basins (broken foreland basin). These sub-basins are known as Tremp, Àger and Vallcebre and are found as synclines, whose axis belong to basin depocenters. Each basin was assimetrical, having its most active margin ti the north. The Tremp basin was bounded to the North by the Bóixols Sant Corneli thust and by the Montsec thrust to the South (Díaz-Molina 1987; Deramont et al., 1993). The Àger Basin was bounded by the Montsec thrust to the north) and by the Ebro massif (passive margin) to the South (Teixell and Muñoz, 2000). The Serra del Cadí outcrops were part of the southern boundary of the basin. Alpine tectonics displaced to the South the Serra del Cadí tectonic units that originally were placed northwards (lower and upper Pedraforca thrusts, Vergés and Martinez, 1988).

The Tremp Formation, also known as 'Garumnian' (Leymerie, 1862) has been largely studied for its reference geological and paleontological record. Stratigraphically, it can be splitted in four units (Rosell *et al*., 2001): a marine-to-continental or lagoonal 'Grey Garumnian' (or Posa formation by Cuevas, 1992) composed of greish marls with invertebrate fauna, charophyte limestones and coals; a fluvial-deltaic 'Lower Red Garumnian', represented by reddish mudstones, sandstones and paleosols; a lacustrine unit with charophyte limestones and *Microcodium* known as 'Vallcebre limestones and laterally equivalent strata', and a fluvial 'Upper Red Garumnian' characterized by red mudstones, sandstones and conglomerates. The former two units are Maastrichtian in base of dinosaur occurrence, rudist, charophytes and planktonic formaminifera biostratigraphy and magnetostratigraphy (Feist and Colombo, 1983; Galbrun *et al.*, 1993; Vicens *et al*., 2004; Oms *et al*., 2007; Riera *et al*., 2009; Vila *et al*., 2012; Díez-Canseco *et al*., 2014; Vicente *et al*., 2015). The 'Grey Garumnian' represents similar lagoonal settings in the Tremp and Vallcebre synclines during the Early Maastrichtian, but in the Àger syncline it represents a more confined lacustrine environments (Villalba-Breva and Martín-Closas, 2012). In the Tremp syncline (Figs. 1,2), the 'Lower Red Garumnian' is mainly represented by fine sandstone bodies that represent meandering rivers with tidal influece (Diez-Canseco *et al.,* 2014). These sandstones are interbedded with thick mudstone units deposited in the floodplains. In the Vallcebre syncline (Figs.1, 2), the unit is featured mainly by fine deposits and scarce sandstone bodies until the very end of the Maastrichtian. Then, coarse sandstone facies representing braided rivers (Reptile sandstone) indicate a maximum regression peak (Oms *et al.*, 2007). Finally, in the Àger syncline and Benabarre sector (Figs.1,2), the 'Lower Red Garumnian' records a transition from fine reddish mudstone deposits with isolated sandstone bodies to a thick, coarse sandstone unit. This facies shift took place at the base of the late Maastrichtian (Galbrun *et al.*, 1993). After the K-Pg transition, there was a major change in the landscapes of the south Pyrenean basin. Hence, the former fluvial-deltaic 'Lower Red Garumnian' was replaced by lacustrine limestones during the Danian (López-Martínez, 2006) in the whole Pyrenean area. Despite all the investigations carried out in the Tremp Formation, its petrology remains largely unknown. A provenance study of the Tremp Formation has a potential for characterizing paleogeographic evolution in terms of physical barriers (thrusts) ruling sediment routing during the early stages of a foreland basin.

3. Samples and methods

Sample localities were selected in order to obtain the most representative petrofacies of the Tremp Formation from the Àger, Vallcebre and Tremp synclines. Samples from the Àger syncline and Benabarre sector were extracted from the Fontllonga and the Benabarre sections (Fig. 2), where the 'Lower Red Garumnian' crops out providing good quality samples. Samples from the Vallcebre syncline were obtained from the Vallcebre section (Figure 2), and a complementary section was analised in the Coll de Pal sector (Cadí area). In the Tremp syncline, samples were collected from the sandstone bodies from the Orcau and Montrebei sections (Fig. 2). A total of 51 sandstone samples were collected and examined in thin section under the polarizing microscope. From these samples, thirty-one were selected according to its representativeness and quality for a detailed quantitative study. Textural features as size and sorting were set for all the samples following the bases of Beard and Weyl (1973). All thin sections were stained using Na-Cobaltinitrite (Chayes, 1952) for accurate identification of feldspar and Alizarine red-S staining was applied for carbonates.

Quantification of detrital modes was performed by petrographic analysis of thin sections using the Gazzi-Dickinson point counting method (Gazzi, 1966; Dickinson, 1970; Zuffa, 1985). With this method grain size effects are minimized, as it classifies crystals and other grains of sand size (>0.0625 mm) that occur in a larger rock fragment by the type of crystal below the cross-hair (Ingersoll *et al*., 1984), as well as the type of rock fragment. The point distance for counting was larger than the coarsest grain fraction in all the studied samples (Van der Plas and Tobi, 1965). From 300 to 500 points were counted for each thin section (according to Dryden, 1931) and 90 petrographic classes were considered, referring to framework grains (71 classes), matrix, cement and porosity (19 classes). Framework grains were grouped into the four main categories defined by Zuffa (1980): noncarbonate extrabasinal (NCE), noncarbonate intrabasinal (NCI), carbonate extrabasinal (CE) and carbonate intrabasinal (CI). All petrologic details of the samples here studies can be found in the supplementary tables.

Tectonically restored paleogeographic schemes have been drawn using compensated cross sections of the southern Pyrenees from Vergés and Martínez (1988), Vergés and Burbank (1996), Muñoz (1992), Teixell and Muñoz (2000), and data from wells (Lanaja, 1987).

4. Results

4.1 Grain types

All the samples show a structure supported by grains, where the matrix ratio is low in most of the samples (usually less than 10%). Main textural features are variable, mainly due to the grain size effect or linked with the depositional environment. Most of the samples are poorly to moderatly sorted, with subangular to well rounded grains.

4.1.1 Non-carbonate extrabasinal grains (NCE)

Grains classified as "Non-carbonate extrabasinal" are siliclastic components, such as quartz, feldspar or lithic fragments. Quartz is a common component (Fig. 3A) that appears in all the samples, with proportions ranging from 7% to 60% (described percenatges for detrital grains are always referred to the total framework grains). Quartz has been classified as monocrystalline, coarse polycrystalline (crystals >0.0625mm), fine polycrystalline (crystals <0.0625mm) or contained in a rock fragment (sandstone, hybrid sandstone, metamorphic and plutonic rock), according to the Gazzi-Dickinson point counting method. Quartz with evaporitic inclusions (Fig. 3A) occurs in almost all the samples, but always with proportions less than 4 %. Occasionally, quartz with inherited syntaxial cement has been identified. Single-grain feldspar occurs in proportions lower than 20 %. Feldspar (Fig.3A,3E) distinction has been made among orthoclase (<20%), microcline (0 %) and plagioclase (<1 %). K-feldspar appears fresh or, in some cases, slightly altered, while when plagioclase occurs, high degrees of sericite alteration can be observed. Most of the samples have a widely representation of lithic grains, classified as metamorphic (MRF), sedimentary (SRF) and plutonic (PRF) rock fragments. Metamorphic rock fragments (Fig. 3A) have been classified according to its composition and metamorphic rank (Garzanti and Vezzoli, 2003). The main types of metamorphic rocks that can be identified are very low to low-grade (metapelites and phyllites) and medium-grade (mica schists and schists). Non-carbonate sedimentary fragments are represented by sandstone, siltstone (Fig. 3B), chert and radiolarites rock fragments. Mixed carbonatic and siliciclastic sandstone fragments are also represented and are classified as hybrid siltstone or hybrid sandstone due to its content in intrabasinal and extrabasinal carbonatic components.

Muscovite and biotite are the most common pyllosilicatic grains (<1 %), appearing in some cases as rock forming fragments, like schists or granitoids. Heavy minerals are always less than 1%, and mainly are tourmaline and zircon, usually with rounded to subangular shapes.

4.1.2 Carbonate extrabasinal grains (CE)

Carbonate grains are widely represented in most of the samples, and are even dominant in some samples. Distinction between intrabasinal and extrabasinal carbonate grain was performed following the criteria proposed by Zuffa (1980,1985).

Extrabasinal carbonate grains (Fig. 3D) can be as high as the 70%. Fragments of bioclastic limestones (Fig. 3F) have been classified according Dunham (1962), appearing as micritic and bioclastic mudstone (<20%), packestone-wackestone (<18%) and grainstone (<14%). Cretaceous bioclasts can be recognized in some of these fossiliferous limestones. Sparitic limestone fragments are also present, and appear as monocrystalline calcite or as polycrystalline sparitic calcite fragments. Dolostone and dolomitized fragments are mainly absent in all the samples. Larger foraminifera identified as orbitolinids (Fig. 3F) imply an extrabasinal origin according to its Cretaceous age, so have been classified as carbonatic extrabasinal grains.

4.1.3. Carbonate intrabasinal grains (CI)

Carbonate intrabasinal grains comprise bioclasts (Fig. 3B, 3D), micritic coated grains, caliche nodules (Fig. 3B) and other micritic intraclasts (<30%). Bioclasts have been grouped in (i) larger benthic foraminifera and planktonic foraminifera (up to 7.5%), (ii) other bioclasts, mainly red and green algae, molluscs, ostracods, bryozoans and corals (< 15 %), (iii) microcodium grains (<5 %) and (iv) silicified bioclasts (<1%). Micritic coated grains are oncolites and are usually nucleated around siliciclastic grains. Caliche nodules and micritic intraclasts can reach high proportions in some layers (up to 25%).

4.1.4 Non-carbonate intrabasinal grains (NCI)

Non-carbonate intrabasinal grains appear always in minor proportions and represented by glauconite and argillaceous rip-up-clasts.

4.2 Diagenetic features

Authigenic minerals represent percentages ranging from 3 % to 40 % of the entire sample, and are mainly related to cementation, which constitutes the main diagenetic process affecting sandstones of the Tremp Formation. Two component types have been classified: (i) calcite and ferroan calcite cement and (ii) ankerite cement. Pore-filling cement reaches amounts up to the 25%, while cement replacing grains appears in lower percentages (<15%). Calcite is the most common authigenic mineral, occurring in the intergranular primary porosity as well as intragranular in bioclasts and filling microfractures (secondary porosity). Calcite cement appears replacing some framework grains like quartz, K-feldspar, plutonic rock fragments, silicified limestones and sandstone fragments. Iron-free calcite is the main composition of the pore-filling cement, while ferroan calcite appears mainly in the primary intragranular porosity of bioclasts and filling microfractures.

4.3 Petrofacies

The term petrofacies is used to describe clastic sediments with distinctive compositional features that can be well identified by the ratio of diferent grain types (Mansfield, 1971). In this sense, by analising lateral and vertical compositional variations of the Tremp Formation clastic materials, three main petrofacies can be recognised depocenters:

4.3.1 Carbonatic extrabasinal enriched petrofacies:

The “Carbonatic extrabasinal enriched” petrofacies (Figs. 3B, 3D, 3F) can be mainly distinguished by its dominant content on these grain types (>50% from the total framework grains). Carbonatic extrabasinal grains are mainly represented by limestone rock fragments and monocrystalline and polycrystalline calcite grains. Intrabasinal grains are always present in percentatges ranging from 5% to 30% of the total framework grains. This petrofacies can be also recognised by its low or absent feldspar content (K-feldspar and plagioclase) and by its particularly dominance of sedimentary rock fragments over metamorphic and plutonic fragments.

4.3.2 Mixed siliciclastic and carbonatic extrabasinal petrofacies:

Siliciclastic grains are in proportions above the 50%, while carbonatic extrabasinal ones are between 10 and 40% of the total framework grains Intrabasinal grains appear in proportions ranging from 1% to 20% mainly represented by micritic coated grains with lower contributions of bioclastic components. One of the most remarkable features of this group is the abundant content of K-feldspar (Plagioclase/K-feldspar<1) and plutonic rock fragments. This highly contrasts with the completely absence of these components in the above described “Carbonatic extrabasinal enriched” petrofacies. Metamorphic and sedimentary rock fragments are also common components that widely appear in all the samples in variable proportions.

4.3.3 Siliciclastic dominant petrofacies:

This petrofacies highlights by the low contents of extrabasinal and intrabasinal carbonatic grains, that appear always in proportions less than 10% or absent in most of the samples (Fig. 3E). Feldspar widely occurs as orthoclase with minor contributions of highly altered plagioclase, being the Plagioclase/K-feldspar ratio <1. This group is also characterized by the high content in quartz grains (monocrystalline and polycrystalline) and plutonic rock fragments. Metamorphic and sedimentary grains are subordinate lithic grains, mainly represented by quartzarenite fragments, metamorphic quartzites and other low-medium grade metamorphic grains like schists and shales.

4.4 Modal sandstone composition

Ternary diagrams (Fig. 4) have been used in order to classify and identify the main compositional changes for the studied systems. The modal composition of sandstones is here represented according to the criteria of Zuffa, 1980 (NCE-CE-CI) and Dickinson *et al*., 1983 (QFL), Gazzi *et al*., 1973 (QFL+CE). Other diagrams have been used to analyse the lithic fraction, such as MRF-(PRF+F)-SRF (Fig.4D). A first order compositional classification has been obtained for all the studied samples by representing the relative content on “non-carbonate extrabasinal” (NCE), “carbonate extrabasinal” (CE) and “carbonate intrabasinal” (CI) components.

4.4.1 Àger syncline and Benabarre sector

All the samples from the Àger and Benabarre sectors (Fig. 2) show higher proportions of non-carbonate components than carbonate components, being all of them plotted in the “sandstone” field sensu Zuffa, 1980 (Fig. 4A) with a mean of $NCE_{62}CE_{25}CI_{13}$.

Regarding to the quartz/feldspar/lithics content, the mean for this system is $Q_{67}F_{19}L_{14}$ (Fig. 4B), as samples can be classified as “subarkoses” (Pettijohn *et al.*, 1972). Single and polycrystalline quartz grains are common, some of them with evaporitic inclusions. Non altered K-feldspar appears as orthoclase (microcline is absent) being the plagioclase to K-feldspar ratio (P/K) less than 1. Most common carbonate extrabasinal grains are micritic and wackestone-grainstone grains, some of them with fossil content such as miliolids and tintinnids. Intrabasinal components are coated grains, that occur in almost all samples, and with lower proportion caliche nodules, bioclasts (including carophyites) and *Microcodium* grains. No clear vertical trends can be observed along both Fontllonga and Benabarre sections. According to its compositional features, all the samples from the Àger syncline correspond to “Mixed siliciclastic and carbonatic extrabasinal” petrofacies and can be well discriminated in the different ternary diagrams (Fig. 4).

4.4.2 Tremp syncline

Samples from Tremp syncline show a clear dominance of extrabasinal and intrabasinal carbonate grains over siliciclastic grains. Limestone fragments are grainstone, wackstone-packstone and biomicritic mudstone, similar to those described in the Àger syncline. Intrabasinal grain types are also similar, but bioclasts are much more represented than coated grains and *Microcodium*. Some layers are rich in caliche nodules due to reworking of interestratified calcrete soils. The mean for this sector is $NCE_{38}CE_{40}CI_{22}$ and samples can be classified as calclithites and hybrid arenites (Fig. 4A). Concerning to the siliciclastic content, the lack of feldspar and plutonic fragments discriminates this area (Figs. 4B, C), being the mean $Q_{50}F_{0}L_{50}$. Sedimentary lithic fraction is constituted by quartz-rich sandstone and siltstone fragments and hybrid sandstones and siltstones. Metamorphic schist and phyllite fragments are also present in minor proportions. Samples from the Tremp syncline show higher amounts of lithic and carbonate extrabasinal grains than those from the Àger syncline (Fig. 4C) and also no clear vertical trends can be distinguished. All these compositional characteristics allow to include samples from the Tremp syncline (Montrebei and Tremp sections) to "Carbonatic extrabasinal enriched" petrofacies (Fig.4).

4.4.3 Vallcebre syncline and Cadí area

Samples from the Coll de Pal section (Cadí area) show a clear predominance of non-carbonatic extrabasinal grains, mainly displayed by high contents of quartz, feldspar (orthoclase) and granitoid fragments (Fig. 4D). Lithic grains such as quartzarenites, metamorphic quartzites and schists and phyllites are also present. The mean for this sector is $Q_{64}F_{18}L_{18}$ and samples can be classified as subarkoses and sublithoarenites (Fig. 4B). Due to the lack of carbonatic grains, samples from the Cadí monocline correspond to "siliciclastic dominant" petrofacies being this petrofacies restricted to this sector.

In the Vallcebre sector most of samples show dominance of non-carbonatic extrabasinal grains over the carbonatic grains (Fig. 4A). Regarding to the quartz/feldspar/lithics content (Fig. 4B), as samples can be classified as "lithoarenites" (Pettijohn *et al*., 1972). Quartz and non altered K-feldspar (orthoclase) are widely represeted, being the plagioclase to K-feldspar ratio (P/K) less than 1. Carbonate extrabasinal grains are bioclastic micritic and wackestone-grainstone fragments. Intrabasinal components are coated grains and caliche nodules. All the samples with this compositional characteristics can be associated to petrofacies "Mixed siliciclastic and carbonatic extrabasinal" being plotted in the same field area of the Àger syncline samples (Fig. 4C). Some layers show a clear predominance of carbonatic grains, represented mainly by a wide variety of cretaceous limestones and recycled single orbitolinid grains, so an additional "Carbonatic extrabasinal enriched" petrofacies is also found in the Vallcebre syncline (Fig. 4A).

5. Implications and discussion

The integration of petrology with regional geology is critical for discussing the paleogeography of the Tremp Formation (Figs. 5, 6). Thus, a first point to consider are the features of the detrital grains of the Tremp Formation that inform about provenance.

Quartz origin in the Tremp Formation may be diverse, as it appears in a wide kind of varieties. Well-rounded quartz can be attributed to long transport distances or recycling from terrigenous grains from older sandstone formations. The presence of inherited quartz overgrowths in detrital quartz grains represents the cementation of grains from a previous sedimentary cycle (Sanderson, 1984). This kind of detrital quartz suggests recycling of Paleozoic (Carboniferous or Permian formations) or Cretaceous formations. Fine-grained polycrystalline quartz can be associated to medium grade metamorphic rocks such as schists and quartzites from the Paleozoic basement. Some euhedral quartz grains with evaporitic inclusions (halite and anhydrite) are coincident to those described from the Triassic Keuper facies (Marfil, 1970). K-feldspar is attributed to crystalline rocks from the Paleozoic basement such as granitoids or metamorphic units. Lithic grains as shales, schists, plutonic and radiolarite fragments are also indicative of contribution from the Paleozoic basement. Quartz-rich sandstones and siltstones can be attributted to a contribution from Triassic Buntsandstein facies or Carboniferous formations, while hybrid sandstone and siltstone rock fragments are interpreted mainly as supplied from erosion of Mesozoic formations (characterised by the presence of carbonatic extrabasinal and intrabasinal components).

Among all the carbonatic extrabasinal grain types, some bioclast contained in terrigenous grains indicates contribution from cretaceous limestones. Wackestone fragments with pithonellid tests indicate provenance from Late Cretaceous limestones while occurrence of single orbitolines can be attributted to erosion from Early Cretaceous formations involved in the Bóixols thrust sheet.

Intrabasinal grains such as oncolites and caliche nodules are coincident with those described for the fluvial environments of the Tremp Formation (Colombo and Cuevas, 1993) indicating reworking of fluvial deposits and interestratified soils.

Paleogeographic reconstruction of the environmental settings of the Tremp Formation has been performed for the four stages comprised between Early Maastrichtian to Paleocene (Figs. 5, 6). Location and nature of source rocks is also established according to the three main petrofacies defined and provenance interpretations of the detrital grains.

5.1 Ager syncline

The Ager basin fluvial systems are far more coarse-grained than those of the Tremp basin. The fluvial systems of the Ager basin have paleocurrents towards the North and Northwest (Colombo and Cuevas, 1993).

The Ager syncline sandstones ("Mixed siliciclastic and carbonatic extrabasinal" petrofacies) were always sourced from areas constituted by a Paleozoic basement (mainly granitic and low-grade metamorphic rocks) and a Mesozoic carbonate cover as proved by the distinctive reworked euhedral quartz with evaporitic inclusions from the Triassic Keuper facies. Additionally, the recycled upper Cretaceous limestones provide further evidence for the erosion of the Mesozoic cover. According to the paleocurrents and facies distribution (Fig. 5) the source area was located to the South (Ebro Massif). Published data from subsurface exploration wells (Lanaja, 1987) demonstrates that the pre-Tertiary emerged basement in the Prades area (Fig. 1) was constituted by a thin Mesozoic cover and crystalline Paleozoic rocks. On the contrary, the easternmost part of the Ebro Massif (Montseny area, see Figs. 5 and 6), was free from the Mesozoic cover due to non-sedimentation (Núñez *et al*., 2000, Gómez-Gras *et a*l., 2000). Thus, we infer the Prades area (in central Ebro Massif) as the most likely source area for the Tremp Formation in the Àger syncline.

The Southern provenance area for the Àger basin sandstones is in conflict with the works by Rosell *et al* (2001) and Ullastre and Masriera (1982). The last authors considered an East origin due to the occurrence of kyanite, interpreted as sourced from the Sardinia and Corsica massifs. In fact, kyanite has also been found in the Oligocene sediments from the Ebro basin that were sourced from the Catalan Coastal Ranges (Allen and Mange, 1982). According to these authors, kyanite is distinctive from the Montsant area (southwestern Catalan Coastal Rages) and has not been reported in the Pyrenean derived sediments neither in the Pyrenean basement. Kyanite has also been found in the Albian Escucha Formation that crops out in the Iberian Ranges (Sainz-Amor *et al*., 1996). Thus, the occurrence of kyanite in the Tremp formation is not at all a diagnostic criteria for inferring an eastern source (Sardinia massif).

5.2 Tremp and Coll de Nargó synclines

The Tremp and Coll de Nargó synclines infill is dominated by the "Carbonatic extrabasinal enriched" petrofacies. The source area of these sediments is exclusively Cretaceous limestones (mainly Late Cretaceous) and few sandstones. These compositions are also found in the Maastrichtian conglomerate and breccia deposits of the Tremp Formation attached to the Bóixols-Sant Corneli cover thrusts. In the Tremp syncline, these deposits are known as Talarn and Abella conglomerates (Krauss, 1990), and Sallent de Montanisell-Coll de Nargó conglomerates (see Rosell et al, 2001). Thus, this composition is radically different from that in the Àger basin, since no fragments of a crystalline basement (K feldspar and plutonic fragments) are found. Undoubtly, the source areas for the Tremp basin resulted from the erosion of the Sant Corneli anticline during the Maastrichtian as recorded by large sintectonic erosions (Díaz-Molina, 1983, Deramond et al, 1993), which are absent in the Montsec anticline Southern limb. According to these distinct provenance signatures, the Tremp basin became isolated from the Àger basin due to the early growth of the Montsec anticline, preventing sediments derived from the Ebro Massif to reach the Tremp syncline (Fig. 6). The Tremp formation in the Benabarre area (Figs 5) was deposited in the Southern limb of the Montsec anticline. Despite this area structurally belongs to the Montsec thrust unit, it was connected to the Àger basin and thus was fed by sediments derived from the Ebro massif (i.e., Benabarre area was to the south of the drainage divide resulting from the Montsec anticline).

5.3 Vallcebre syncline and Cadí area

The "Siliciclastic dominant" petrofacies is the only one found in the Cadí area, while in the Vallcebre syncline both "Carbonatic extrabasinal enriched" and "Mixed siliciclastic and carbonatic extrabasinal" petrofacies are found. Some samples from the Vallcebre syncline display a large amount of Early and Late Cretaceous recycled Orbitolinid grains and Late Cretaceous limestone fragments. These marine Cretaceous limestone fragments are the main component in the Coll de la Trapa conglomerates (Martínez et al., 2001). These conglomerates crop out stratigraphically below the Vallcebre limestone (i.e. they belong to the 'Lower Red Garumnian') and are derived from the early erosion of the Upper Pedraforca thrust sheet (Fig. 6).

The large amount of plutonic rock fragments, K-feldspar, quartz grains and metamorphic fragments in the Cadí area indicate erosion of a crystalline basement with no sedimentary cover. We interpret this source area as located in the southeast Montseny area (Ebro Massif), which would also source the Vallcebre basin, since the carbonate source area is related to the erosion of the Pedraforca massif. This is also supported by the lack of Mesozoic cover under Tertiary sediments that lay directly on the crystalline basement (Puig-reig well).

Additionally, in the Montseny cratonic area, crystalline rocks underwent an intense weathering due to a long exposure time from Triassic to Cretaceous (Gómez-Gras, 1993; Gómez-Gras and Ferrer, 1999; Gómez-Gras *et al.,* 2004; Parcerisa *et al*., 2007). This intense weathering is supported by the low P/K ratios found in all the samples from the Vallcebre and Àger synclines.

The southeast source area is also indicated by paleocurrents (Aepler, 1967) and the fact that the whole succession in Cadí monocline is coarser than in the Vallcebre syncline (Fig. 6). It has to be taken into account that the Cadí unit (where proximal fluvial facies are found) was originally located to the South of the Pedraforca unit (Vergés and Martínez, 1988).

6. CONCLUSIONS

Petrofacies and sediment routing permit an accurate paleogeographic reconstruction and evolution of the Tremp Formation. Three main petrofacies can be identified: "Carbonatic extrabasinal enriched", "Siliciclastic dominant" and "Mixed siliciclastic and carbonatic extrabasinal".

The Àger and Vallcebre syncline sandstones were always sourced from areas constituted by a Paleozoic basement and a Mesozoic carbonate cover, interpreted as situated in the Ebro Massif (located to the South). In contrast, in the Tremp syncline these sandstones lacked the Paleozoic basement signal, indicating a main contribution from the Mesozoic cover derived from the erosion of the Bóixols-Sant Corneli anticline.

A South and Southeast source area (Ebro Massif) is also supported by the fluvial features of the Tremp Formation, being coarser in the southern parts (Àger basin and Cadí area). The S and SE derived clasts only reached the northern edge of the southpyrenean basin in the present day Vallcebre syncline. On the contrary, the growth of the Montsec thrust topographic high, prevented South derived sediments to go further to the N.

In conclusion, the Àger basin was fed from the S (Prades area) and the Cadí-Vallcebre from the SE (Montseny area), both belonging to the Ebro Massif. The Pyrenean basement (Axial Zone) was not a source area during the sedimentation of the Tremp Formation. This last point is in strong contradiction with previous works lacking significant petrological information. The only source areas located to the north of the South Pyrenean Basin were the topographic highs resulting from cover thrusts. These last provided marine Cretaceous rock fragments (both as sandstones and conglomerate deposits) that coexisted with preeminent south-dominated source area.

The complex foreland evolution of the South Pyrenean basin can now be better constrained in terms of basin partitioning. In this way, Tremp, Àger and Vallcebre subbasins are integrated in a broken foreland basin scheme. The Tremp basin became isolated from the rest of the Southpyrenean basin due to the growth of the Montsec thrust. This isolation prevented sediments derived from the Ebro massif to reach the Tremp syncline, in agreement with sedimentological data.

7. ACKNOWLEDGMENTS

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Figure captions:

Figure 1. Top: Geological setting of NW Iberia, with indication of the Pyrenees, Catalan Coastal Ranges and Iberian Ranges. See location of a segment of the ECORS profile (Middle) (Muñoz, 1992). Bottom: Tremp formation outcrops of the Southern Pyrenees, with location of the sampled sections. 1: Campo; 2: Benabarre/Benavarri; 3: Embassament Canelles; 4: Montrebei; 5: Fontllonga; 6: Costa de Castelltallat, Costa de la Serra and Masia de Ramon; 7: Orcau; 8: Mina Tumí; 9: Cal Borni-Mirador de Vallcebre; 10: Coll de Pal

Figure 2. Stratigraphic location of the studied samples. (A) Samples from Benabarre (BN) and Fontllonga (FON) located in their respective sections. Both sections can be directly correlated with each other (López-Martínez et al., 1998). The sample of Embassament de Canelles (CAN1) is projected in the Fontllonga section. (B) Samples from Montrebei (MRB) and Orcau (TC and GL), Costa de Castelltallat (CT), Costa de la Serra (CS) and Masia de Ramon (MR). The latters are projected in a section measured in the Orcau area (modified from Oms et al., 2014). (C) Samples from Mina Tumí (MT), Cal Borni (CB) and Mirador de Vallcebre (MR) projected in a Vallcebre composite section.

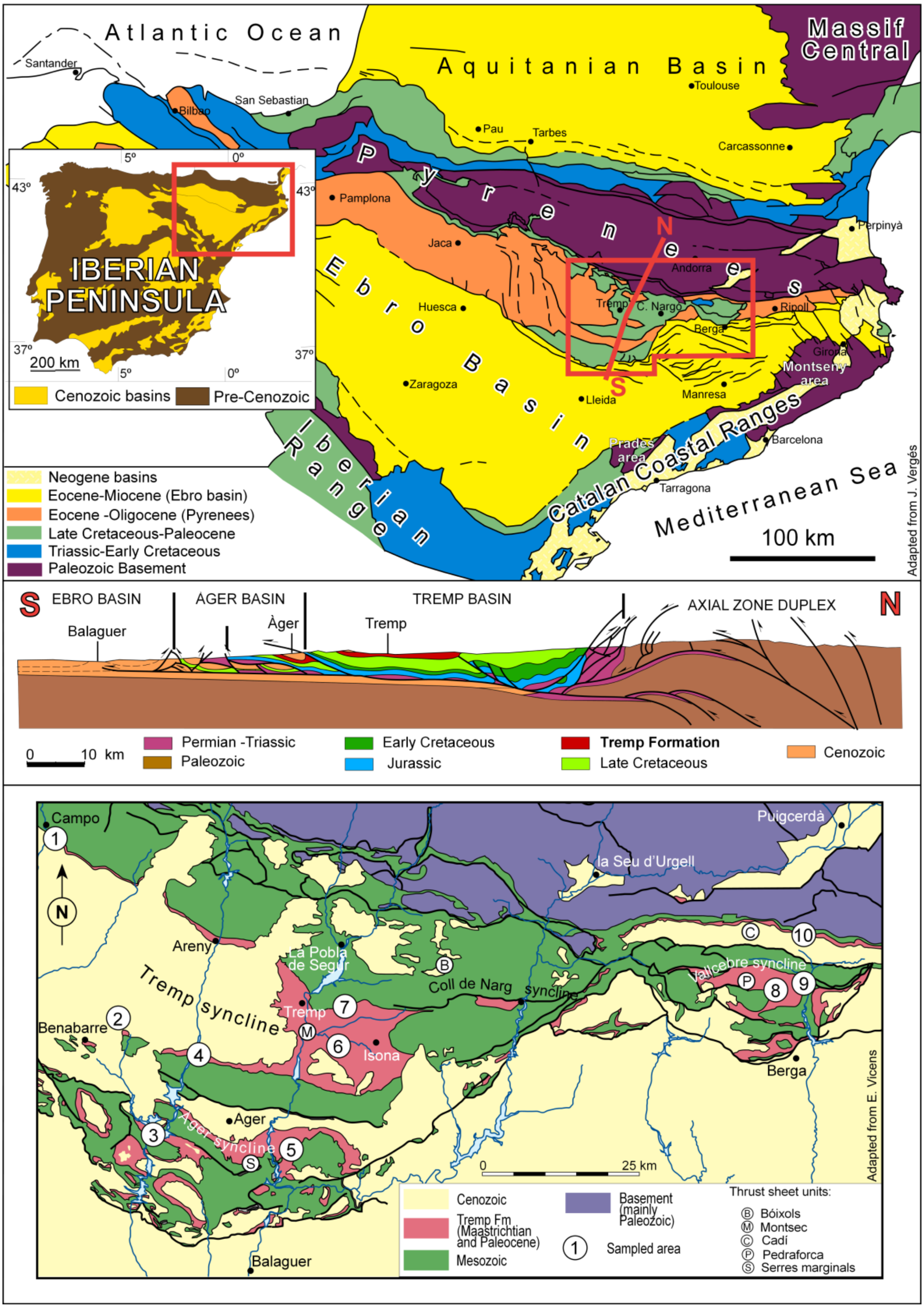
Figure 3. Optical photomicrographs of extra and intrabasinal grains: (A) General view of “Mixed siliciclastic and carbonatic extrabasinal” petrofacies showing extrabasinal grains as quartz (Qz), K-feldspar (Kf), a schist metamorphic rock fragment (Mrf) and micritic limestones (Lmc) (plane polarized, PPL); (B) “Carbonatic extrabasinal enriched” petrofacies showing extrabasinal grains as hybrid sandstone rock fragments (Hybr), and carbonate intrabasinal grains as caliche nodules (Clh) and single foraminifera bioclast (Bioc)(PPL); (C) “Mixed siliciclastic and carbonatic extrabasinal” petrofacies showing some quartz grains riddled with salt crystals inclusions (QzK), bivalve fragments (Bioc) and sparitic limestone rock fragments (Lmc)(cross-polarized, XPL); D “Carbonatic extrabasinal enriched” petrofacies showing intrabasinal grains as foraminifera bioclasts (Bioc) and extrabasinal components as hybrid sandstone fragments (Hybr) and micritic limestone (Lmc) rock fragments (PPL); E “Siliciclastic

dominant" petrofacies showing monocrystalline and polycrystalline quartz (Qz), orthoclase (Kf), plutonic fragments (Prf) and quartzarenite fragments (Snd) (XPL); F "Carbonatic extrabasinal enriched" petrofacies showing extrabasinal orbitolinid grains (Orbt) and grainstone and packstone rock fragments (Lmc) (PPL). The red scale bar is 1 mm.

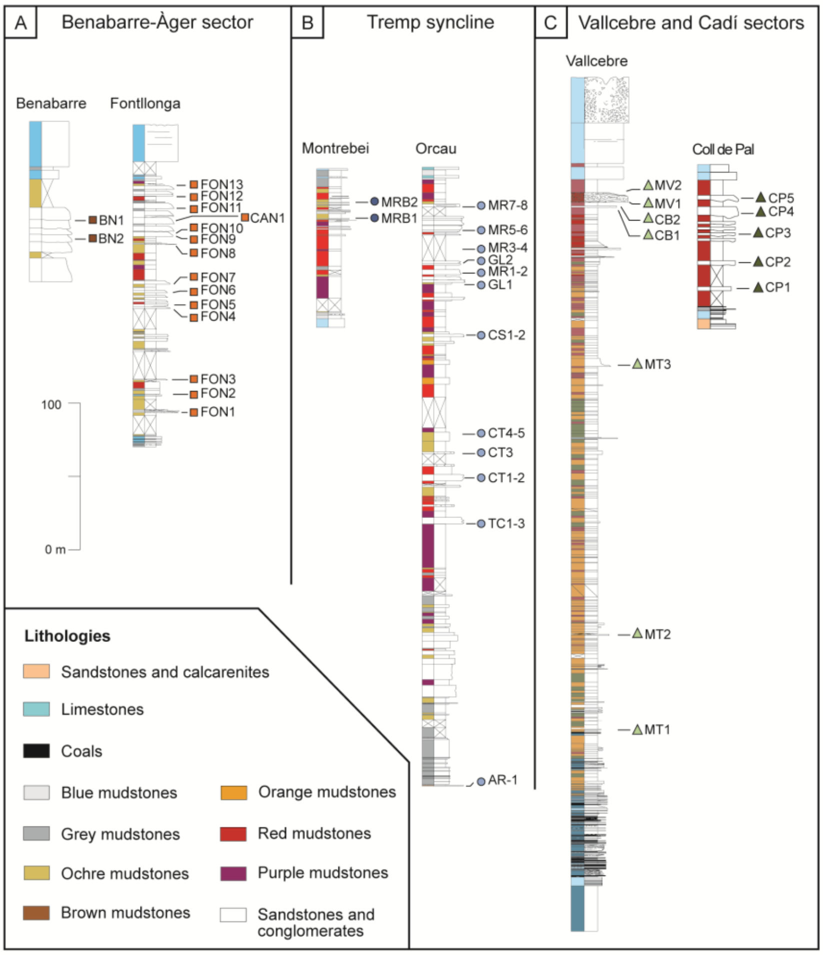
Figure 4. Sandstone composition plots for the clastic systems of the Tremp Formation (see location in Figure 2). Compositional ternary diagrams are: (A) First-order compositional plot (Zuffa, 1980) where NCE, Non-Carbonate Extrabasinal grains; CE, Carbonate Extrabasinal; and CI, Carbonate Intrabasinal, (B) QFL compositional plot (Dickinson et al., 1983) where Q, Quartz; F, Feldspar; and L, Lithic grains, (C) QFL+CE compositional plot (Gazzi et al., 1973) where Q, Quartz; F, Feldspar; and L+CE, Lithic and carbonate extrabasinal grains, (D) Compositional plot of lithic grains where SRF, Sedimentary rock fragments; MRF, Metamorphic fragments, and F+PRF, Feldspar and Plutonic fragments.

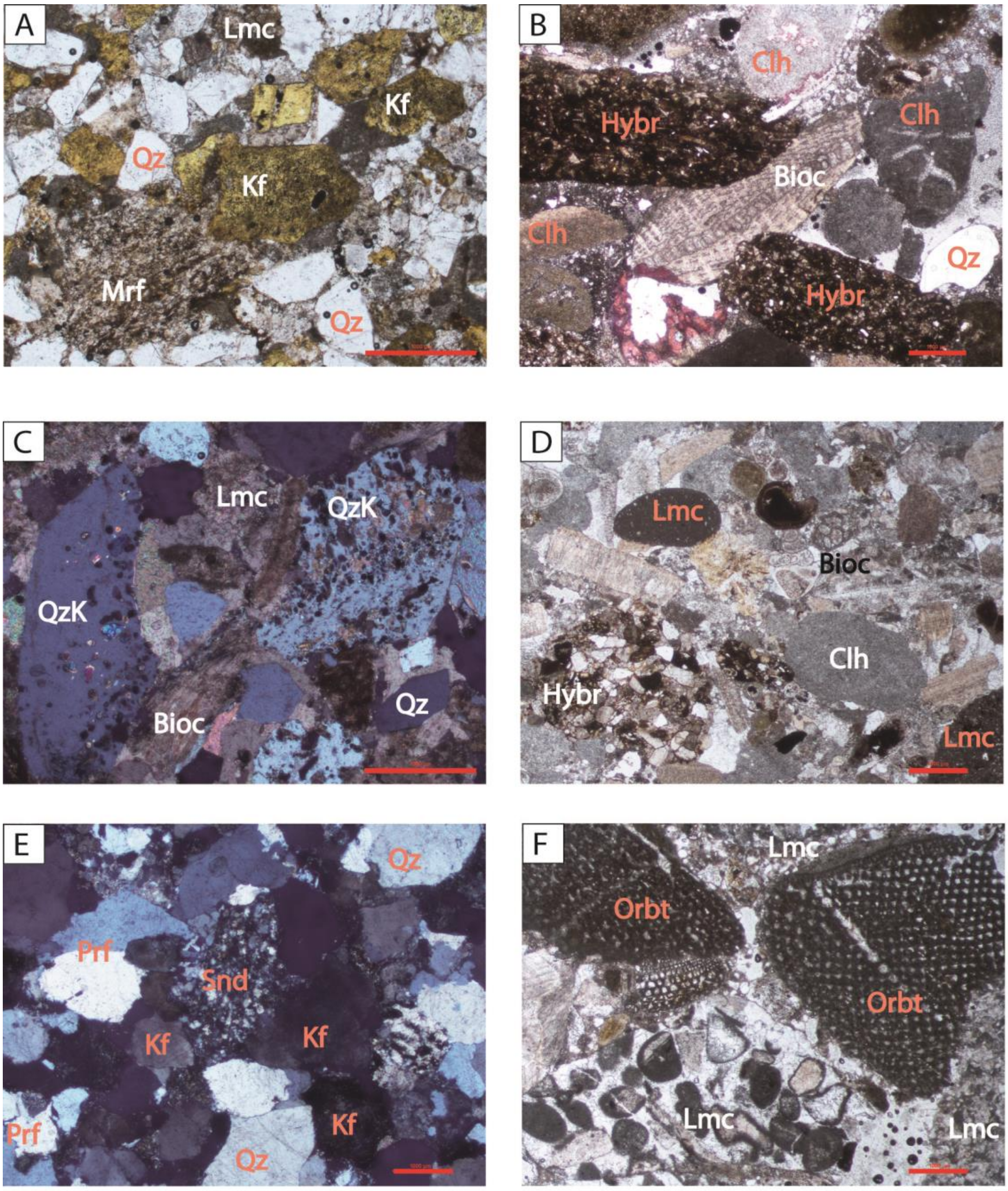
Figure 5. Tectonically restored palaeogeographic reconstruction of the Tremp Formation during (A) the early Maastrichtian (lagoonal setting represented by the Grey Garumniant ; and during (B)the late Maastrichtian (fluvial-coastal setting represented by the Lower Red Garumnian. Numbers represent the studied sections (see Fig. 1). Alphabetic characters represent areas or sections whose palaeoenvironment has been studied or is work in progress. a: Serraduy (López-Martínez et al., 2001); b: Iscles (López-Martínez et al., 2001; Vila et al., 2013); c: Areny (López-Martínez et al. 2001; Oms and Canudo, 2004; Pereda-Suberbiola et al., 2009); d: Embassament de Santa Anna e-f: Terradets and Isona, respectively (Oms et al., this issue); g: Coll de Nargó (Riera et al., 2013); h: Pedraforca i: northern Vallcebre sector (Oms et al., this volume); j: Peguera (Vila et al., 2011); k: Le Mas d'Azil (Bilotte et al., 1983); l: Espéraza (Fondevilla et al., this issue); m: Albas (Galbrun, 1997); n: Boadella o: Montseny.

Figure 6. Tectonically restored palaeogeographic reconstruction of the Tremp Formation during (A) Latest-Maastrichtian Lower (fluvial-coastal setting represented by the Lower Red Garumnian) and (B) early Paleocene (lacustrine setting represented by the Vallcebre limestones and laterally equivalent strata). See legend in fig. 5.



Atlantic Ocean
Aquitanian Basin
Massif Central
Santander
Bilbao
San Sebastian
Toulouse
Pau
Tarbes
Carcassonne
Pamplona
Perpinyà
Jaca
Andorra
Pyrenees
N
Tremp
C. Nargo
Ripoll
Huesca
Berga
Girona
Montseny area
Ebro Basin
Zaragoza
S
Lleida
Manresa
Prades area
Barcelona
Catalan Coastal Ranges
Iberian Range
Tarragona
Mediterranean Sea
100 km
Adapted from J. Vergés
IBERIAN PENINSULA
43º
5º
0º
37º
200 km
Cenozoic basins
Pre-Cenozoic
Neogene basins
Eocene-Miocene (Ebro basin)
Eocene -Oligocene (Pyrenees)
Late Cretaceous-Paleocene
Triassic-Early Cretaceous
Paleozoic Basement
S
EBRO BASIN
ÀGER BASIN
TREMP BASIN
AXIAL ZONE DUPLEX
N
Balaguer
Àger
Tremp
0 10 km
Permian -Triassic
Paleozoic
Early Cretaceous
Jurassic
Tremp Formation
Late Cretaceous
Cenozoic
Campo
Puigcerdà
la Seu d'Urgell
N
Areny
La Pobla de Segur
Coll de Narg
syncline
Vallcebre syncline
Tremp syncline
Benabarre
Tremp
Isona
Berga
Ager
Àger syncline
Balaguer
0 25 km
Adapted from E. Vicens
Cenozoic
Tremp Fm (Maastrichtian and Paleocene)
Mesozoic
Basement (mainly Paleozoic)
Sampled area
Thrust sheet units:
B Bóixols
M Montsec
C Cadí
P Pedraforca
S Serres marginals


A
Benabarre-Àger sector
B
Tremp syncline
C
Vallcebre and Cadí sectors
Benabarre
Fontllonga
BN1
BN2
FON13
FON12
FON11
CAN1
FON10
FON9
FON8
FON7
FON6
FON5
FON4
FON3
FON2
FON1
100
0 m
Montrebei
Orcau
MRB2
MRB1
MR7-8
MR5-6
MR3-4
GL2
MR1-2
GL1
CS1-2
CT4-5
CT3
CT1-2
TC1-3
AR-1
Vallcebre
Coll de Pal
MV2
MV1
CB2
CB1
CP5
CP4
CP3
CP2
CP1
MT3
MT2
MT1
Lithologies
Sandstones and calcarenites
Limestones
Coals
Blue mudstones
Grey mudstones
Ochre mudstones
Brown mudstones
Orange mudstones
Red mudstones
Purple mudstones
Sandstones and conglomerates


A
Lmc
Kf
Qz
Kf
Mrf
Qz
B
Clh
Hybr
Clh
Bioc
Clh
Qz
Hybr
C
Lmc
QzK
QzK
Bioc
Qz
D
Lmc
Bioc
Clh
Hybr
Lmc
E
Qz
Prf
Snd
Kf
Kf
Kf
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F
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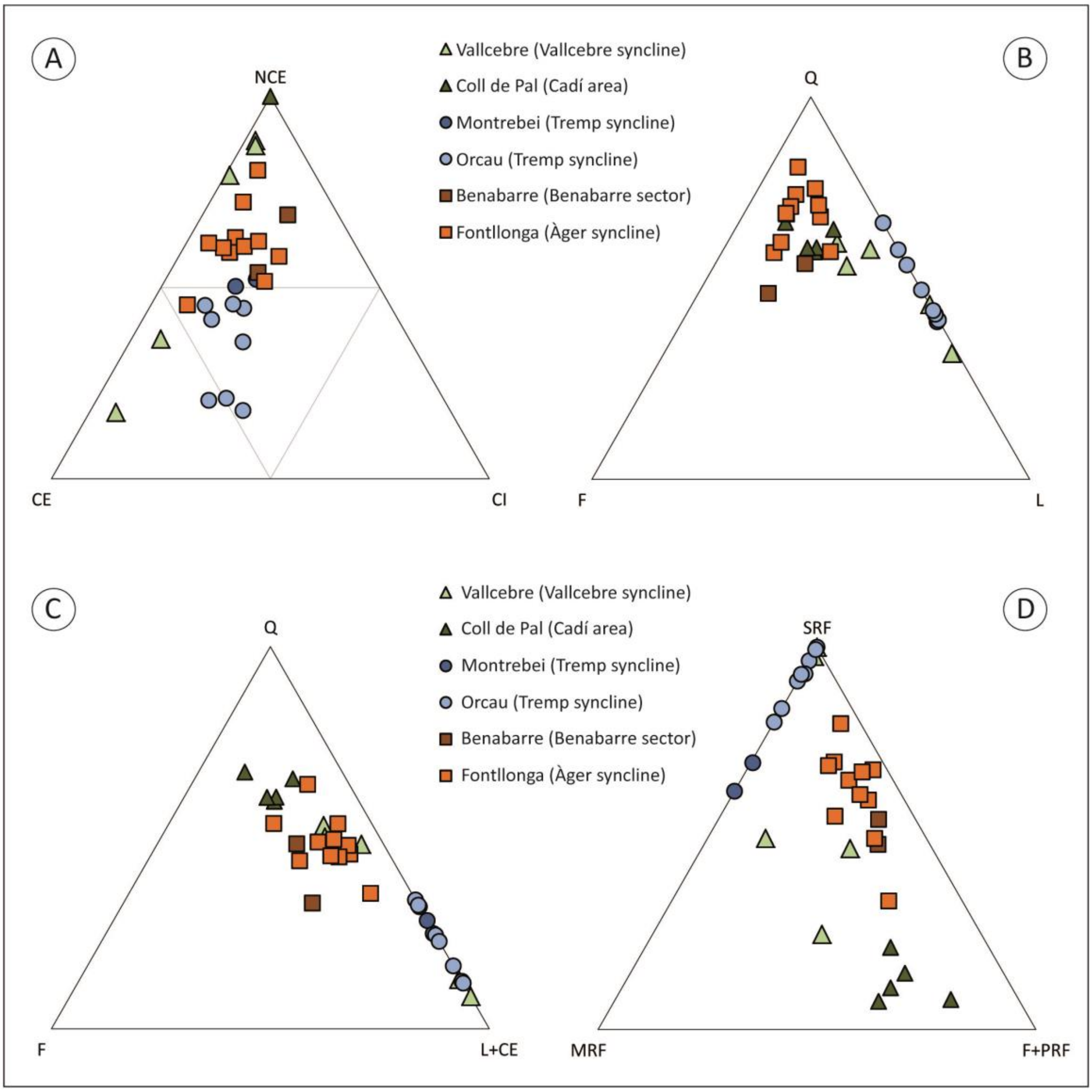
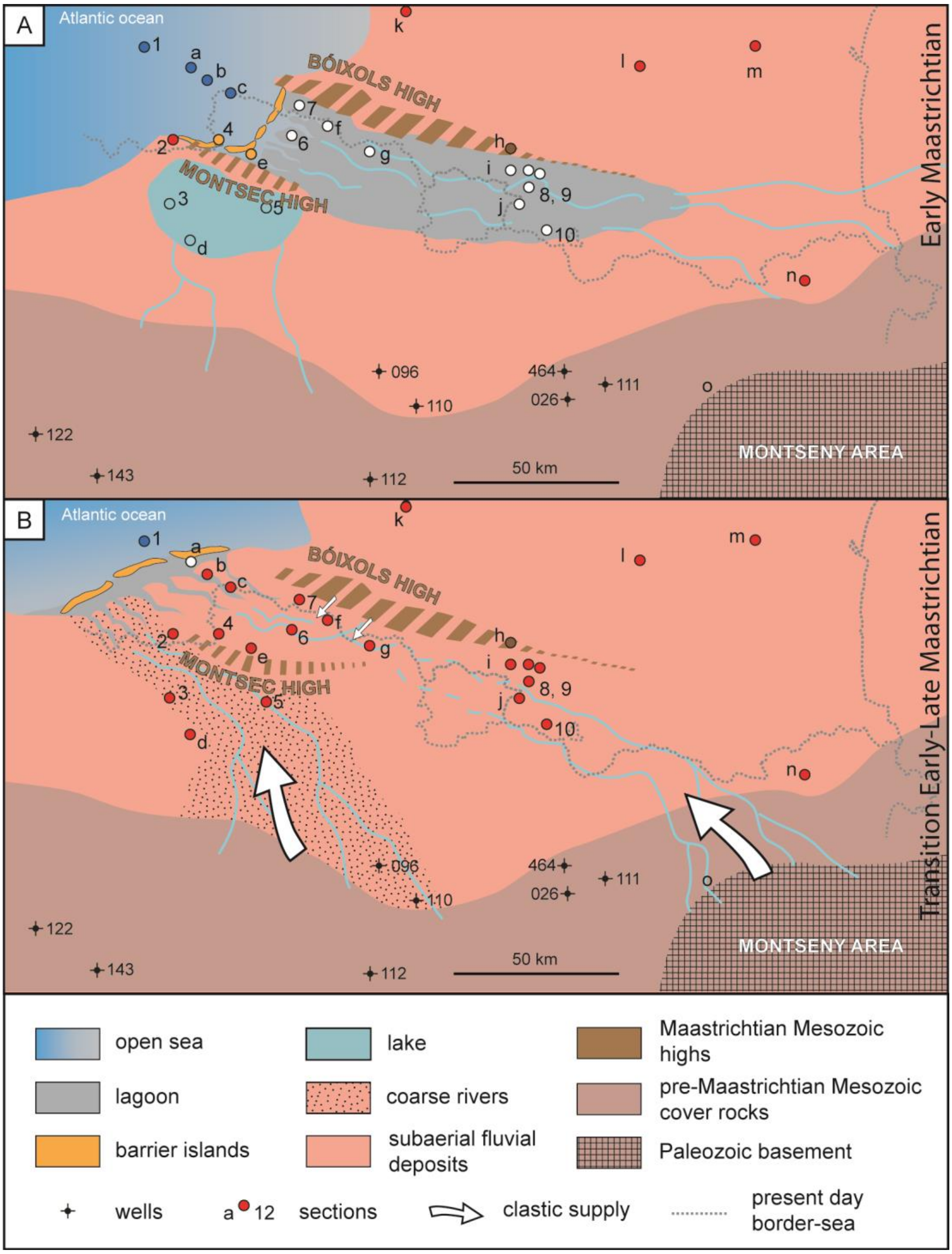
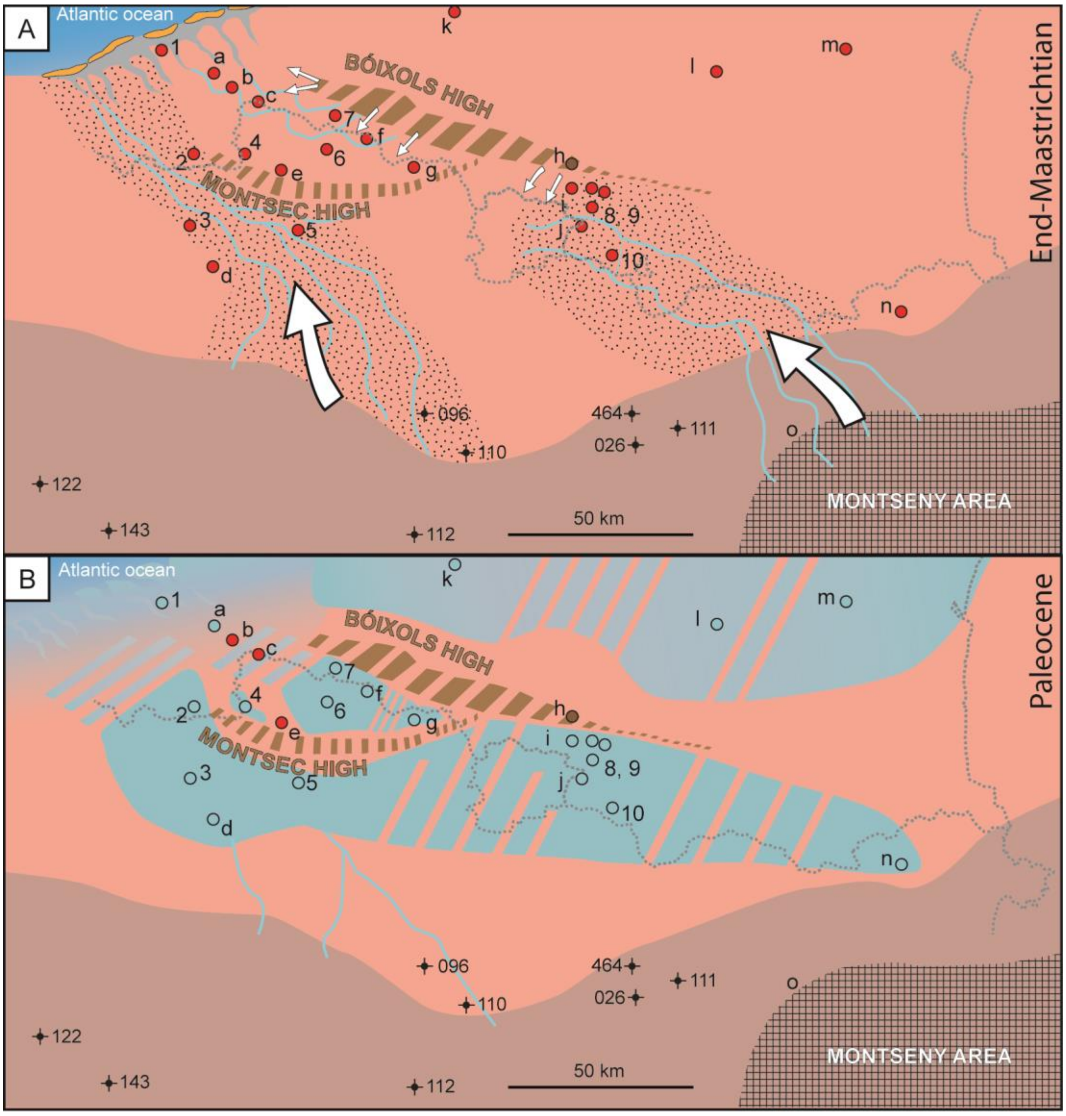

A
B
C
D
Vallcebre (Vallcebre syncline)
Coll de Pal (Cadí area)
Montrebei (Tremp syncline)
Orcau (Tremp syncline)
Benabarre (Benabarre sector)
Fontllonga (Àger syncline)
NCE
CE
CI
Q
F
L
Q
F
L+CE
SRF
MRF
F+PRF



A
Atlantic ocean
BÓIXOLS HIGH
MONTSEC HIGH
Early Maastrichtian
MONTSENY AREA
50 km
1
2
3
4
5
6
7
8, 9
10
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
096
464
111
026
110
122
143
112
B
Atlantic ocean
BÓIXOLS HIGH
MONTSEC HIGH
Transition Early-Late Maastrichtian
MONTSENY AREA
50 km
open sea
lagoon
barrier islands
lake
coarse rivers
subaerial fluvial deposits
Maastrichtian Mesozoic highs
pre-Maastrichtian Mesozoic cover rocks
Paleozoic basement
wells
a 12 sections
clastic supply
present day border-sea



A
Atlantic ocean
End-Maastrichtian
BÓIXOLS HIGH
MONTSEC HIGH
MONTSENY AREA
50 km
B
Atlantic ocean
Paleocene
BÓIXOLS HIGH
MONTSEC HIGH
MONTSENY AREA
50 km