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Lower Paleocene *Microcodium*-rich calcarenites in hemipelagic areas of the Subbetic Zone, SE Spain: Sr isotopes, source area and palaeogeographic implications

Calcarenitas con* Microcodium *del Paleoceno inferior en áreas hemipelágicas de la Zona Subbética, SE de España: isótopos de Sr, área fuente e implicaciones paleogeográficas

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ABSTRACT

The Danian–early Selandian Olivares and Majalcorón formations are two calcarenite units rich in Microcodium *remains that were accumulated in a marine hemipelagic setting of the Subbetic Zone (Betic Cordillera, southern Spain). Their outcrops are restricted to relatively small areas surrounded by uplifted Jurassic calcareous massifs, some of them with volcanic intercalations. The calcarenites contain lithoclasts of Lower Jurassic and lowermost Cretaceous age, and the $^{87}Sr/^{86}Sr$ isotopic ratios of the* Microcodium *remains suggest that they were originated in roots of plants that grew on Lower Jurassic carbonates. These facts entail that the* Microcodium *remains came from the calcareous massifs adjacent to their outcrops, the upper parts of which were subaerially exposed and colonized by* Microcodium*-producing plants during the Danian–early Selandian interval. The subaerial exposure of these massifs may have resulted from a coeval tectonic reactivation of Mesozoic syn-rift faults and folds, a eustatic sea level fall, or a combination of both processes.*

Key-words: *resedimented* Microcodium, *Paleocene, Subbetic, Sr isotopes.*

RESUMEN

Las formaciones Olivares y Majalcorón del Daniense-Selandiense inferior son unidades de calcarenitas ricas en restos de Microcodium *acumuladas en un ambiente marino hemipelágico de la Zona Subbética (Cordillera Bética). Sus afloramientos están restringidos a áreas relativamente pequeñas rodeadas por elevados macizos de carbonatos jurásicos, algunos de ellos con intercalaciones volcánicas. Las calcarenitas contienen litoclastos del Jurásico Inferior y de la parte más baja del Cretácico, y los valores isotópicos $^{87}Sr/^{86}Sr$ de los restos de Microcodium sugieren que los mismos se originaron en raíces de plantas que crecían sobre carbonatos del Jurásico Inferior. Estos hechos implican que los restos de Microcodium proceden de los macizos carbonatados adyacentes a sus afloramientos, cuyas partes superiores estarían expuestas subaéreamente y colonizadas por plantas productoras de* Microcodium *durante el Daniense-Selandiense inferior. La exposición subaérea de dichos macizos pudo deberse a una reactivación tectónica de fallas y pliegues mesozoicos preexistentes, a un descenso eustático del nivel del mar, o a una combinación de ambos procesos.*

Palabras clave: Microcodium *resedimentado, Paleoceno, Subbética, isótopos de Sr.*

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Introduction

The Danian and early Selandian are represented in the Subbetic Zone of the Betic Cordillera by two very different and mutually exclusive types of deposits. The most extensive consists of a relatively thin succession (≤15 m) of hemipelagic marls (Martínez Gallego, 1977), which are part of the Upper Cretaceous–Eocene Capas Rojas Formation (Vera *et al.*, 1982). According to Vera and Molina (1999) this unit overlies a faulted submarine palaeorelief created during the Mesozoic rifting phase. The second type, which occurs in scattered areas of comparatively reduced extent (≤150 km^2), is made up of up to 100 m thick accumulations of calcarenites composed, wholly or mainly, of *Microcodium* remains (Comas, 1978; Smit, 1979; Vera *et al*, 2003, 2004; Molina *et al.*, 2006).

This study is centred in two of these *Microcodium*-rich calcarenite units (Fig. 1), respectively defined as the Olivares Formation (Comas, 1978) and the Majalcorón Formation (Molina *et al.*, 2003). Calcareous nannoplancton and planktonic foraminifera demonstrate that the age of both units is middle Danian-early Selandian (Molina *et al.*, 2006; Pujalte *et al.*, 2017). Their depositional depth is somewhat controversial. Molina *et al.* (2006), based on the existence of hummocky cross stratification, advocate for a shallow marine environment affected by storm waves, whereas Pujalte *et al.* (2017) argue that the benthic foraminiferal

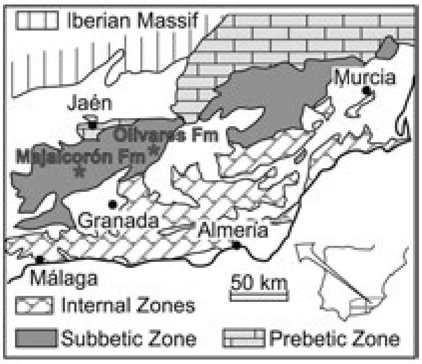

Fig. 1.- Geological location of the studied formations. See color figure in the web.

Fig. 1.- Localización geológica de las formaciones estudiadas. Ver figura en color en la web.

assemblages and the high planktonic/benthonic foraminiferal ratio (~95%) in the Olivares Formation indicate a marine environment deeper than 500–700 m.

The purposes of this study are to investigate the source areas of the *Microcodium* remains of both units and to discuss their palaeogeographic implications. To this end, 36 thin sections of calcarenite samples were analyzed, paying special attention to intraclasts and bioclasts with provenance meaning. In addition, five fine-grained calcarenites of the Olivares Formation, exclusively formed of *Microcodium* prisms, were collected at regular intervals spanning the whole thickness of the units, which were analyzed for their $^{87}Sr/^{86}Sr$ isotopic values at the Geochronology and Isotope Geochemistry Research Facility of the University of the Basque Country. The rationale for such analyses was that $^{87}Sr/^{86}Sr$ ratios reflect the source of strontium available during the formation of natural materials (Capo *et al.*, 1998).

The Olivares Formation

The outcrops of the Olivares Formation (Comas, 1978) are situated in the Guadix region (Granada province), scattered in an area of ~60 km^2 along the Fardes and Gor river valleys (Fig. 2A). The unit is near 100 m thick in the Olivares and Río Gor sections (Comas, 1978; Pujalte *et al.*, 2017), but only 15–40 m thick in the southernmost outcrops (Martínez Gallego, 1977). The map and cross-sections in figure 2 demonstrate that the unit is located within a SW-NE trending graben, along which flows the present day Fardes River (Fig. 2A). The most prominent faults bounding the NW side of the graben are those delimiting the Cerro Mencal, a 1449 m high inselberg mostly made up of Lower Jurassic limestones (Comas *et al.*, 1970, 1973). Just below the 1300 m contour line of this mountain, however, a small outcrop of upper Campanian marlstones rests directly on Lower Jurassic limestones (Figs. 2A, B; Aguado *et al.*, 2005). Yet, Middle-Upper Jurassic and Lower Cretaceous deposits about 200 m thick are preserved in the down-faulted Morrón del Cerro block (Fig. 2B), their absence in the Cerro Mencal being indicative of the activity of the fault separating both blocks during the Mesozoic rifting phase in the Betic Cordillera.

The two most significant faults at the SE side of the graben are respectively situated near the Alicun de las Torres Spa and about 250 m to the south of the Cortijo del Gallego (Fig. 2A). The former brings into near contact Lower Jurassic limestones and

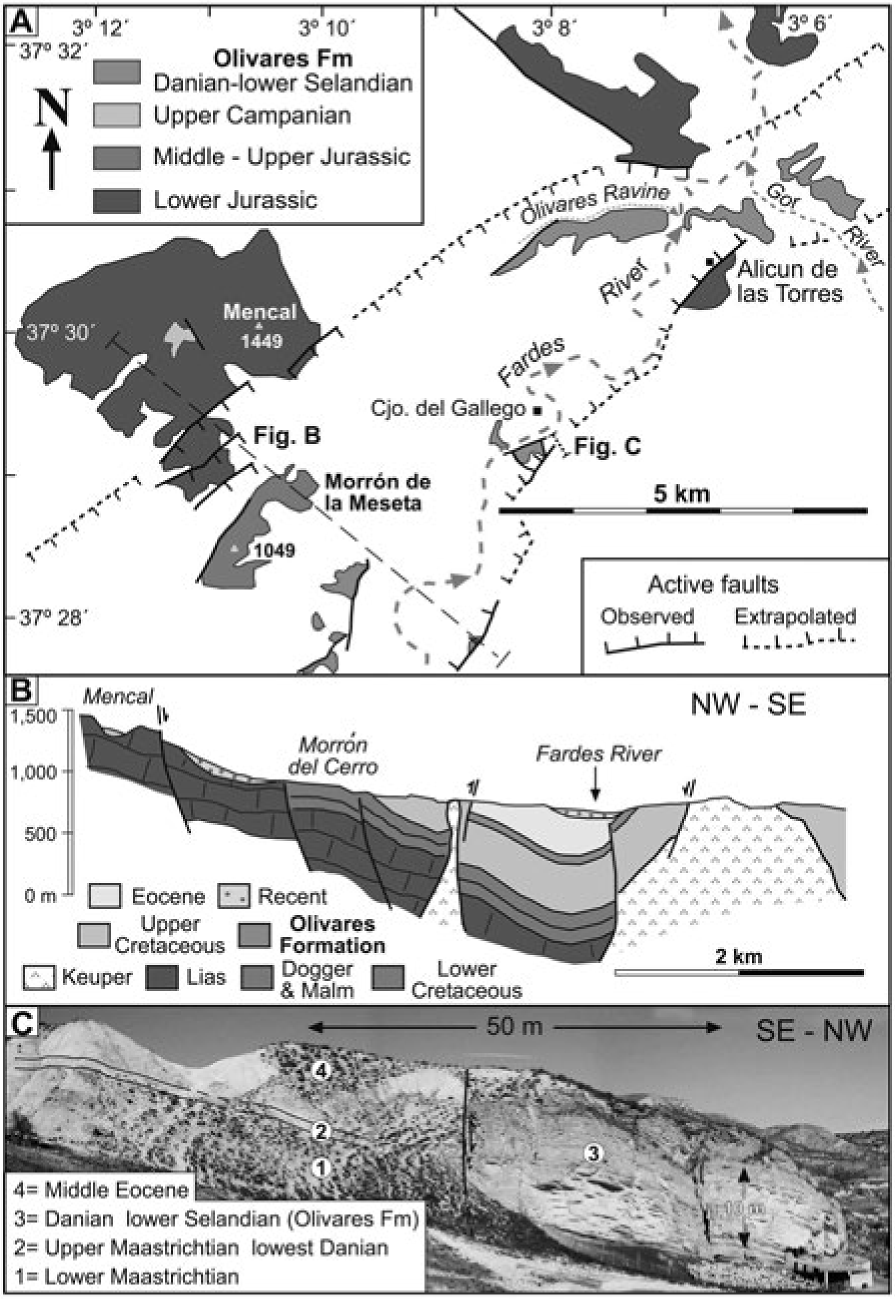

Fig. 2.- A) Outcrops of the Jurassic and the Olivares Formation in the Guadix region. B) Structural cross-section (location in A). C) Structural cross-section across the Cortijo del Gallego fault (A and B, modified from Comas *et al.*, 1973; C, after Pujalte *et al.*, 2014). See color figure in the web.

Fig. 2.- A) Afloramientos del Jurásico y de la Formación Olivares en la comarca de Guadix. B) Sección estructural (localización en A). C) Sección estructural a través de la falla Cortijo del Gallego (A y B, modificados de Comas et al.***, 1973; C, según Pujalte*** et al.***, 2014). Ver figura en color en la web.***

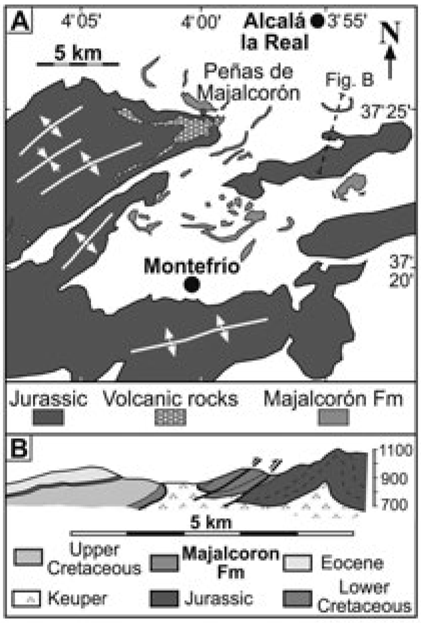

Fig. 3.- A) Outcrops of the Jurassic and the Majalcorón Formation between de villages of Alcalá la Real and Montefrío. B) Structural cross-section (location in A) (A and B, modified from Díaz de Neira *et al.*, 1988). See color figure in the web.

Fig. 3.- (A) Afloramientos del Jurásico y de la Formación Majalcorón entre los pueblos de Alcalá la Real y Montefrío. (B) Sección estructural (localización en A). (A y B, modificados de Díaz de Neira et al., 1988). Ver figura en color en la web.

Upper Cretaceous marls, and it is clearly deep-seated, as it is linked with the hot water spring feeding the spa. The throw of the latter is modest but it marks the easternmost extension of the Olivares Formation (absent in the footwall of the fault; Fig. 2C), and it provides evidence of extensional tectonic activity in the area during the early Palaeogene (Pujalte *et al.*, 2014).

The Majalcorón Formation

The outcrops of this unit, similarly to those of the Olivares Formation, are restricted to a relative small area (~150 km^2) located between the villages of Alcalá la Real and Montefrío (Jaén and Granada provinces, Fig. 3A). The thickness of the unit at the Peñas de Majalcorón type section is 56 m, but it decreases gradually away from this locality (Vera *et al.*, 2004; Molina *et al.*, 2006). The Majalcorón Formation outcrops are also flanked by Jurassic calcareous massifs, although in this case in folded anticlinorial structures seemingly linked to Keuper halokinesis (Fig. 3B). The nearest massif to Peñas de Majalcorón intercalates basic volcanic rocks akin to basalts (Fig. 3A; Díaz de Neira *et al.*, 1988).

Provenance of the *Microcodium*: palaeogeographic implications

Microcodium consists of aggregates of individual monocrystalline prisms of calcite 0.1–1 mm long that, when *in situ*, usually appear radially disposed around a central axis ("rosettes" or ear of maize arrangement; *e.g.*, Smit, 1979). Its exact origin is somewhat controversial (*e.g.*, Košir, 2004; Kabanov *et al.*, 2008), but it is accepted that it is formed within or around roots of terrestrial plants growing in carbonate rich soils, calcretes and subaerially exposed carbonate substrates. The studied formations occur in a hemipelagic setting and their *Microcodium* remains must therefore be resedimented (Comas, 1978; Molina *et al.*, 2006). However, the location of their source area has not been specifically tackled to date.

One possibility is a derivation from the Prebetic and/or the Betic Internal Zones, where in situ Paleocene *Microcodium* has been reported (Smit, 1979; Martín Martín *et al.*, 1998; Maaté *et al.*, 2000). Interestingly, Maaté *et al*. (2000) observed *Microcodium* accumulations within fissures and cavities developed in Upper Cretaceous carbonates and around Mesozoic conglomerate clasts, clear proof that Paleocene *Microcodium*-producing plants grew on Mesozoic carbonate substrates. However, the *Microcodium* remains would have had to travel a long way from these possible sources to reach the depositional areas of the Olivares and Majalcorón formations, which today are far from both the Prebetic and the Betic Internal Zones and even farther during the Paleocene, before the Alpine shortening. Vera *et al*. (2004) and Molina *et al*. (2006) suggested a different alternative, namely that the *Microcodium* remains of the Majalcorón Formation were derived from the External Subbetic Zone. However, the only evidence supporting their proposal is that the Mesozoic deposits of that zone exhibit palaeoweathering and erosive features.

The thin sections of samples from both formations here studied provide some clues to clarify this issue. A majority of them are formed exclusively, or almost exclusively, of disarticulated fine-sized *Microcodium* prisms (≤ 0.16 mm) and cement (Fig. 4A). However, a lesser but still significant number of samples are medium-coarse grained and include broken *Microcodium* rosettes and subangular quartz grains (Fig. 4B). The incomplete disarticulation of the rosettes and the angularity of the quartz grains indicate little abrasion and, consequently, short transport. More significant, medium-coarse grained samples of the Olivares Formation contain intraclasts of partially recrystallized oolithic packstones (Fig. 4C) and wackestones with calpionellids (Fig. 4D). Comas *et al*. (1970) reported oosparite beds in the Lower Jurassic of the Cerro Mencal and observed *Tintinopsellas* (calpionellids) in the lowermost Cretaceous beds from the Morrón del Cerro, from which both kinds of intraclasts may have respectively been derived. A coarse-grained sample from the Majalcorón Formation contains altered volcanic clasts with axis almost 1 cm long (Fig. 4E, F), clearly eroded from the volcanic rocks intercalated in the nearby Jurassic outcrops. Abundant land-derived plant remains, some of them preserving delicate features, are strewn on the bedding planes of the same sample (Fig. 4F), an additional proof of proximal derivation.

The pilot study of the $^{87}Sr/^{86}Sr$ ratio of five fine-grained samples of the Olivares Formation provides further information. The range of ratios, from 0.707617 to 0.707661, correspond to either the Sinemurian or to the upper Campanian according to McArthur *et al*. (2012, their Fig. 7.2). These values are probably somewhat altered due to the cement of the samples, but the distortion must be small because the analyzed samples almost exclusively consist of disarticulated *Microcodium* prisms (Fig. 4A). Therefore, and taking into account the type of clasts found in the calcarenites, it is safe to assume that the Microcodium-producing plants grew on lower Lower Jurassic carbonates and incorporated their Sr isotope signature.

The bulk of data thus indicate that the *Microcodium* remains of the Olivares and Majalcorón formations were resedimented from the Jurassic carbonate massifs adjacent to their outcrops, the top parts of which must have been subaerially exposed and colonized by *Microcodium*-producing plants in Danian-early Selandian times. It is likely that such massifs corresponded to higher parts of the faulted topography inherited from the Mesozoic rifting. Their emergence in the early Danian may be explained by a coeval reactivation of inherited tectonic structures or by a combination of both processes.

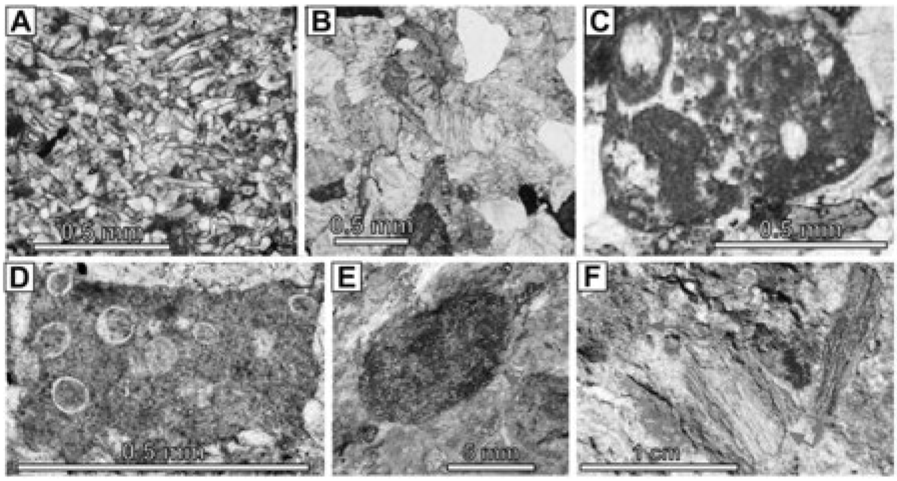

Fig. 4.- A-D) Microphotographs of thin sections of the Olivares Formation. A) Fine-grained calcarenite formed of disarticulated *Microcodium* prisms. B) Medium-grained calcarenite with incomplete *Microcodium* rosettes and quartz grains. C) Lithoclast of a partially recrystallized oolithic packstone. D) Lithoclast of a wackestone with calpionellids. E-F) Microphotographs from the bedding plane of a coarse-grained calcarenite from the Majalcorón Formation illustrating altered volcanic grains (red arrows) and plant remains (green arrows). See color figure in the web.

Fig. 4.- A-D) Microfotografías de secciones delgadas de la Formación Olivares. (A) Calcarenita de grano fino formada por prismas desarticulados de **Microcodium*****. B) Calcarenita de grano medio con rosetas de*** **Microcodium** ***incompletas y granos de cuarzo. C) Litoclasto de*** **packstone** ***oolítico parcialmente recristalizado. D) Litoclasto de*** **wackestone** ***con Calpionélidos. E-F) Microfotografías de un plano de estratificación de una calcarenita de grano grueso de la Formación Majalcorón mostrando clastos volcánicos alterados (flechas rojas) y restos de plantas (flechas verdes). Ver figura en color en la web.***

Conclusions

The early Paleocene is recorded in most of the Subbetic Zone by a thin succession of hemipelagic marls but, locally, by thicker accumulations of calcarenites rich in resedimented *Microcodium* remains. Thin sections and hand samples from two of these *Microcodium*-rich units, the Olivares and the Majalcorón formations, contain Jurassic and lowermost Cretaceous sedimentary and volcanic lithoclasts and abundant plants remains. These facts, combined with $^{87}Sr/^{86}Sr$ isotopic evidence from the Olivares Formation, indicate that the *Microcodium* remains making up the bulk of both units were derived from emergent massifs of Jurassic carbonates adjacent to their outcrops. Such massifs likely corresponded to the high parts of an inherited submarine topography created during the Mesozoic rifting in the Subbetic margin. Their partial emergence during the earlier Danian was either brought about by a coeval reactivation of some of the rift faults, a eustatic lowering of the sea level, or a combination of both processes.

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