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Cyclicity recorded in the provenance sandstones in the sedimentary infill of the Cameros basin (N. Spain)

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ABSTRACT

The intraplate Cameros rift basin in the north of Spain was formed came into being between the Tithonian and the Early Albian and contains 9000 m of mostly continental sediments. This basin is a good example of cyclicity of different depositional sequences (DSs) in sedimentary environments, which show clear repetition in their sandstone composition (petrofacies) and diagenetic patterns. The DSs are arranged in two megasequences (MSs) separated by a tectonic unconformity. A similar vertical sandstone compositional evolution, subdivided into two stages that repeat cyclically, has been recognised in both MSs: the first comprises quartzo-sedimentolithic petrofacies and the second is made up of several quartzo-feldspathic petrofacies. This was caused by a progression from the recycling of the pre-rift sedimentary cover to the erosion of the mainly plutonic and metamorphic crystalline basement. These changes in the erosion of the different source areas were conditioned by the tectonics of the basin. Furthermore, the original sandstone framework composition conditioned the diagenetic pattern of the two stages: quartzo-sedimentolithic sandstones containing large amounts of very pervasive carbonate cement that reduce their original porosity considerably, and quartzo-feldspathic petrofacies with a rigid framework that maintained the original pores during burial diagenesis. This compositional and diagenetic pattern is probably applicable to other non-volcanic rifted basins, depending upon the original amount of carbonate rock fragments present.

Key words: Cameros basin, cyclicity, diagenesis, petrofacies, sandstones

Ciclicidad de la procedencia de areniscas en el registro sedimentario de la cuenca de Cameros (Norte de España)

RESUMEN

La cuenca intraplaca de rift *de Cameros se localiza al norte de España. Se desarrolló entre el Titónico y el Albiense Inferior, depositándose 9000 m de sedimentos fundamentalmente continentales. La cuenca es un buen ejemplo de ciclicidad en los medios sedimentarios en las diferentes Secuencias Deposicionales (SD), lo que genera una clara repetición de la composición de las areniscas (petrofacies) y de las pautas diagenéticas. Las SD están organizadas en dos megasecuencias (MS) separadas por una discordancia de carácter tectónico. Ambas MS presentan una evolución vertical similar en la composición de las areniscas, generando una repetición de dos estadios: (1°) constituido por una petrofacies cuarzosedimentolítica y (2°) formado por varias petrofacies cuarzofeldespáticas. Este hecho viene motivado por el cambio desde la erosión de una cobertera sedimentaria pre-*rift *a la erosión del basamento cristalino, principalmente constituido por áreas fuente plutónicas y metamórficas. Estos cambios en la erosión de distintas áreas fuente están controlados por la tectónica de la cuenca. Además, la composición original del esqueleto de las areniscas condiciona el tipo de diagénesis para los dos estadios anteriormente descritos: las areniscas cuarzosedimentolíticas contienen abundante cemento de carbonato, que reduce su porosidad inicial drásticamente. Sin embargo, las areniscas cuarzofeldespáticas presentan un esqueleto más rígido que mantiene los poros originales durante la diagénesis de enterramiento. Este patrón composicional y diagenético es probablemente aplicable a otras cuencas de* rift *intraplaca no volcánicas, dependiendo de la cantidad inicial de fragmentos de roca carbonática.*

Palabras clave: areniscas, ciclicidad, cuenca de Cameros, diagénesis, petrofacies

VERSION ABREVIADA EN CASTELLANO

Introducción y métodos

Este trabajo presenta una síntesis de la caracterización del relleno sedimentario de la Cuenca de Cameros, fundamentalmente desde el punto de vista de la petrología de las areniscas, considerando tanto las implicaciones de procedencia como las diagenéticas. Pretende ser una síntesis de trabajos previos, que permita al lector apreciar la ciclicidad del registro arenoso de la cuenca.

La ciclicidad del registro sedimentario puede observarse en la repetición de materiales a varias escalas: facies, secuencias, sistemas deposicionales, secuencias deposicionales y megasecuencias. Esta ciclicidad también produce recurrencia de petrofacies, generando "ciclos de procedencia" (Arribas et al.*, 2003, 2007) y repetición de patrones diagenéticos (Arribas* et al.*, 2002 y 2013 en prensa). A pesar de que los estudios de procedencia y diagénesis están muy extendidos, existen pocas publicaciones relacionadas con la ciclicidad de las petrofacies arenosas (*cf: *Weltje* et al.*, 1996).*

La Cuenca de Cameros, situada al norte de España, es una cuenca de rift *intraplaca (Fig. 1) cuyo relleno sedimentario se formó desde el Titoniense al Albiense Inferior (Mas* et al.*, 2002, 2003, 2004). Se trata de un registro fundamentalmente continental con algunas incursiones marinas que coinciden con los máximos eustáticos (Alonso y Mas, 1993). Su registro sedimentario se ha dividido en dos megasecuencias (MS), y ocho Secuencias Deposionales (SD, Fig. 2). Las dos MS están separadas entre sí por una discordancia de origen tectónico. La primera MS se corresponde con el registro de las SD 1 a 3 (10 Ma) y la segunda con las SD 4 a 8 (30 Ma) (Arribas* et al*. 2007 y 2013 en prensa).*

Las muestras de este trabajo proceden de 39 columnas estratigráficas (Fig. 1). Se han reelaborado datos de carácter fundamentalmente petrológico procedentes de Arribas et al*. (2002, 2003, 2007 y 2013 en prensa), Ochoa (2006), Ochoa* et al*. (2007a) y González-Acebrón* et al*. (2007, 2010a), considerándose un total de 338 análisis por contaje de puntos. Además, se han incluido 28 nuevos contajes. Asimismo, se han elaborado diagramas diagnósticos de procedencia de areniscas para el sector occidental y oriental de la cuenca (Figs. 3 y 4).*

Resultados y discusión

El sector oriental de la cuenca está representado por un total de 256 muestras de areniscas, que en función de su composición las hemos dividido en 6 petrofacies (Figs. 3 y 5), que se corresponden respectivamente con la SD 1 (P1-E), SD 2 (P2-E), SD 3 (P3-E), SD 5, 6 y 7 (P4-E) y SD 8 (P5A-E y P5B-E). El sector occidental está representado por 110 muestras que hemos agrupado en 4 petrofacies (Figs. 4 y 6), correspondientes con el registro arenoso de la SD 1 (P1-W), SD 2 y 3 (P2-W), SD 4 (P3-W) y SD 5, 6 y 7 (P4-W). Es importante señalar que la SD 8 no ha quedado registrada en el sector occidental. Asimismo, la SD 4 está constituida casi exclusivamente por carbonatos en el sector oriental. Por lo tanto, no hay muestras de areniscas para estos dos casos.

Se establecen dos "ciclos de procedencia", asociados a las dos MS. El Ciclo 1 tiene una duración aproximada de 10 Ma y se corresponde con el intervalo entre la SD 1 y 3. El Ciclo 2 de una duración aproximada de 30 Ma y se corresponde con las SD 4 a 7. Cada uno de ellos está constituido por dos etapas, asociadas a registros sedimentarios de espesor muy distinto: 1ª etapa) una petrofacies sedimentoclástica o cuarzofeldespática, en función de la presencia o no de un área madre carbonática en las proximidades. Esta etapa genera espesores de sedimento inferiores a los 100 m; 2ª etapa) formada por varias petrofacies cuarzofeldespáticas, con áreas fuente fundamentalmente plutónicas y metamórficas. Durante esta última etapa se generó un espesor de sedimentos de hasta 6000 m en el sector depocentral de la cuenca.

Las áreas fuente plutónicas estuvieron probablemente situadas hacia el sur de la Cuenca de Cameros, en la Zona Centro-Ibérica (Fig. 7). La erosión de dichas áreas fuente se manifiesta antes en el sector E de la cuenca, durante la sedimentación de la SD1, mientras que, en el sector O comienza a registrarse durante la sedimentación de la SD2. Las áreas fuente metamórficas, en general, de bajo y medio grado, se situaban probablemente en la Zona Asturoccidental Leonesa (Fig. 7).

Por otra parte, la composición original del esqueleto de las areniscas y, por tanto, su procedencia, condicionó la diagénesis que estas sufrieron durante el enterramiento. En areniscas con un esqueleto constituido por fragmentos de rocas carbonáticas, como aquellas formadas en etapas de tipo 1, los cementos de carbonato son mucho más abundantes y tienden a ocluir la porosidad (Fig. 8 A y B).

Por el contrario, las areniscas cuarzofeldespáticas, que caracterizan la 2ª etapa, presentan un esqueleto más rígido que mantiene mejor la porosidad inicial en profundidad y su diagénesis está relacionada con procesos de cementación y reemplazamientos de minerales de la arcilla (Fig. 8C). Además, estas areniscas presentan una mayor porosidad secundaria debido a la disolución de los feldespatos (Fig. 8D).

Esta sucesión de las dos etapas es característica de una cuenca de rift *no volcánica, por lo que permite elaborar patrones predictivos de la composición de las areniscas y su porosidad en este tipo de cuencas.*

Introduction

This work provides a synthesis of the characterization of the sedimentary infill of the Cameros basin, particularly from the point of view of the sandstone petrography, including both its provenance and diagenetic implications. This synthesis is fundamental to an appreciation of the cyclicity in the sandstone record of the basin.

The Cameros basin in northern Spain is an intraplate rift basin (Fig. 1) that developed from the Tithonian to the Early Albian (Mas *et al.*, 2002, 2003, 2004). The sedimentary infill comprises eight depositional sequences (DSs) (Fig. 2), mainly laid down in continental environments (Mas *et al.*, 2002, 2003, 2004) and consisting of alluvial fans or fluvial deposits that commonly pass upward into lacustrine deposits, resulting in considerable repetition in the sedimentary facies.

Cyclicity in the sedimentary record can be observed by the recurrence of materials on several scales: facies, sequences, depositional systems, depositional sequences, and megasequences. This cyclicity leads to a recurrence of petrofacies, generating "provenance cycles" (Arribas *et al.*, 2007) and repetition of diagenetic patterns (Arribas *et al.*, 2002 and 2013, in press). Although provenance and diagenetic studies are widespread, little work has been done to characterize cyclicity in sandstone petrofacies (*cf:* Weltje *et al.*, 1996). Geochemical investigations have been successfully carried out by testing facies and stratigraphic units of different rank (Amorosi *et al.*, 2007, Ochoa *et al.*, 2007b). A good summary of how petrofacies changes can be framed into a sequence-stratigraphic scheme on multiple timescales is recorded by Amorosi and Zuffa (2011).

Cyclicity has been related mainly to eustatic changes (Mitchum and Wagoner, 1990; Soreghan and Dickinson, 1994) but, nevertheless, tectonic activity was a principal factor in controlling the cyclicity in continental basins (Einsele, 1992, Miall, 2000, Allen, 2005).

Tectonic activity not only generates changes in basin accommodation but also makes hinterland source rocks available and modifies drainage patterns, thus changing the provenance of the sandstone. We describe here an example of cyclicity in a continental

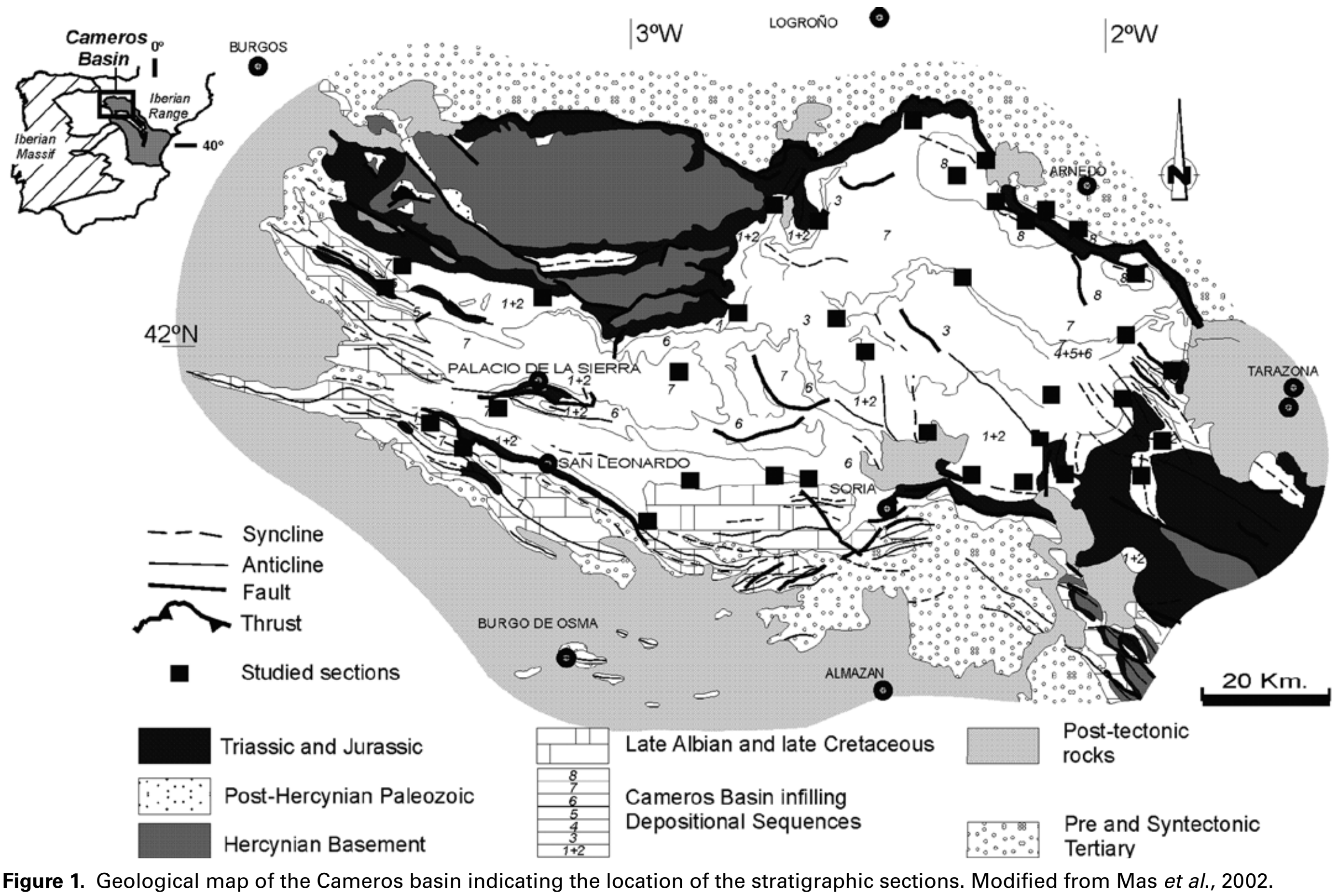

Figure 1. Geological map of the Cameros basin indicating the location of the stratigraphic sections. Modified from Mas *et al.*, 2002.
Figura 1. *Mapa geológico de la Cuenca de Cameros indicando la posición de las secciones estratigráficas. Modificada de Mas* et al.*, 2002.*

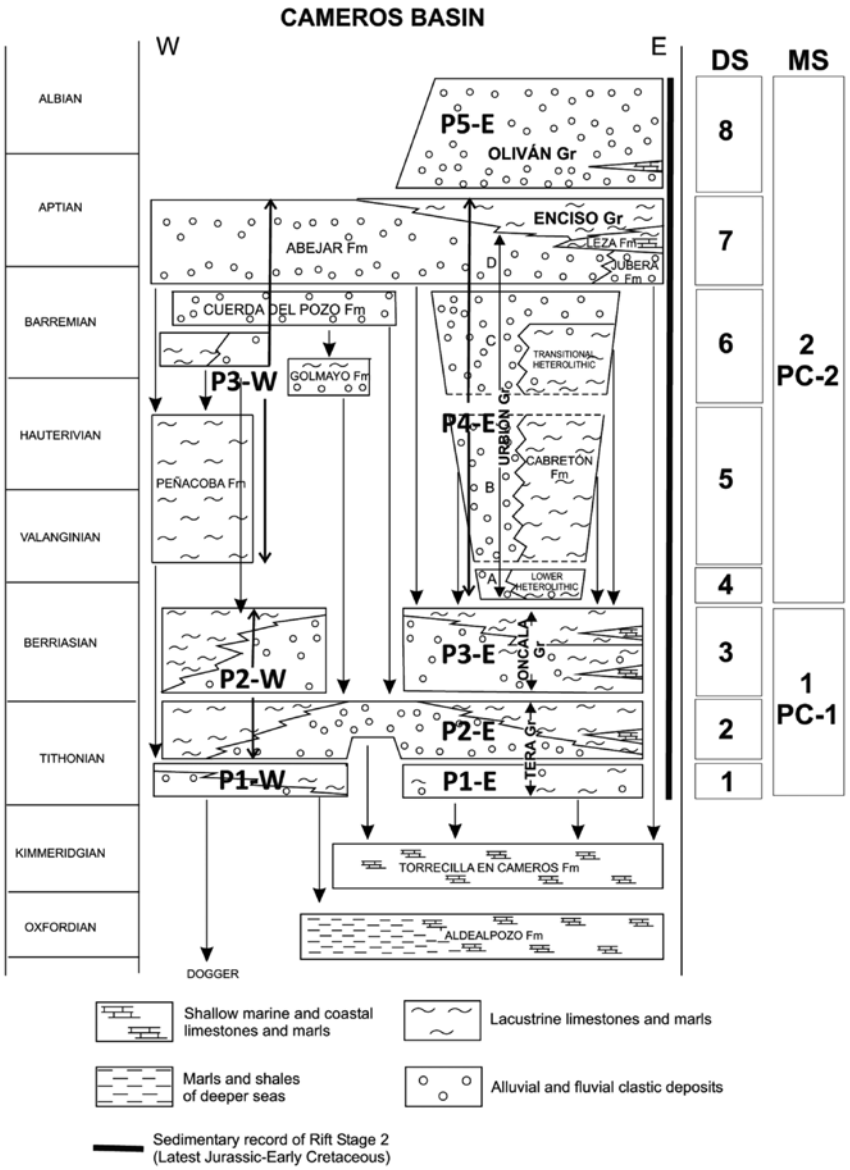

Figure 2. Stratigraphy of the depositional sequences (DSs) and megasequences (MSs) in the Cameros basin with the names of the petrofacies marked for each sector. PC: Provenance cycle. Modified from Mas *et al.*, 2004.

Figura 2. *Estratigrafía de las Secuencias Deposicionales (DS) y Megasecuencias (MS) de la Cuenca de Cameros con los nombres de las petrofacies marcados para cada sector. PC: Ciclo de procedencia. Modificada de Mas* et al.*, 2004.*

intraplate rift basin (Cameros basin), showing the repetition of sedimentary environments, lithofacies and sandstone petrofacies. Within this context we shall explain some provenance and diagenetic implications that can be used as tools for prediction purposes in the exploration for gas and oil in this kind of basin.

Geological setting

The Cameros basin is an extensional basin generated over a south-dipping crustal detachment formed by a ramp linking two sub-horizontal flats approximately 7000 and 11000 m deep (Mas *et al.*, 1993; Guimerà *et al.*, 1995; Mas *et al.*, 2002, 2003). The basin-fill succession is composed of 9000 m of sediments (Mas *et al.*, 2002, 2011). These deposits overlie Upper Jurassic marine strata and are separated from them by an erosional unconformity with associated palaeosols and/or palaeokarst features (Alonso and Mas, 1990; Benito and Mas, 2002).

The basin infill has been subdivided in eight depositional sequences sseparated by unconformities and relative conformities. The unconformities are relative to tectonic events that affected the basin during its evolution (Mas *et al.*, 1993 and 2011). The depocenters of depositional sequences progressively migrate northward, on-lapping the marine Jurassic substratum (Mas *et al.*, 2003, 2011; Omodeo-Salè *et al.*, 2011). A clear unconformity can be distinguished between DS

3 and DS 4, which even involved a big change in the progression of the depocentre areas (Mas *et al.*, 2003; Omodeo-Salè *et al.*, 2011). This unconformity separates two main megasequences: MS-1, made up of DS 1 to DS 3 (10 Ma), and MS-2, made up of DS 4 to DS 8 (30 Ma) (Mas *et al.*, 2003; Arribas *et al.*, 2003, 2007).

Depositional settings of the basin sedimentary infill

The sedimentary record of the Cameros basin is composed mostly of continental facies, related to alluvial-fluvial and lacustrine depositional systems. Marine influence has been recognised by various authors (Alonso and Mas, 1993: top of DSs 2, 7 and 8; Gómez-Fernández and Meléndez, 1994a, b: top of DS 2). More recently several studies have shown that the marine influence in the basin was stronger than initially thought, containing fluvial-deltaic environments, dominated by tides in the case of some siliciclastic units (Quijada *et al.*, 2010; and 2013, in press: DS 3) and coastal lakes, lagoons and tidal flats in the case of some carbonate units (Suárez *et al.*, 2010: top of DS 7, Sacristán *et al.*, 2012: top of DS 3). These episodes of marine influence are related to maximum eustatic levels (Alonso and Mas, 1993).

A clear vertical repetition of the facies, hence of the depositional systems, can be observed in the sedimentary record of the basin. In fact each DS starts with alluvial facies that evolve upwards into fluvial facies and finally to lacustrine deposits, sometimes affected by some marine influence. Spatially, in most of the DSs, a progressive evolution can be discerned from proximal deposition areas (coarse-grained deposits in alluvial fan systems), located in the southern sectors to distal lacustrine facies in the northern sectors of the basin (Mas *et al.*, 2002; Mas *et al.*, 2011).

Petrofacies in the basin sedimentary infill

We have undertaken a synthesis of the main petrofacies recognised so far in the Cameros basin. The information presented here includes data contained in previous works on the provenance of sandstones in the Cameros basin together with new observations. Data have been taken from Arribas *et al.* (2002, 2003, 2007 and 2013, in press), Ochoa (2006), Ochoa *et al.* (2007a) and González-Acebrón *et al.* (2007, 2010a) and collated in order to compare the evolution of all the depositional sequences in the different sectors of the basin.

Characterization of the petrofacies

The samples considered in this work relate to 39 stratigraphic sections (Fig. 1), some of them representing more than 2000 m of sedimentary record. We carried out 338 point-counting analyses on samples already studied and 28 on new ones. These compositional data were used to define the different petrofacies that configure the stratigraphic record.

The petrofacies are represented in provenance diagnostic diagrams as QmFLt (monocrystalline quartz, feldspar and lithic fragments), QmKP (monocrystalline quartz, K-feldspar and plagioclases) and RgRsRm (coarse-grained plutonic, sedimentary and metamorphic rock fragments) following the criteria of Dickinson and Suckzek (1979), Dickinson (1985) and Arribas *et al.* (1990) respectively (Figs. 3 and 4).

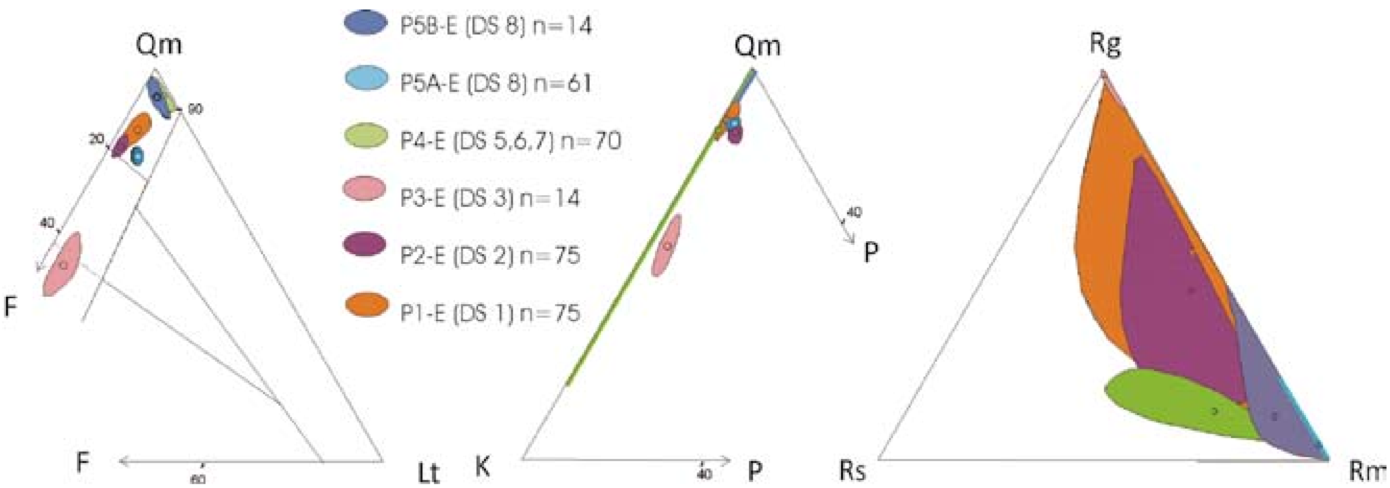

Figure 3. Ternary plots describing the sandstone composition of the different petrofacies in the eastern sector of the Cameros basin. Each petrofacies is represented by the 95% confidence region of the mean and by the mean itself.
Figura 3. *Diagramas ternarios para la composición de las distintas petrofacies del sector este de la cuenca de Cameros. Cada petrofacies está representada por la región del 95% de confianza de la media y por la media propiamente dicha.*

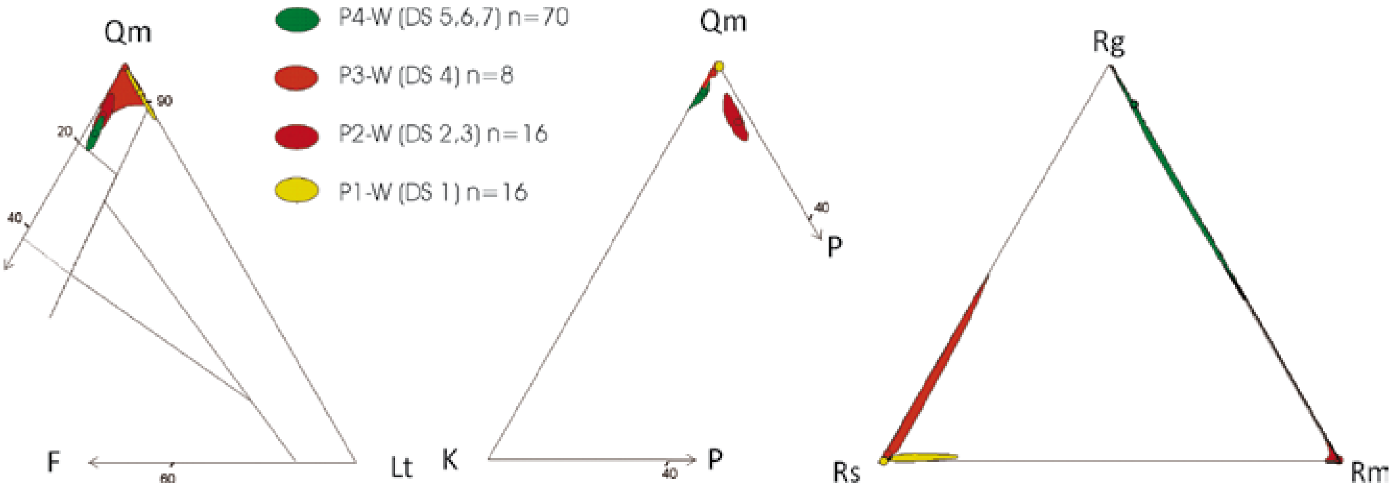

Figure 4. Ternary plots describing the sandstone composition of the different petrofacies in the western sector of the Cameros basin. Each petrofacies is represented by the 95% confidence region of the mean and by the mean itself.
Figura 4. *Diagramas ternarios para la composición de las distintas petrofacies del sector oeste de la cuenca de Cameros. Cada petrofacies está representada por la región del 95% de confianza de la media y por la media propiamente dicha.*

The ternary diagrams were constructed by grouping sandstone samples for each sector. In this way the eastern sector is represented by 256 samples and 6 petrofacies (Fig. 3), which correspond to DS 1 (P1-E), DS 2 (P2-E), DS 3 (P3-E), DSs 5, 6 and 7 (P4-E) and DS 8 (P5A-E and P5B-E) respectively. The western sector is represented by 110 samples grouped into four petrofacies (Fig. 4), which correspond to DS 1 (P1-W), DSs 2 and 3 (P2-W), DS 4 (P3-W) and DSs 5, 6 and 7 (P4-W) respectively. It is important to highlight that DS 8 does not occur in the western sector and DS 4, in the eastern one, is composed mainly of carbonate deposits. Thus there are no samples from these DSs in these sectors.

Description and interpretation of the petrofacies

Eastern sector:

P1-E

The first petrofacies (P1-E) was developed during the deposition of DS 1 and is quartzo-feldspathic (Figs. 3a and 5a). Rounded monocrystalline quartz grains dominate and some display abraded overgrowths. Microcline can be seen (Fig. 5a) and plagioclases are very scarce (Fig. 3b) and always twinned. This petrofacies presents some slates and minor schist fragments (Fig. 3c). Coarse-grained plutonic rock fragments can also be seen towards the top of DS 1. Locally (southward) the petrofacies becomes quartzo-sedimentolithic due to considerable inputs of carbonate rocks at the bottom of DS 1, including echinoderm plates with abraded overgrowths.

Interpretation: The presence of carbonate rock fragments and echinoderm plates points to the erosion of the carbonate pre-rift sedimentary cover (Torrecilla en Cameros Fm., Kimmeridgian, Fig. 2) in the southern sector. In addition, the abundance of monocrystalline quartz grains and their recycling features indicates the erosion of pre-rift Mesozoic siliciclastic units (probably Callovian quartzarenites). In the rest of the area the higher proportion of feldspars together with the presence of metamorphic rock fragments points to the erosion of low-to-medium-grade metamorphic terranes. Furthermore, microcline and plutonic rock fragments imply that the erosion of plutonic source areas started at DS 1 in this part of the basin.

P2-E

The second petrofacies (P2-E) corresponds to DS 2 and is quartzo-feldspathic (Fig. 3a). It presents a higher plagioclase/K-feldspar ratio (P/K) than P1-E (Figs. 3b, 5b and c) and a higher influence of polycrystalline quartz, slates (Fig. 5d) and schist rock fragments than the former petrofacies (Fig. 3c). In addition, microcline plus twinned and untwinned plagioclases can be seen. The twinned plagioclases are polysynthetic and allotriomorphic (Fig. 5b) and the untwinned ones are very idiomorphic (Fig. 5c).

Interpretation: Plutonic and low-to-medium-grade source areas were eroded during the deposition of DS 2. A new input of plagioclase is shown by the presence of untwinned plagioclases (not found in P1-E) and the higher P/K index. Thus, new plutonic source rocks are

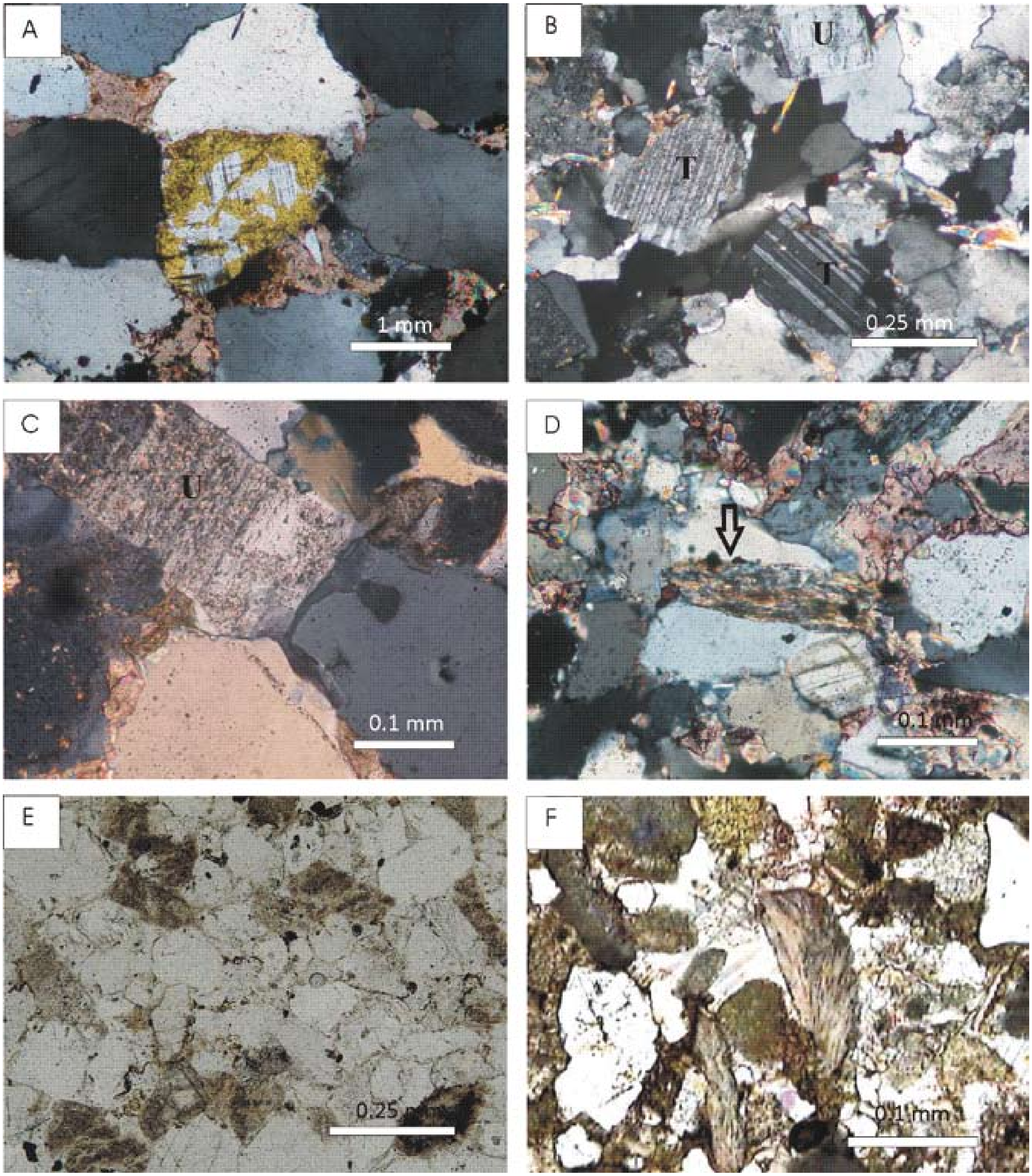

Figure 5. Microphotographs of the detrital components in the eastern sector of the Cameros basin. A: Microcline in P1-E. B: General aspect of P2-E and detail of twinned (T) and untwinned (U) plagioclases, P2-E. Notice that the twinned plagioclases are allotriomorphic. C: Example of an idiomorphic, untwinned (U) plagioclase, P2-E. D: Slate fragment (arrow), P2-E. E: General aspect of P3-E. All dark grains are K-feldspars (K) F: Quartzo-sedimentolithic petrofacies in the northern part of P4-E. Notice the presence of shell fragments and micritic rock fragments. A, B, C, D: Cross-polarized light. E, F: Plane-polarized light.

***Figura 5.** Microfotografías de los componentes detríticos del sector este de la Cuenca de Cameros A: Microclina en P1-E. B: Aspecto general de P2-E y detalle de las plagioclasas macladas (T) y no macladas (U), P2-E. Nótese que las plagioclasas macladas son alotriomorfas, P2-E. C: Ejemplo de plagioclasa idiomorfa no maclada (U), P2-E. D: Fragmento de pizarra (flecha), P2-E. E: Aspecto general de P3-E. Todos los granos oscuros son de feldespato K. F: Petrofacies cuarzo-sedimentolítica en la parte norte de P4-E. Nótese la presencia de fragmentos de bioclastos y fragmentos de carbonatos micríticos. A, B, C, D: nícoles cruzados. E y F: nícoles paralelos.*

probably present compared to P1-E. The idiomorphic character of these untwinned plagioclases rules out any metamorphic origin.

P3-E

The third petrofacies (P3-E) corresponds to DS 3 and is quartzo-feldspathic, showing a very high feldspar content (Figs. 3a and 5e). K-feldspars are much more abundant than plagioclase (Fig. 3b). Polycrystalline quartz is less abundant than in P2-E. Coarse-grained plutonic rock fragments are the main lithic typology (Fig. 3c). Slate and schist rock fragments are also present.

Interpretation: This petrofacies represents a higher level of erosion of the crystalline basement, from both plutonic and low-to-medium-grade metamorphic source rocks.

P4-E

The fourth petrofacies (P4-E) corresponds to sandstones from DSs 5, 6 and 7. In its southern sector this petrofacies is mainly quartzo-feldspathic in composition (Figs. 3a and 5f). The feldspar content is very variable and increases towards the top of DS 7. Furthermore, plagioclases are very scarce. This petrofacies is rich in metamorphic rock fragments, mainly slates (Fig. 3c). Plutonic rock fragments are more numerous in DS 7 than in the previous ones and tend to increase upwards in the sequence. P4-E evolves northwards to a quartzo-sedimentolithic petrofacies, characterized by a very high monocrystalline quartz content caused by the breakdown of feldspars during transport (Fig. 5f). In addition, quartz grains with abraded overgrowths and carbonate rock fragments, including foraminifera and echinoderm plates, are common.

Interpretation: An increase in maturity is recorded from the south northwards, related to fluvial transport and the palaeogeographic position of the source areas: plutonic source areas were located towards the south of this part of the basin. The higher input of plutonic rock fragments in DS 7 suggests a greater degree of erosion of the crystalline basement than in the previous sequences. Additional supplies from low-grade metamorphic rocks are also deduced.

P5-E

This petrofacies corresponds to DS 8 and two different sub-petrofacies can be distinguished: P5A-E, which is located at the hanging wall of the north Cameros thrust (NCT) and P5B-E at the footwall of the NCT.

P5A-E is a quartzo-feldspathic petrofacies (Fig. 3a). The K-feldspars occasionally show pertite textures. The plagioclases are both twinned and untwinned but either type is scarce. The rock fragments are mainly metamorphic slates and minor amounts of schist, and coarse-grained plutonites are also to be seen (Fig. 3c).

P5B-E is quartzolithic and very rich in monocrystalline quartz (Fig. 3a). K-feldspars are scarce and plagioclases have not been observed (Fig. 3b). Slate and schist rock fragments are very abundant. Plutonic rock fragments are also present (Fig. 3c).

Interpretation: The pertite textures in P5A-E can be associated with plutonic sources. This petrofacies contains similar source rocks, mainly deriving from low-grade metamorphic and plutonic terranes similar to those in P4-E. P5B-E presents more monocrystalline quartz and less feldspar because it corresponds to more distal areas and thus the sediments have been transported farther. During the later Alpine orogeny two sub-petrofacies became separated by the thrust. P5-E is an example of a sandstone compositional change across a facies boundary, similar to other examples described by Amorosi and Zuffa (2011), who interpreted this type of petrofacies change as a being the result of autogenic factors (transport distance in our case) that control sandstone composition.

The western sector:

P1-W

The first petrofacies (P1-W) corresponds to DS 1 and is quartzo-sedimentolithic (Fig. 6a), because it presents high contents of monocrystalline quartz and sedimentary rock fragments. As in P1-E, monocrystalline quartz grains dominate (Fig. 6a) and some display abraded overgrowths. Furthermore, both K-feldspars and plagioclases, either twinned or untwinned, are rare. The rock fragments are mainly carbonate and sandstone and include echinoderm plates.

Interpretation: As in P1-E, the underlying Jurassic marine deposits are the main source of this petrofacies (Torrecilla en Cameros Fm., Kimmeridgian, Fig. 2), as indicated by the presence of carbonate rock fragments. The sandstone rock fragments and the high content in monocrystalline quartz are related to the erosion of siliciclastic sedimentary sources of older Jurassic formations (Pozalmuro Fm and Aldealpozo Fm, Callovian and Late Oxfordian respectivelly).

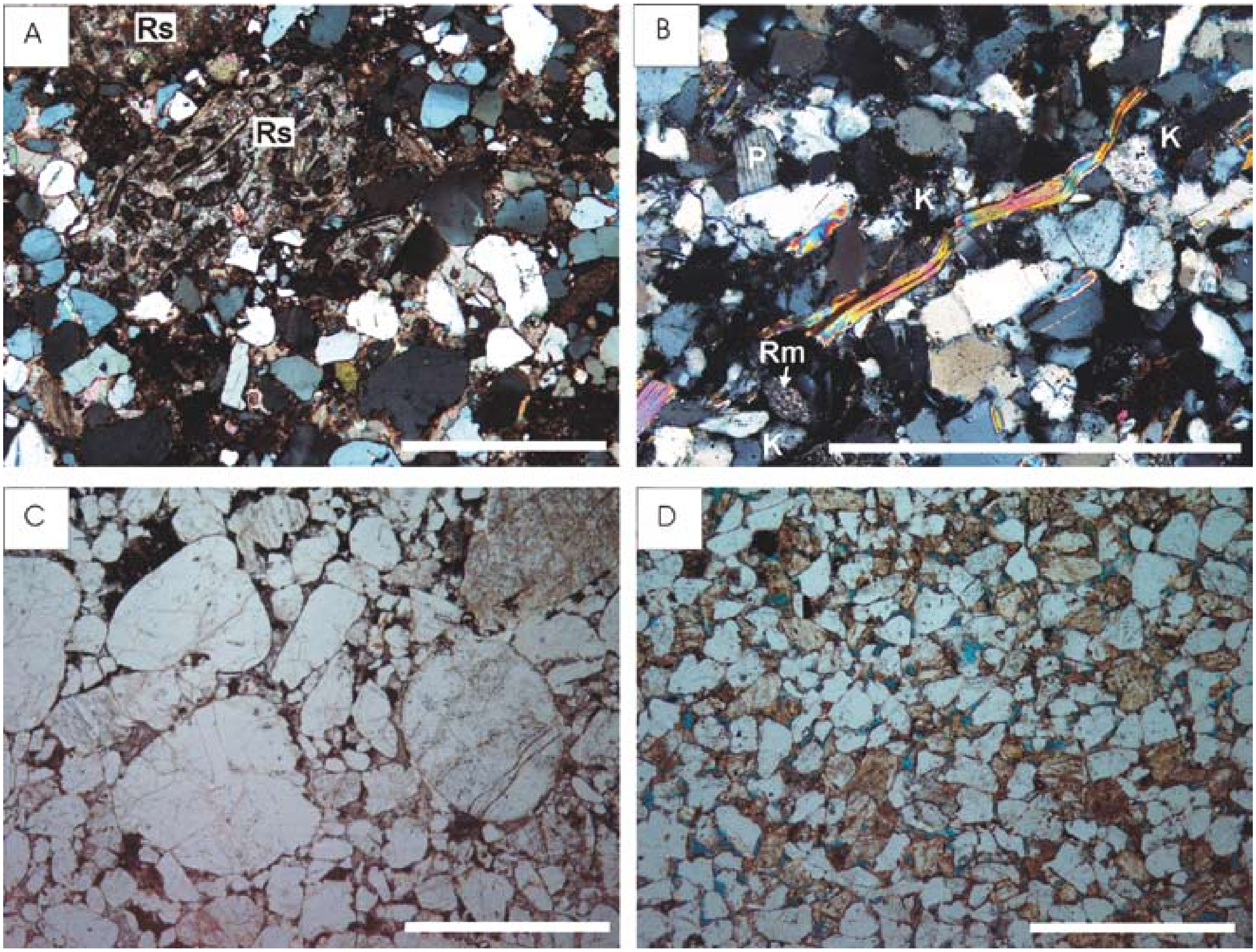

Figure 6. Microphotographs of the detrital components in the western sector of the Cameros basin in cross-polarized light. A: General aspect of P1-W, showing carbonate rock fragments (Rs) from the marine Jurassic. Cross-polarized light. B: General aspect of P2-W. K: K-feldspar, P: Plagioclase, Rm: Metamorphic rock fragment. Cross-polarized light. C: General aspect of P3-W. Notice the dominance of rounded, monocrystalline, quartz grains. Plane-polarized light. D: General aspect of P4-W, showing the abundance of K-feldspars (dark grains). Plane-polarized light. All scale bars in all photographs represent 1 mm.

Figura 6. *Microfotografías de los componentes detríticos del sector oeste de la Cuenca de Cameros. A: Aspecto general de la petrofacies P1-W mostrando fragmentos de roca carbonática (Rs) del Jurásico marino. Nícoles cruzados. B: Aspecto general de P2-W. K: feldespato K, P: plagioclasa, Rm: fragmento de roca metamórfica. Nícoles cruzados. C: Aspecto general de P3-W. Dominan los granos de cuarzo monocristalino redondeados. Nícoles paralelos. D: Aspecto general de la petrofacies P4-W, mostrando la abundancia de feldespato K (granos oscuros). Nícoles paralelos. La barra de la escala en todas las fotografías mide 1 mm.*

P2-W

The second petrofacies (P2-W) corresponds to DS 2 and 3 and is quartzo-feldspathic (Figs. 4a and 6b). This petrofacies has a higher feldspar content than P1-W (Fig. 4a). Plagioclases are both twinned and untwinned and are much more abundant than K-feldspars (Figs. 4b and 6b). In addition, polycrystalline quartz is more common than in P1-E. This petrofacies contains metamorphic fragments of slates and micaschists (Fig. 4c). Feldspars and rock fragments decrease concomitantly from DS 2 to DS 3. Scarce plutonic rock fragments appear from the top of DS 2 and in DS 3. Plutonic rock fragments are less frequent than in P2-E and P3-E (Fig. 4c).

Interpretation: DSs 2 and 3 derive from low-to-medium-grade metamorphic terranes, based on the presence of slate and schist fragments and an increase in feldspar and polycrystalline quartz grains compared to P1-E. Erosion of plutonic terrains starts at the end of DS 2. An increase in maturation, revealed by lower amount of feldspars and lithic fragments, is recorded from DS 2 towards the top of DS 3, probably due to transport processes.

P3-W

The third petrofacies (P3-W) corresponds to DS 4 and is quartzo-sedimentolithic (Fig. 4a). K-feldspars are scarce and plagioclases are not found (Figs 4b and 6c). The quartz grains are characterized by rounded grains with a predominance of monocrystalline types (Fig. 6c), and some show abraded overgrowths. Furthermore, carbonate rock fragments dominate the lithic population, and plutonic rock fragments can also be seen (Fig. 4c).

Interpretation: DS 4 shows evidence of recycling from sedimentary source areas, both carbonate and siliciclastic, related to the erosion of Jurassic and probably Triassic rocks. Plutonic source rocks, probably free of plagioclase, are also present.

P4-W

The fourth petrofacies (P4-W) belongs to DSs 5, 6 and 7 and is quartzo-feldspathic (Figs. 4a and 6d). The proportion of polycrystalline quartz increases compared to the former petrofacies. Plagioclase grains are not to be seen or are very scarce (Figs. 4b and 6d). In addition, both coarse grained crystalline and metamorphic slate fragments are present (Fig. 4c).

Interpretation: this petrofacies derives from granite or gneiss source areas, with other supplies from low-grade metamorphic terranes.

The successive disposition of petrofacies in the sedimentary record of the Cameros rift basin correlates extremely well with the hierarchy of the main bounding surfaces between depositional sequences and megasequences. A direct relationship exists between the petrofacies and the main rifting stages (Arribas *et al.*, 2003; 2007).

Provenance

On the basis of the above descriptions and interpretations of the petrofacies, two main "provenance cycles" can be established: Cycle 1 and Cycle 2. Each provenance cycle is formed by two successive stages:

- Stage 1: made up of a quartzo-sedimentolithic or quartzolithic petrofacies (as in P1-E in the southwest area, P4-E in the north area, P5B-E, P1-W and P3-W) or by a quartzo-feldspathic petrofacies with several features that indicate the recycling of the sedimentary cover (high proportions of monocrystalline quartz or the presence of inherited quartz overgrowths, as in P1-E).
- Stage 2: made up of several quartzo-felspathic petrofacies (P2-E, P3-E, P4-E in the southern sector, P5A-E; P2-W and P4-W).

The boundary between the first and the second provenance cycle (Cycle 1 and Cycle 2) coincides with that between the stratigraphic megasequences (MSs-1 and MSs-2), indicating a direct relationship between the petrofacies and the main rifting stages (Arribas *et al.*, 2003, 2007). Provenance Cycle 1 corresponds to MS-1 (10 Ma) and provenance Cycle 2 to MS-2 (30 Ma) (Fig. 2). We consider them to be cycles even though their deposition time was different, because they are both formed by the two stages described above. Furthermore, different durations are to be expected when tectonic activity is the main genetic factor.

In addition, the thickness of each provenance cycle varies from one sector of the basin to another (Table 1) because the depocentres are located in the eastern sector. The petrofacies indicate the erosion of the pre-rift sedimentary substratum (quartzo-sedimentolithic petrofacies) as rifting commenced, followed by the erosion of the crystalline/metamorphic basement during later stages to generate quartzo-feldspathic petrofacies. The palaeogeography of the carbonate source rocks in the vicinity is responsible for whether the first stage of each provenance cycle is made up a a quartzo-sedimentolithic petrofacies or a quartz-feldspathic one.

	Provenance Cycle 1	**Provenance Cycle 2**
Stage 1	<100 m	<100 m
Stage 2	E: 3500m W: 400 m	E: 6000 m W: 1600 m

Table 1. Provenance cycles of the Cameros basin and the thicknesses of their respective sedimentary record
Tabla 1. *Ciclos de procedencia de la Cuenca de Cameros y espesores de sus registros sedimentarios correspondientes*

Similar changes in provenance from the first to the second stage have been described by Garzanti *et al.* (2001, 2003) in the Red Sea. These authors interpreted that this succession represents the evolution from an undissected rift shoulder stage to more advanced stages of rifting (dissected rift shoulder) in a rifted basin.

In our case, the metamorphic supplies were probably related to the Variscan basement of the West Asturian Leonese Zone and the plutonic source areas were probably located in the eastern part of the Central Iberian Zone (CIZ) located towards the south of the Cameros basin (Arribas *et al.*, 2003, 2007) (Fig. 7). On the basis of the P/K index of the different petrofacies we presume the existence of different source areas within the CIZ, which can be related to changes in the direction of the main alluvial/fluvial systems. For example, from P1-E to P2-E the compositional change can be explained by the higher influence of transversal supplies during the fluvial-fan stage of DS 1 to

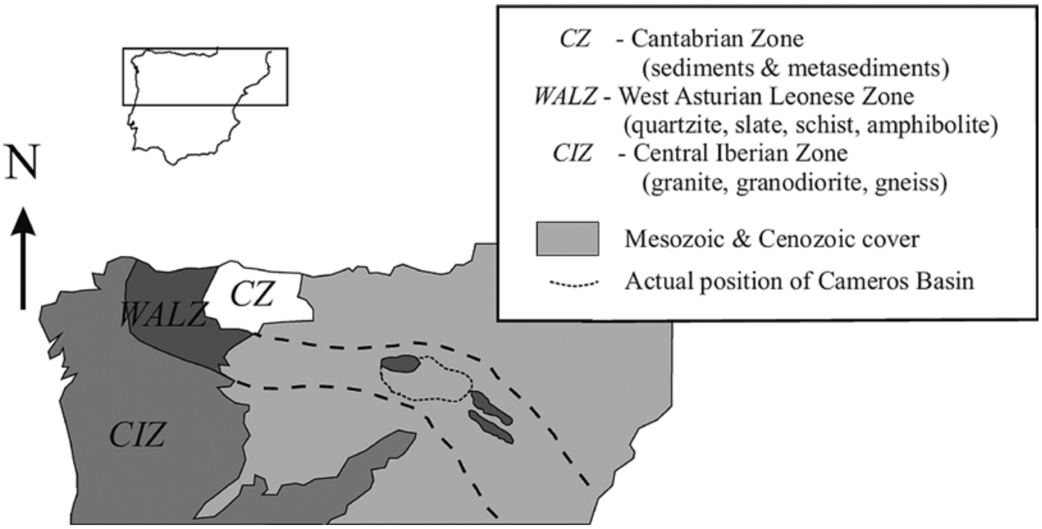

Figure 7. Location of the possible source area cited in the text.
Figura 7. *Localización de las posibles áreas fuente citadas en el texto.*

more significant axial inputs during the fluvial stage of DS 2 (González-Acebrón *et al*, 2010a).

As far as a comparison between the two sectors of the basin is concerned, we must highlight the following differences:

– The carbonate sedimentary inputs at the bottom of the first provenance cycle in the eastern sector are lower than to the west. This fact is conditioned by the palaeogeographic distribution of the Jurassic limestones during the deposition of DS 1.
– Plutonic rock fragments are common during the second stage of the first provenance cycle in the western sector but less abundant in the eastern one. This can be related either to a higher level of erosion reached in the western sector or to the palaeogeographic position of the plutonic source areas. In fact, different source lithologies from the CIZ are required to explain the plutonic inputs to the two sectors because microcline has only been found in the western one.
– There is a change in sandstone composition from DS 2 to DS 3 in the eastern sector (from P2-E to P3-E), which is not recorded in the western sector (P2-W).
– The second provenance cycle in the western sector presents more mature sandstones that are very rich in quartz (Fig. 6c) in comparison to the same cycle in the eastern area.

Diagenesis

Diagenetic processes in sandstones differ according to the composition of the original framework and subsequently on the petrofacies types.

The sedimentolithic petrofacies exhibit large quantities of carbonate cements from an early burial diagenesis (Fig. 8a). The origin of the early carbonate cement can be related to the dissolution of carbonate clasts, both intrabasinal and extrabasinal, commonly present in the sandstone framework of the sedimentoclastic petrofacies. The early diagenetic phases are made up of non-ferroan calcite and present mesocrystalline mosaic and poikilotopic textures. The calcite crystals are usually of a similar size to the framework grains, probably because they are replacements of K-feldspars (Fig. 8a). Subsequently, ferroan dolomite precipitated into the pore space (Fig. 8a). The replacement of ankerite has also been observed (Fig. 8b).

In general, the carbonate cements reduce the original porosity substantially. On the other hand, quartz and K-feldspars cements are scarce, and the presence of diagenetic clay minerals (i.e. kaolinite and illite) is rare and very local. Mechanical compaction is in part inhibited by early carbonate cementation, thus maintaining a significant intergranular volume (21% to 24% of intergranular volume, IGV). Porosity, if present, is very low (<1%) and corresponds to secondary porosity generated by local carbonate dissolution during exhumation.

Diagenesis in quartzo-feldspathic petrofacies is characterized by an intense reduction of intergranular volume, showing values from 11% to 13% of IGV, by the action of compaction, both mechanical and chemical. Quartz and K-feldspar overgrowths are the most abundant cements. Kaolinite is also a well developed diagenetic phase (Fig. 8c), appearing as an early pore filling and K-feldspar replacement (epimatrix, Fig. 8c). Illite appears locally as an early pore lining, either coating grains or as a mesodiagenetic replacement of

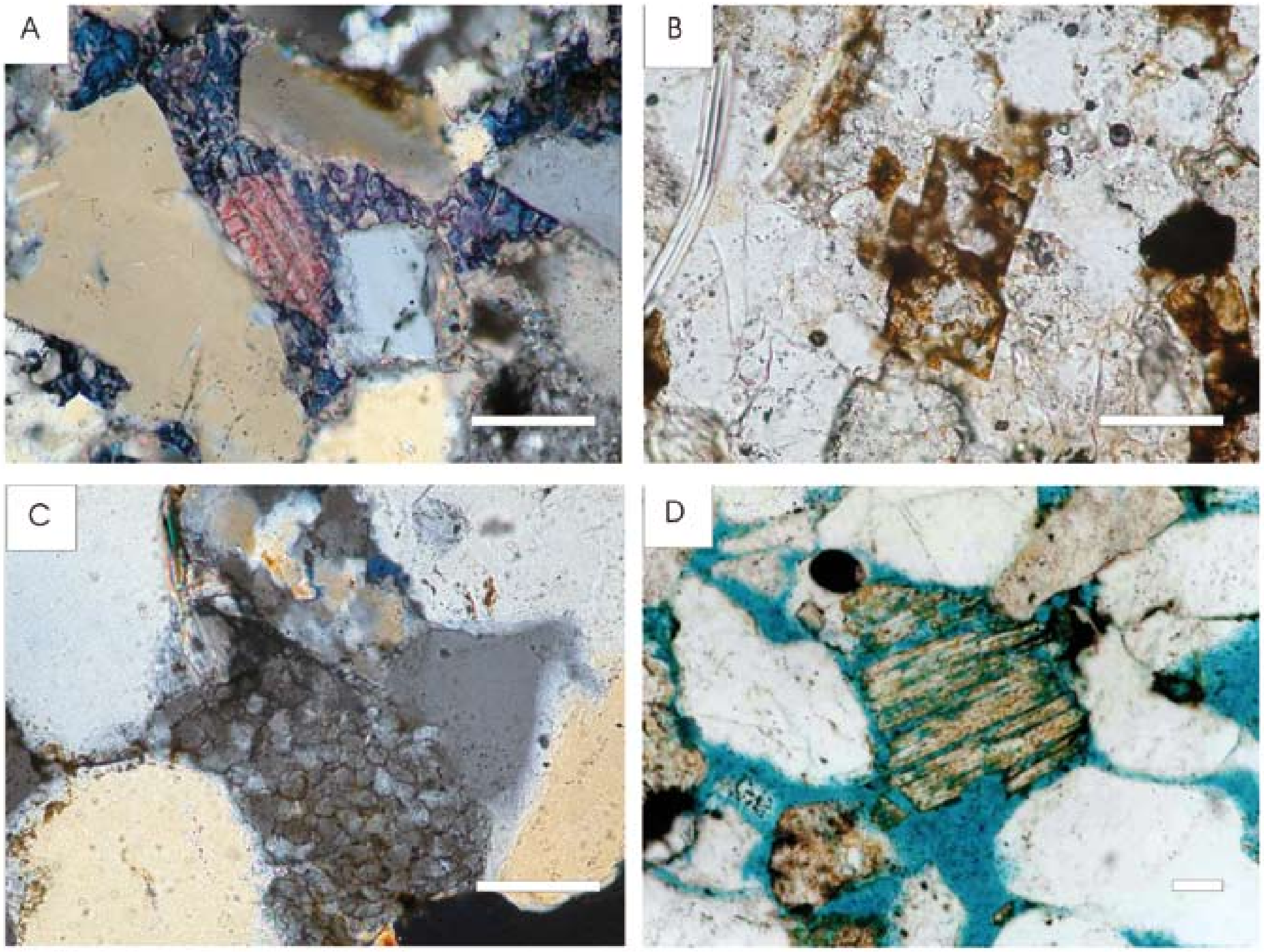

Figure 8. Microphotographs of the diagenetic features of the different petrofacies. A: Early carbonate cements of non-ferroan calcite (stained in pink) followed by burial carbonate cements of ferroan dolomite (stained in blue). B: Ankerite ghost replacement of the framework. C: Kaolinite epimatrix on K-feldspar. D: Secondary porosity generated by the dissolution of K-feldspar grains in the southern part of P4-E. A and C, cross-polarized light; B and D, plane-polarized light. All scale bars represent 0.1 mm.

Figura 8. *Microfotografías de los rasgos diagenéticos de las distintas petrofacies. A: Cementos de carbonato temprano de calcita no ferrosa (teñidos de rosa) seguidos de cementos de enterramiento de calcita ferrosa (teñida en azul). B: Reemplazamiento por anquerita (fantasmas). C: Epimatriz de caolinita en feldespato K. D: Porosidad secundaria (teñida de azul) generada por la disolución de granos de feldespato K en la zona sur de la petrofacies P4-E. A y C nícoles cruzados, B y D nícoles paralelos. Las barras de la escala miden en todas las imágenes 0.1 mm.*

kaolinite pore filling and epimatrix. The replacement of kaolinite by illite is more common in the western sector, where the temperatures were higher due to metamorphic influence.

Primary porosity is preserved (5% to 7%) in the sandstones in DS 5 to DS 7 in the southern part of the basin (Fig. 8d). Secondary porosity is also present, generated by the dissolution of K-feldspar grains, generating intergranular, oversized pores (Fig. 8d). The absence of early phases of carbonate cementation favoured compaction and the reduction of intergranular volume during diagenesis. In the south-western part of the basin, however, the rigidity of the quartzo-feldspathic framework was able to maintain the primary pores. In the western sector, on the other hand, the development of considerable quartz overgrowths by hydrothermal processes (Mas *et al.*, 2011) drastically occluded porosity (Ochoa *et al.*, 2007a; González-Acebrón *et al.*, 2011).

Furthermore, the quartzo-feldspathic petrofacies has undergone a process of albitization, at least in P2-E (González-Acebrón *et al.*, 2010b) and to some extent in P2-W, P3-E and P4-E (Ochoa, 2006). Both plagioclases and K-feldspars are albitized, showing a very Na-rich composition (mean composition for P2-E $Ab_{94.0}$ $An_{4.5}$ $Or_{1.5}$). Chemically pure albite (>99%) is relatively common in all the albitized petrofacies. In addition, an associated phase of calcite cement was generated as a result of Ca-plagioclase albitization (González-Acebrón *et al.*, 2010b). This calcite by-product resulted in a slight decrease in porosity. On the basis of petrographic relationships and homogenization temperatures in fluid inclusions we consider this albitization to have been a diagenetic process (González-Acebrón *et al.*, 2010b). The origin of Na can be related to the percolation of moderate-to-high-salinity residual brines from related alkaline lakes or to marine incursions.

To sum up, the quartzo-feldspathic petrofacies underwent a more intense porosity loss by compaction, reducing the intergranular space substantially. In contrast, the quartzo-sedimentolithic petrofacies have wider intergranular spacing, mainly due to early carbonate cementation, although no primary porosity is preserved. Nevertheless, the quartzofeldspathic petrofacies maintained their primary pores whenever their framework was rigid enough. In addition, secondary porosity by K-feldspar dissolution/replacement is frequent.

Cyclicity

Cyclicity has been recognised at different levels in the sedimentary records of the Cameros basin.

Sedimentary facies, and consequently the depositional environments, repeat cyclically throughout the basin infill. This cyclicity has been used to define the 8 depositional sequences (Mas *et al.*, 1993; 2002; 2011), each formed by alluvial deposits evolving upwards to palustrine-lacustrine deposits, which show evidence of marine influence in several cases. The depositional sequence boundaries are unconformity surfaces, mostly tectonic in origin (Mas *et al.*, 1993). Consequently, the cyclicity of the recognised depositional systems can be attributed mainly to the extensional tectonic activity that affected the basin during the rifting stage. Tectonic activity controlled both the variations in accommodations space and the activation/deactivation cycles of the sediment sources.

Cyclicity has even been recognised in the distribution of the petrofacies. In fact the petrofacies repeat with similar sequences, from quartzo-sedimentolithic to quartzo-feldspathic, in both "provenance cycles" (Arribas *et al.*, 2007), which correspond to the stratigraphic megasequences MS-1 and MS-2 (Mas *et al.*, 2003). The tectonic nature of the boundary between these two megasequences suggests that this cyclicity in the petrofacies can be attributed to tectonic causes. Furthermore, the change in petrofacies observed in each "provenance cycle" is related to the evolution of erosion cycles, from the pre-rift sedimentary substratum to the crystalline/metamorphic basement.

Due to the close relationship between the petrofacies and diagenesis the diagenetic properties are also cyclically repeated. In fact each "provenance cycle" (Cycle 1 and Cycle 2), and consequently each megasequence (MS-1 and MS-2) repeats a diagenetic cycle made up of a lower diagenetic facies, characterized by a very pervasive carbonate cement that substantially reduces its porosity, which evolves upwards into a diagenetic facies with a very rigid framework that maintains the original pores during burial diagenesis.

Concluding Remarks

Tectonics was the main factor that controlled cyclicity in the Cameros rifted basin, generating two stratigraphic megasequences. Each megasequence has been interpreted as a "provenance cycle", formed by two stages, from quartzo-sedimentolithic to quartzofeldspathic petrofacies. These two stages are characteristic of non-volcanic rifted basins.

The first stage of each provenance cycle is made up of either a quartzo-sedimentolithic or a quartzo-feldspathic petrofacies, depending upon the presence of the carbonate source rocks in the vicinity. The plutonic source areas were probably located towards the south of the Cameros basin in the Central Iberian Zone. Their erosion started originally in the eastern sector of the basin during the deposition of DS 1, whereas in the western sector it started during DS 2. The metamorphic areas, mostly of low-to-medium grade, were probably located in the West Asturian Leonese Zone. The succession of these two stages reflects two main cycles, one of 10 Ma and another of 30 Ma, representing the progressive erosion of their sources. Such a succession is typical of a non-volcanic rift basin. Although the two cycles occurred over different lengths of time, both contain the two characteristic stages.

In addition, during their diagenesis the quartzo-sedimentolithic sandstones of the first stage developed large amounts of very pervasive carbonate cement which reduced their original porosity considerably. The quarzofeldspathic sandstones of second stage, on the other hand, have a rigid framework that maintained the original pores during burial diagenesis. This study corroborates the close relationship between the provenance of the sandstones and their reservoir potential in continental rift basins.

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