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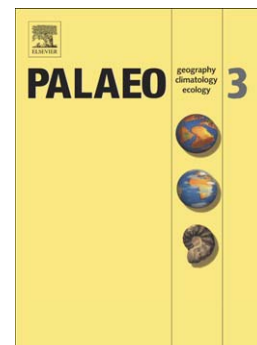
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Palaeoenvironments and ichnotaxonomy of insect trace fossils in continental mudflat deposits of the Miocene Calatayud-Daroca Basin, Zaragoza, Spain.

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## ABSTRACT

The Miocene continental deposits in the Orera area, Calatayud-Daroca Basin, are composed of red and brown mudstones deposited in the dry mudflat, sepiolite and dolomicrites deposited in periodically desiccated alkaline shallow lakes by direct precipitation, and mudstones with carbonate laminae formed in wet mudflat areas by groundwater cementation during rise of water table. The mudstone/sepiolite+dolomite sequences represent dry-wet cycles. Two different ichnospecies of insect trace fossils were found: *Fictovichnus gobiensis* and *Fictovichnus aragon* n. isp.. *Fictovichnus gobiensis*, are 15–18 mm long, 8–9 mm wide ellipsoid casts showing smooth surface. One end is rounded, whereas a truncated tunnel protrudes from the other. They have no discrete wall but some show an outer micritic layer. One end of *Fictovichnus aragon* n. isp. is rounded and the other pointed. The holotype is 26 mm long and 9 mm wide. In the contact with the matrix specimens show two micritic layers, interpreted as remains of the original silky wall constructed by the wasp larva. In both ichnospecies the micromorphology of the casts is similar to the matrix where they are found. Possible producers of *Fictovichnus gobiensis* are coleopterans, whereas *Fictovichnus aragon* was probably produced by sphecid or pompilid wasps. Indicative of subaerial exposition, *Fictovichnus gobiensis* is found in all four facies/environments. Occurrence of *Fictovichnus aragon* n. isp., restricted to the wet mudflat, is controlled by: a) shallow groundwater that permit the growth of phreatophytic plants but also the nesting of wasps in dry upper soil horizons, and b) the rise of groundwater table that favoured decomposition of plants and cementation and preservation of the traces.

In the study area the sedimentary environments controlled the location of the different traces, and diagenetic processes were crucial for their preservation. The lack of early diagenetic processes may explain the rarity of insect trace fossils in other similar continental basins.

## 1. Introduction

Insect trace fossils, very good indicators of palaeoenvironmental conditions (Genise et al., 2004; Buatois and Mángano, 2011), have been increasingly studied in the last twenty years. Great effort has been devoted to establish the different continental ichnofacies and their palaeoenvironments (Genise et al., 2000; Genise et al., 2010; Melchor et al., 2012). The *Celliforma* ichnofacies, developed in carbonate rich palaeosols, is dominated by wasp, bee and beetle traces, indicating scarce plant coverage and arid to semi-arid climates (Genise et al., 2010). It is widely recognized in calcretes and palustrine limestones worldwide, and particularly studied in Cretaceous and Cenozoic sequences of Uruguay and Argentina (Genise et al., 2010; Alonso-Zarza et al., 2011). In Europe, the scarce records come from France (Freytet and Plaziat, 1982; Kuntz, 2012), the Isle of Wight in England (Edwards et al., 1998) and Czech Republic (Fejfar and Kaiser, 2005), and pupation chambers in the Balearic (Mas and Ripoll, 2010) and Canary Islands (Alonso-Zarza and Silva, 2002; Genise et al., 2013)

In the Spain very rare terrestrial trace fossils have been recorded in the Cenozoic of the Madrid (Rodríguez-Aranda and Calvo, 1998), the Calatayud and Teruel basins (Uchman and Álvaro, 2000; Alonso-Zarza et al., 2012) and Ebro Basin (de Gibert and Sáez, 2009).

The continental mudflats of the Miocene of Orera area, in the Calatayud-Daroca Basin, are unique as they contain a large number of insect trace fossils, described for the first time in this contribution. The objectives of this contribution are: 1) to describe and provide an ichnotaxonomical arrangement for the trace fossils from the Calatayud-Daroca Basin, 2) to determine the sedimentary controls of the presence and/or preservation of trace fossils, 3) to propose possible causes for the rarity of these traces in similar continental basins, 4) to point out the utility of insect trace fossils as palaeoenvironmental indicators in continental deposits.

## 2. Geological Setting

Our study area is situated in the narrow, elongated to the NNE–SSW Calatayud-Daroca Basin, bounded by low-grade metamorphic Palaeozoic reliefs and by normal faults (Julivert, 1954), formed by extensional movements affecting NE Spain during the Miocene (Anadón and Moissenet, 1996; Anadón et al., 2004) (Figs. 1,2). It is filled by 1,200 m of Palaeogene and Neogene continental deposits. The Neogene deposits, outcropping in most of the area, consist of three sedimentary units: Lower, Intermediate and Upper (Fig. 1B) (Sanz-Rubio, 1999; Alcalá et al., 2000). All units have detrital deposits in the marginal areas of the basin, which grade to different carbonate and/or evaporitic deposits. The Lower Unit is mainly evaporitic. The Intermediate Unit is the more complex, showing different transitions from alluvial to mudflat and/or lacustrine deposits either carbonate or evaporitic (Fig. 1B). The Upper Unit is dominated by freshwater limestones (Sanz-Rubio et al., 1999). Trace fossils occur in red-green mudstones, sepiolite and carbonates of the Intermediate Unit. In the Orera area previous

studies have shown that the Intermediate Unit is characterized by well stratified beds arranged in cycles of metre scale. High-resolution magnetostratigraphy of the entire sequence yields an age of 12.8–10.7 Ma (Abdul Aziz et al., 2000), which fits well with the characteristic Aragonian to lower Vallesian faunas found in the area (Canudo and Cuenca, 1989). The short term ( $\approx 23,000$  yr) cycles have been interpreted as astronomically controlled (Abdul Aziz et al., 2003). The area has also been the aim of a number of detailed mineralogical and geochemical studies that indicate that these deposits formed in alkaline environments (Arauzo et al., 1989; Mayayo et al., 1995). These previous contributions lack any mention of insect trace fossils, which in this study were found in two sites of the Orera area, one in Orera Quarry and other in the vicinity of Orera Village (Fig. 2, 3).

### 3. *Materials and Methods*

The trace fossils, collected during two field trips (October 2009 and June 2012), are housed in the Museo de Paleontológico de la Universidad de Zaragoza (MPZ).

Two sedimentary sections were chosen for study due to their content in insect trace fossils, which were detected by MYTA (Orera Quarry) and ourselves (Orera Village). Thin sections of rocks and traces were examined by petrographic microscopy. Due to their fragility, the trace fossils were embedded in a resin containing Epofer EX 401 and Epofer E 432 in a vacuum system. Mineralogical characterization was done by X-ray diffraction using a Philips PW-1710 XRD system operating at 40 kV and 30 mA, at  $2^\circ/\text{min}$ , with monochromated  $\text{CuK}\alpha$  radiation. XRD spectra of ten were obtained from  $2$  to  $66^\circ 2\theta$ .

#### 4.1. Sedimentology

##### 4.1.1. Red and brown mudstones

These mudstones occur as dm-thick laminated or massive beds (Figs. 3, 4A), containing different amounts of silt to sand-sized grains, mostly of quartz and minor feldspars and micas. Some beds show a dense network of white cracks, which separate millimetric mudstone fragments, and in some cases give them a granular aspect (Fig. 4B). Some of the cracks are planar, probably formed by desiccation; others are more irregular, connected vertically through ovoidal pores, probably due to roots. Both root penetration and desiccation could have played a role in the formation of the crack network. In many cases cracks and pores are outlined by a micritic lining and filled by coarse mosaic spar; other cracks are empty (Fig. 4B). One of these beds, at Orera Quarry contains a large number of *Fictovichnus gobiensis* (Fig. 4B). Peloids occurring in some ovoidal cavities are distributed in irregular pockets within the sample.

##### 4.1.2. Sepiolite

Sepiolite beds are white to grey, massive or cracked decimetric to a few metres thick (Fig. 4C). Mineralogically they are mainly composed by sepiolite and contain different amounts of dolomite, quartz and feldspar. Sepiolite beds grade gradually and vertically to dolomicrite beds. Sepiolite-dolomicrite contacts are irregular. Dolomicrite intraclasts, insect and root traces are very common in these transition zones (Fig. 4C). Under the microscope the sepiolite show fibres oriented in different directions (sepic fabrics). Desiccation and/or root cracks in the sepiolite are also filled by a coarse

mosaic of calcite cement. Whitish specimens of *Fictovichnus gobiensis* within the sepiolite, are connected to a network of white sepiolite+dolomicrite fillings (Fig. 4D).

#### 4.1.3. Dolomicrites

Dolomicrites are in some cases difficult to distinguish from sepiolite in the field, because they are white. Dolomicrites occurring as homogeneous beds or with prismatic structure, very commonly show a network of cracks, which may or may not be filled with calcite cement. Some dolomicrite beds contain sepiolite and in cases dolomite intraclasts embedded in a grey sepiolite matrix (Fig. 4E). Dolomicrite under the microscope is seen as a fine crystalline matrix. Some detrital grains are also found within the dolomite beds, which also contain *Fictovichnus gobiensis* (Fig. 4F).

#### 4.1.4. Mudstones with carbonate laminae

These mudstones, situated in the transition from red mudstones to dolomicrites or sepiolite (Figs 3, 4G), include mm-thick laminae of carbonates connected vertically by carbonate veins and/or root cracks and root traces commonly filled by calcite (Fig. 4G). These laminae give a platy aspect to the mudstones. These green, pink or pale brown mudstones have a granular structure consisting of mm subangular to rounded fragments (Fig. 4H). White, irregular, mainly horizontal, carbonate laminae consist of coarse calcite crystals that in some cases include micrite linings in contact with mudstones (Fig. 4I). Root traces are filled by fragments of mudstones with a large number of cracks cemented by coarse spar cement. Linings of micrite are common but

also appear as micrite filaments in the inner-most part of cavities (Fig. 4I). *Fictovichnus aragon* is restricted to this facies in the Orera Quarry.

## 5. Ichnotaxonomy

### 5.1. Pallichnidae Genise, 2004

#### 5.1.1. *Fictovichnus* Johnston et al., 1996

##### 5.1.1.1. Type ichnospecies

*Fictovichnus gobiensis* Johnston et al., 1996

##### 5.1.1.2. Emended diagnosis

Horizontal to subvertically oriented, ellipsoid to ovoid chambers, occurring as empty spaces in the matrix or as egg-shaped or ellipsoid internal moulds of smooth or faintly sculptured surface but lacking a discrete wall to the unaided eye. They may show a terminal rounded scar that may be sub-terminal or medial, on the upper surface of the chamber relative to bedding (modified from Johnston *et al.*, 1996).

##### 5.1.1.3. Comments

The original diagnosis was modified to avoid micromorphological characters, variations referring to preservation in different substrates; also to avoid interpretative expressions such as “exit holes”; to include the new ichnospecies; and to homogenize nomenclature used in diagnoses. Also to include the subvertical orientation presented in this study.

Both ichnospecies of *Fictovichnus* named originally by Johnston et al. (1996), *F. gobiensis* and *F. parvus*, were separated only by their different sizes, a character that

has no ichnotaxonomic value, and accordingly they were considered as synonyms by Genise (2004). Genise et al. (2010) reviewed and included in *Fictovichnus gobiensis* former records of ovoid casts described or mentioned in the literature as ‘cocoon’, ‘ovoid structures’ and/or illustrated showing an ovoid shape. Specimens from Australia showing a thick discrete wall were also included in *Fictovichnus* by Johnston et al. (1996), and subsequently transferred to *Rebuffoichnus* (Genise et al., 2002). When preserved as infilled chambers in the matrix, the casts of *Fictovichnus* show an external surface clearly defined and smooth but lacking a discrete wall as in *Rebuffoichnus*.

*Fictovichnus sciuttoi* (Genise et al., 2007) *comb. n.*, was originally described as *Rebuffoichnus* because the best-preserved specimens showed a thin but discrete wall assumed to be of the constructional type as in other *Rebuffoichnus* Genise (2004). However, the discrete wall of *F. sciuttoi* is observable only in thin sections of the best preserved specimens, which is impractical, not always possible and to some extent interpretative. To the unaided eye the ichnospecies *sciuttoi* is more similar to the type ichnospecies of *Fictovichnus (gobiensis)* than to ichnospecies of *Rebuffoichnus*. Accordingly, the new combination proposed herein is more practical and less interpretative.

#### 5.1.1.4. *Fictovichnus gobiensis* Johnston et al., 1996

Emended diagnosis: *Fictovichnus* showing both extremes rounded and smooth surface in casts detached from matrix. There is no flat surface near one extreme.

Comments: Differences between *F. gobiensis* and *F. sciuttoi* are minor. The former lacks the helical surface texture, of fine dense ridges impressed over wide flattened lobes, of the latter. Whereas the outer surface of *F. gobiensis* is completely smooth. Also *F. gobiensis* lacks the flat, oval, smoothed area near the end opposite to the scar or truncated end, which was interpreted as the attachment area of the cocoon to

the floor (Genise et al., 2007). In contrast to both ichnospecies, the newly described *Fictovichnus aragon* n. isp. has one pointed extreme.

Examined material: 33 complete specimens and 52 fragments (MPZ 2013/88 to 125) from Orera Village, and 106 complete specimens and 129 fragments from Orera Quarry (MPZ 2013/126 to 137 and 261 to 355).

Description: specimens were found as internal, mostly ellipsoid casts of smooth surface, detached from the matrix or included in it, with subvertical orientation (Fig. 5A). At Orera Village casts are mostly whitish, whereas at Orera Quarry, they are pale brown. They range in length from 22 mm to 15 mm and in maximum diameter from 11 mm to 7 mm ( $n = 140$ ). The most common are 15–18 mm long (90%) and 8–9 mm wide (80%). Specimens show one rounded end whereas in the other may be a scar (8%), a short cylindrical protuberance (54%), a longer well-defined tunnel (15%), or they may be truncated (14%) or broken (7%). Rare specimens may have scars at both extremes (Fig. 5B). Scars are rounded, slightly concave, 6 mm in diameter, with a rim and a regular surface (Fig. 5C). There are three types of tunnels connected to the chambers. One type ranges in length from 7 mm to 26 mm and is connected near one of the extremes (Fig. 5D). In some cases the cast and tunnel outline is curved (Fig. 5E). The diameter is a particular feature of this type of tunnels, which are mostly 7–8 mm in diameter and show a constriction of 5–6 mm in diameter in the connection (Fig. 5F). The diameter is similar to that of the chamber, which may indicate that these tunnels are entrances, or more probably, emergence tunnels from the chambers. Most specimens (54%) show a second type of tunnel: a cylindrical protuberance, 7 mm in diameter, constricted at the base, with irregular surface, considered to be a short remnant of a tunnel similar to type one (Fig. 5G). This structure is distinguishable from scars, which are concave, rimmed, and smooth surfaced. The third type of tunnel connected to casts

are of 3–4 mm in diameter, up to 14 mm long, straight, inclined and connected to the lower surface either near the extremes (Fig. 5A, H, I) or nearer the center (Fig. 5J). Diameters of these tunnels are consistently smaller than those of emergence tunnels and chambers and also lack the constriction at the base. Specimens show smooth surfaces overprinted by nets, which in the case of Orera Village are mostly minute channels and pits carved on the surface (Fig. 5C, K), and in the case of Orera Quarry are mostly ridges or strings (Fig. 5D). In some specimens the external surface shows a lamellar texture as if it were composed of several overlapping layers (Fig. 5L–M).

Thin sections show that *Fictovichnus gobiensis* has no discrete wall, and the contact between the cast and the matrix is a crack (Fig. 6A). Some specimens have a thin micritic layer of coarse calcite crystals in their outer-most part, in the contact with the crack (Fig. 6B, C). Micro-morphology of the casts is diverse but similar to the matrix where they are found, such as cracked mudstones (Fig. 6A) or homogeneous dolomicrite (Fig. 6F). Traces found in cracked mudstones consist of irregular fragments of micrite mud and cracked clays cemented by a coarse calcite mosaic that both fills the porosity and partially replaces clays (Fig. 6A, B, C).

#### 5.1.1.5. *Fictovichnus aragon* Genise, Verde and Alonso-Zarza isp. n.

Diagnosis: *Fictovichnus* showing one extreme rounded and the other pointed.

Casts with smooth surface. There is no flat surface near one extreme.

Comments: *Fictovichnus aragon* is clearly distinguishable from *F. gobiensis* and *F. sciuttoi* because of one of its tapering extremes, and from the latter also by the lack of external surface morphology composed of ridges and lobes.

Etymology: after Aragón, the region of Spain where Orera is located.

Holotype: a complete specimen from Orera Quarry (MPZ 2013/394).

Paratype: a less complete specimen from Orera Quarry (MPZ 2013/361).

Examined material: five incomplete to fragmentary specimens from the same locality of the types (MPZ 2013/356 to 360). All the material was collected during a field trip on October 2009.

Description: the holotype (Fig. 7A-D) is a whitish cast 26 mm long and 9 mm in maximum diameter. Close to the pointed extreme the diameter is 6 mm, whereas close to the rounded one it is 7 mm. This outline is typical character of this ichnospecies. The surface is smooth and shows networks of ridges (Fig. 7A, C), minute channels and pits (Fig. 7B), and also lamellar texture (Fig. 7D). The surface also shows two irregular depressions, one smaller at the equator (Fig. 7A) and a larger one toward the rounded extreme. The paratype (Fig. 7E, F), which lacks the rounded extreme is 19 mm long and 7 mm in maximum diameter. Close to the pointed extreme the diameter is 4 mm, whereas toward the other extreme it is 5 mm, copying the outline of the holotype. The surface is smooth (Fig. 7E) and in some parts shows a lamellar texture as if the wall were composed of overlapping layers (Fig. 7E, F). At the equator this specimen shows two small and sharp protuberances (Fig. 7F). The remaining specimens show different degrees of preservation. MPZ 2013/356, a fragment including the rounded extreme, is tentatively included in this ichnospecies because of its small diameter (6 mm). MPZ 2013/357, a remnant of a central section, which shows smooth surface, is also tentatively included in this ichnospecies because of its small diameter (6 mm).

A studied thin section of *Fictovichnus aragon* is a cast preserving part of the matrix. It shows that at the contact there is a very thin, inner, micritic layer surrounded by a thicker one (0.2 mm) composed of roughly laminated micrite with quartz grains and locally calcite cement (Fig. 8A, B). These quartz grains are not oriented and are distributed similarly to the matrix. The inner part of the thin layer is relatively regular,

probably corresponding to the external part of the cast. The outer layer is more irregular and shows some swellings (Fig. 8B). The matrix of the chamber is composed of fragments of the clay clasts with quartz grains cemented by a coarse mosaic of calcite.

MPZ 2013/359, an incomplete, broken specimen 16 mm long and 7 mm in maximum diameter, preserves the pointed extreme, which is slightly more rounded than the holotype. The outer surface is smooth with some faint ridges and the broken side shows a thin layer surrounding an irregular filling. MPZ 2013/360, a complete specimen, 20 mm long and 7 mm in maximum diameter, also shows a less pointed extreme than in the holotype and a more constant diameter along the longitudinal axis. The surface is smooth, lamellar in some parts, with faint ridges and remains of matrix.

## 6. Discussion

### 6.1. Trace fossils and trace makers

With the new ichnotaxonomical arrangement *Fictovichnus* has three ichnospecies: *F. gobiensis*, *F. sciuttoi*, and *F. aragon*. Unlike *Rebuffoichnus*, which shows a thick discrete wall, *Fictovichnus* has no discrete thick wall visible to the unaided eye. Some specimens of *F. sciuttoi* and *F. aragon* may preserve a thin outer layer, which may be interpreted either as diagenetic or as the remains of the original thin wall of a wasp cocoon (Genise et al., 2007). In contrast, *F. gobiensis* lacks this thin layer and is interpreted as a coleopteran pupation chamber (Johnston et al., 1996; Genise et al., 2007).

Possible producers of *Fictovichnus gobiensis* are representatives of Coleoptera that pupate in soils which, according to Lawrence (1991), may belong to more than 50 families. Among them, Johnston et al. (1996) proposed chafers that feed on roots

(Scarabaeidae), weevils (Curculionidae) and Tenebrionidae, as potential producers. The similar *Rebuffoichnus casamiquelai*, which could be interpreted as a *Fictovichnus gobiensis* with a discrete wall, was unequivocally attributed to weevils since the trace maker was found inside one specimen (Lea, 1925). The interior of pupation chambers are completely smooth at both ends, since the larva works from the inside of the chamber, as in *Rebuffoichnus* (Genise et al., 2013) and the specimens of *F. gobiensis* described herein. According to May (1961, 1966) weevil pupation chambers are produced by rotation of the body while cementing and smoothing the walls with droplets of anal secretion. Walls become thickly coated and smooth in some species, whereas in others, chambers are smooth but unlined (May, 1966). Tilley et al. (1997) described a similar larval behavior, also mentioning the use of body fluids to stabilize walls of pupation chambers, adding that the wall could be subsequently hardened by infiltration of calcium-rich water or fossilized within bauxite deposits in some Australian cases. The presence of a lining observable to the unaided eye, thicker and detachable from soil, may be the result of differential use of secretions to line the wall. Probably species using little or no secretions may produce *Fictovichnus*-like chambers with thin linings not detachable from soils, whereas those using more secretions will produce *Rebuffoichnus*-like chambers with thicker linings detachable from soils. In any case diversity of putative producers involved restricts the scope of palaeo-environmental inferences. The subaerial exposure of the deposit can be inferred from the presence of air-breathing insect larvae and roots. In addition, *Fictovichnus* is a dominant component of the *Celliforma* ichnofacies developing in carbonate-rich palaeosols of semiarid to subhumid environments (Genise et al., 2010).

Some characters of *Fictovichnus gobiensis* from Orera deserve a more detailed analysis. The scars were also described from *Pallichnus dakotensis* (Retallack, 1984;

Genise et al., 2007) and from *Fictovichnus gobiensis* of the type locality (Johnston et al., 1996), and considered to be emergence holes, and from *F. sciuttoi* (Genise et al., 2007). In the latter case it was shown that scars were not remains of emergence tunnels, since emergence truncates specimens (i.e. a complete extreme of the specimen is missing leaving a flat surface). In turn, scars were compared to the cap of some wasp cocoons (Evans, 1966, fig. 207a) (Genise et al., 2007). In the case of *F. gobiensis* from Orera, the scar clearly is an interruption of the smoothness of the external surface of casts with diametres similar to those of constricted tunnels described below. Thus, herein scars are considered an indication of the constricted area of connection between chambers and tunnels. Nets of channels or ridges on the surface of specimens are interpreted to be rootlet networks, which commonly developed extensively between the filling and wall of traces in soils (Martin and Bennett, 1977; Grown and Richardson 1988; Johnston et al. 1996; Bedatou et al., 2008; Genise et al., 2013). Small 3–4 mm tunnels connected to the lower surface of *F. gobiensis* are considered herein as produced by parasitoids. Similar tunnels, 2–5 mm in diameter connected to possibly large (20.7 mm x 10.4 mm) wasp cocoons were described from the Late Cretaceous Two Medicine Formation of the USA (Martin, 2001; Martin and Varricchio, 2011). Another specimen was recorded by Mikuláš and Genise (2003), who illustrated part of a *Celliforma* from the Oligocene of Dětaň (Czech Republic) that preserves short truncated protuberances. These authors discussed the different possibilities for the producers of these structures, including cell intruders (i.e. cleptoparasites, parasitoids, detritivores) but also roots.

Thin sections of *Fictovichnus gobiensis* show that the small amounts of quartz grains in the clay-micrite matrix show similar packing degree in the traces than in the host matrix, and do not show orientation. This contrasts with specimens from Mongolia (Johnston et al., 1996), which show increased packing and orientation of quartz grains.

Probably, these differences are not based on the behavior of insects, but in the presence of fewer quartz grains in the matrix of Orera. The fine-grained texture (clays and micrite) of our specimens of *F. gobiensis* would favour the formation of the smooth outer surface of casts.

The shape of the paratype and particularly the holotype of *Fictovichnus aragon* closely resembles cocoons of sphecid and pompilid wasps (Evans, 1966; Genise et al., 2007) (Fig. 7G, H). Change in diameter along the longitudinal axis of casts gives these trace fossils a shape that is almost identical to cocoons of some wasps. The thin wall, similar to that of *F. sciuttoi*, also considered a wasp cocoon, has a micritic layer that may have replaced or precipitated in the place occupied by silk.

Resemblance to wasp cocoons in the case of the paratype is reinforced by the presence at the equator of small and sharp protuberances like the pores of some wasp cocoons (Evans, 1966; Genise and Cladera, 2004).

Digger wasps, widely distributed in semiarid to sub-humid regions, probably produced this new ichnospecies of *Fictovichnus* in carbonate-rich palaeosols, which may be considered potentially a new component of the *Celliforma* ichnofacies (Genise et al., 2010).

## 6.2. Palaeoenvironmental interpretation

Alluvial fans and small telescoped fan/slope-scrée deposits situated on the NE margin of the Calatayud Basin supplied the mudflat area with detrital material. Deposits studied herein were previously interpreted as a very flat lacustrine area (mudflat) located between two main alluvial fan systems (Abdul Aziz et al., 2003). Red and brown mudstones, deposited as distal fan deposits in dry areas of the mudflat, were

often exposed as indicated by desiccation cracks and root and insect traces. Progressive rise of water table accounted for the formation of shallow lakes in which sepiolite and dolomicrite beds deposited (Fig.9). The mudstone/dolomite+sepiolite cycles seems to reflect a transition from dry (mudflat) to wet (lake) conditions in the sedimentation area (Abdul Aziz et al., 2003).

Formation of sepiolite took place by direct precipitation in alkaline ( $\text{pH} \geq 8$ ), but not saline, environments with reduced amounts of aluminum (Starkey and Blackmon, 1979) and silica concentration of 20–150 ppm (Arauzo et al., 1989). A similar situation has been interpreted in the Madrid Basin where sepiolite also comes from chemical precipitation, in semi-arid conditions, in shallow non-saline lakes (Cuevas et al., 2003). These conditions are also suitable for the precipitation of dolomite. The necessary ions were supplied to surface and phreatic waters from weathered basin margin siliceous and carbonate materials. Mg-rich waters necessary for the formation of sepiolite and dolomite came from the progressive concentration of lake waters by evaporation (Abdul Aziz et al., 2003). Precipitation of sepiolite versus dolomite in these alkaline lakes is controlled by Mg/Ca ratio and  $\text{PCO}_2$  (Arauzo et al., 1991). There is no indication that this dolomite had a previous carbonate or non-carbonate phase, so it could be a primary precipitate (Last, 1990; García del Cura et al., 2001). Although the possibility of biogenical precipitation of sepiolite and dolomite (Vasconcelos and McKenzie, 1997; Leguey et al., 2010) cannot be discarded, recent studies (Casado et al. 2014) have shown that abiogenic dolomite can form once the kinetic barriers for dolomite precipitation are overcome in highly alkaline Mg-rich environment during sedimentation, pedogenesis and early diagenesis. Experimental studies also support the idea of direct precipitation of abiogenic dolomite (Roberts et al., 2013).

The lacustrine area was commonly exposed as indicated by: the prismatic structure produced by roots in some dolomite beds, the sepic (pedogenic) fabric of the sepiolite beds, the intraclasts and the desiccation cracks. All these features indicate that these deposits are palustrine dolostones and/or sepiolite (Bustillo and Alonso-Zarza 2007; Alonso-Zarza and Wright, 2010) and so favourable sites for insect trace fossil occurrence.

In the study area previously undescribed mudstones with carbonate laminae are of special interest because they contain *Fictovichnus aragon*. The granular structure of these mudstones is commonly described in A-horizons of soils supporting herbaceous plants (Retallack, 2001), as is also indicated by the presence of small rhizoliths. The carbonate laminae cemented the porosity left after decomposition by fine, mostly horizontal root networks, mainly evidenced by rhizolith connection of different carbonate laminae and by micritic linings that could be relics of alveolar septal structures (Wright, 1986). Porosity was filled by coarse phreatic calcite cement during water table rise. As indicated by the lighter isotope values of the cements (Mayayo et al., 1998) in comparison with those of the dolostones groundwater was relatively fresh. The intermediate position of these facies between red mudstones (dry mudflat) and sepiolite or dolomicrite (lake or playa) indicate that these mudstones formed in the wet mudflat environments of the system when the lake level was rising.

Specimens of *Fictovichnus gobiensis*, by far more common than *Fictovichnus aragon*, occur in all subaerially exposed environments, either in dry mudflats or after desiccation of lakes (Fig. 9). *Fictovichnus aragon*, restricted to the mudflat, formed in dry subaerial conditions, but with high groundwater levels that permitted the life of probably phreatophytic plants and the nesting of wasps. In stages of rising of lake levels, groundwater cements (coarse calcite mosaics) filled porosity left by the

decomposition of plants; desiccation cracks; porosity within the insect chambers and in some cases, porosity between the chamber filling and matrix. Thus, preservation of these insect trace fossils is not only controlled by the characteristics of the sedimentary environments (subaerial exposure) in which the insects nest or pupate, but also by the early diagenetic processes (calcite cementation) that occurred during the rise of the water table. Subaerial exposure followed by rise water table occurred during the development of the dry-wet sedimentary cycles that characterized the Orera deposits. Probably the lack of this cyclic sedimentary pattern in other similar continental areas/basins is responsible for the absence of insect trace fossils.

## 6. Conclusions

The mudflat deposits of the Orera area, in Spain, contain two ichnospecies of insect trace fossils, described for the first time for the Iberian Peninsula. Specimens of *Fictovichnus gobiensis* are mostly ellipsoid casts connected to truncated tunnels and *Fictovichnus aragon* n. isp has one extreme rounded and the other pointed. Some specimens of *F. gobiensis* show small tunnels from parasites. *Fictovichnus aragon* n. isp has a micritic layer that may have formed during diagenesis in the space previously occupied by silk. Based on their meso- and micromorphological features, *F. gobiensis* was probably produced by coleopterans, whereas sphecid or pompilid wasps were likely the producers of *F. aragon*. Both ichnospecies should be considered components of the *Celliforma* ichnofacies.

The traces are preserved in mudflat deposits comprising four main facies: red and brown mudstones deposited in the dry mudflat; sepiolite and dolomicrites formed in

periodically desiccated shallow lakes; whereas mudstones with carbonates laminae characterized the wet mudflat areas. The mudstone/sepiolite+dolomite sequences represent the rise of the water table or dry/wet cycles. The overall was a semi-arid environment with shallow alkaline lakes in which sepiolite and dolomite precipitated directly. *F. gobiensis*, requiring subaerial exposure in either mudflat or lake (palustrine) environments, occurs in all the facies and environments described. *F. aragon*, occurring only in mudstones with carbonate laminae, indicates that wasps probably nested in subaerially exposed areas of the mudflat. The rise of groundwater enabled the cementation and preservation of both *F. gobiensis* and *F. aragon*. Thus, very early diagenetic processes, driven by the rise of groundwater, are key for the preservation of these insect traces. In the study area, the conditions for preservation were somehow exceptional and related to the short term dry-wet sedimentary cycles. Similar processes may be the responsible for the preservation of insect trace fossils in other comparable continental environments.

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## Figure Captions

**Fig. 1.** A. Location of the study area within the Calatayud-Daroca Basin. B.

Stratigraphy of the Calatayud Daroca Basin. The unit containing the traces is in blue.

**Fig. 2.** Image of the study area showing the location of the sites containing the traces.

**Fig. 3.** Sedimentary logs of the studied sections in Orera Quarry and Orera Village.

**Fig. 4.** Facies from Orera deposits. (A) Orera Quarry showing the red mudstones alternating with dolostone/sepiolite beds (white colour). (B) Thin section of the red mudstones with desiccation cracks. An insect trace fossil (*Fictovichnus gobiensis*) is observed in the lower part (arrow). The contact between the matrix and the trace is an empty crack. (C) Orera Village. *Fictovichnus gobiensis* (arrow) is found in the transition between sepiolite beds (s) and dolomicrites (d). (D) Sepiolite containing white *Fictovichnus gobiensis* (arrow), which is connected to a network of sepiolite+dolomite fillings (arrow). (E) Brecciated dolomicrite forming intraclasts which are embedded in sepiolite. (F) Thin section of homogeneous dolomicrites containing *Fictovichnus gobiensis* (arrow). (G) Red mudstones grading to mudstones with platy-like carbonates. Vertical rhizoliths (arrow) are connected by horizontal carbonate layers. (H) Microstructure of the mudstones with carbonate laminae consisting of angular mudstone fragments separated by a dense network of carbonate veins that locally are connected with rhizoliths (arrow). (I) Detailed view of (H) showing a small vertical rhizolith, the horizontal carbonate veins and the angular fragments of mudstones (m).

**Fig. 5.** *Fictovichnus gobiensis*. (A) Field photograph showing location in the rock matrix and a small tunnel in its lower end. (B) Specimen with scars at both ends. (C) Detail of a scar showing its circular contour, a rim and concave and regular internal

surface. (D) Specimen with a straight emergence tunnel (type I). (E) Specimen with a curved tunnel. (F) Specimen showing a constriction between the chamber and tunnel. (G) Specimen in which a short portion of tunnel (type II) has been preserved. (H) Same material as in A, showing detail of a slender parasite tunnel (type III) in its lower end. (I) Specimen with a short parasite tunnel (type III) in one pole. (J) Specimen with a type III tunnel in its equatorial zone. (K) Channels and pits interpreted as rootlet traces on the cast surface. (L) Specimen with lamellar surface texture (M) Specimen with ridges. Scales: 5 mm, except in A which is 1 cm.

**Fig. 6.** Micromorphology of *Fictovichnus gobiensis*. (A) Detailed view of Fig 3B showing the porosity between the matrix and the trace and the lack of a discrete wall. (B) Cross section of the trace that is composed of fragments of mudstones embedded in coarse calcite cement (cc). The outer micrite layer is arrowed. (C) Detailed view of the outer micrite layer (arrow) and calcite cement (cc).

**Fig. 7.** *Fictovichnus aragon*. (A–D) Holotype (MPZ 2013/394). (A, B) Side views showing smooth surface texture and channels and pits in (B). (C, D) Details of the surface showing fine ridges (C) and lamellar texture (D). (E–F) Paratype (MPZ 2013/361) showing an acute, small protuberance at the equator in F. (G, H) Cocoons of extant wasps. Note the shape in both cases and compare with *F. aragon*. (G) *Tachypompilus* isp. cocoon. (H) *Rubrica nasuta* cocoon. Note pores at the equator. Scales: 5 mm, except in C, D that are 2 mm.

**Fig. 8.** Micromorphology of *Fictovichnus aragon*. A) In cross section, the trace is composed of fragments of mudstones cemented by calcite (cc) surrounded by a continuous and irregular outer micrite layer (arrow). (B) Detailed view of (A) showing the two micritic layers (m1 and m2) and an area of thickened micrite.

**Fig. 9.** Sketch showing the situation of the insect trace fossils in the different sedimentary environments. A. Intermediate water table level with some exposed areas suitable for insect activity. B. Low water tables allow larger exposed areas increasing insect activity. C. The rise of water table reduced the suitable area for the life of insects, but favoured cementation and preservation of the previous traces.

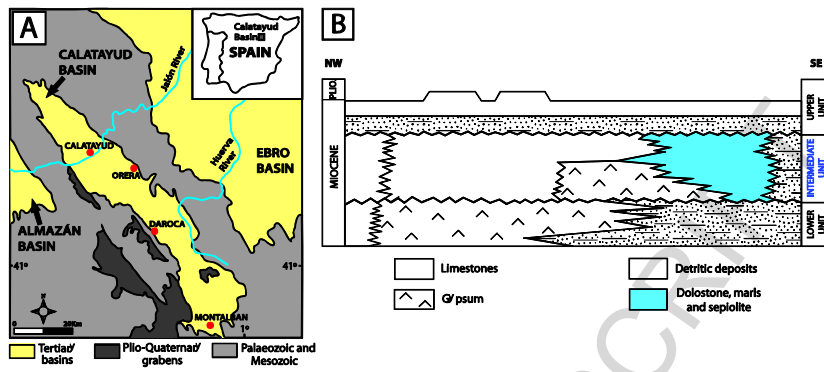


Figure 1

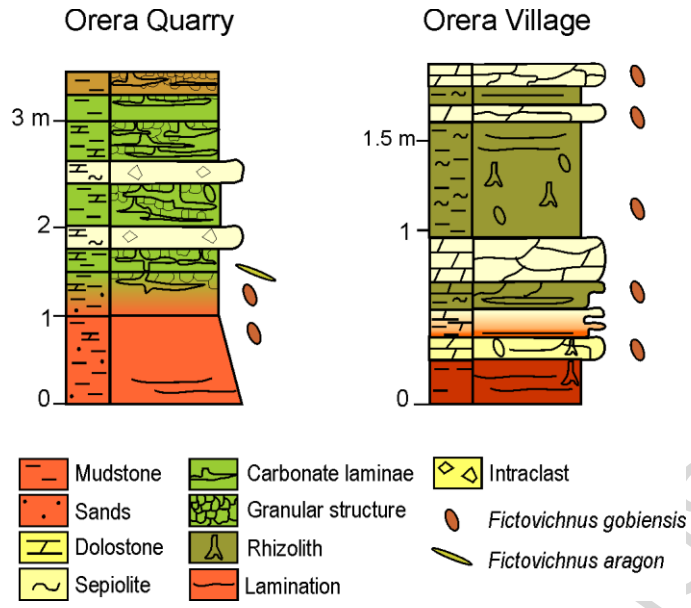


Figure 3

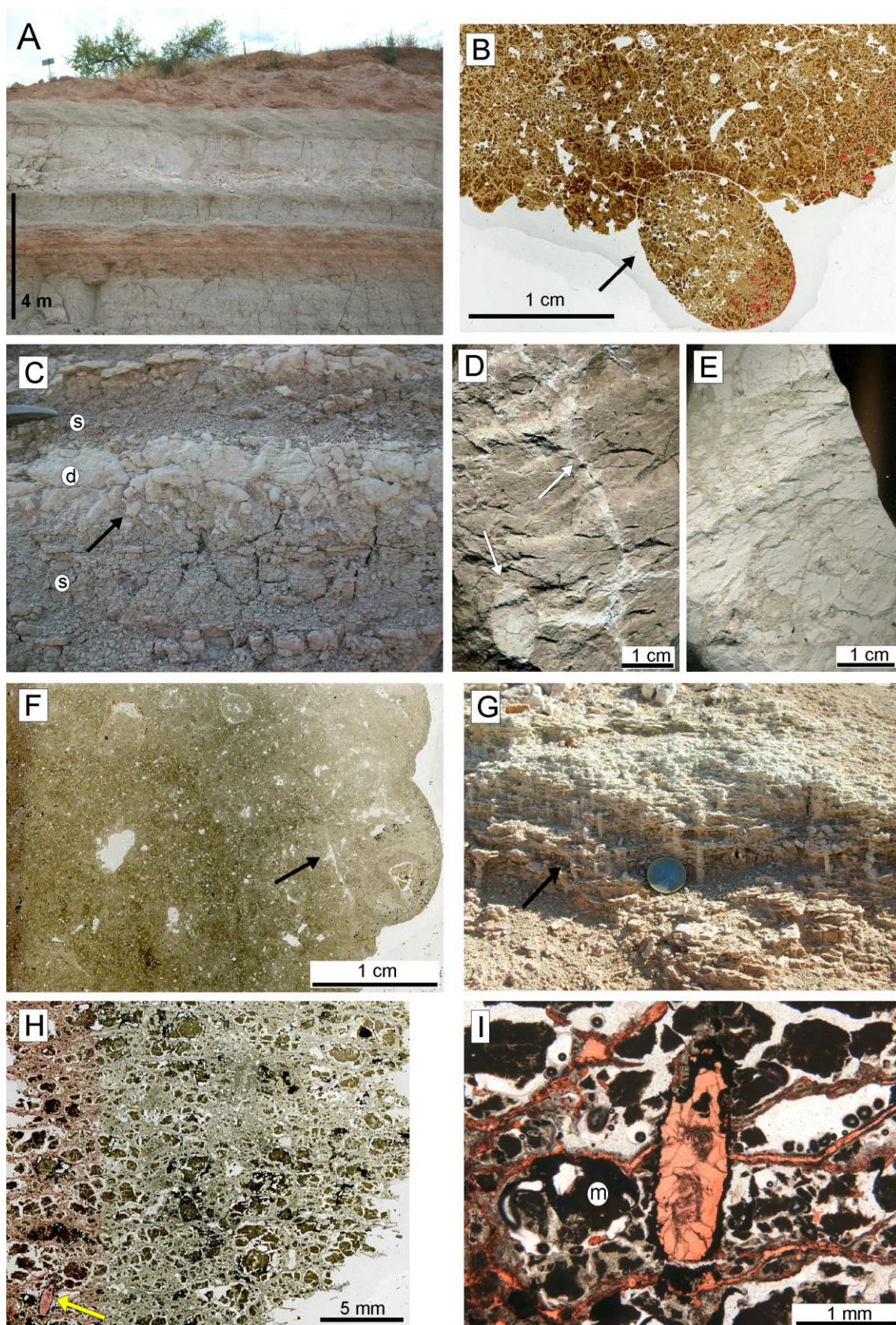


Figure 4

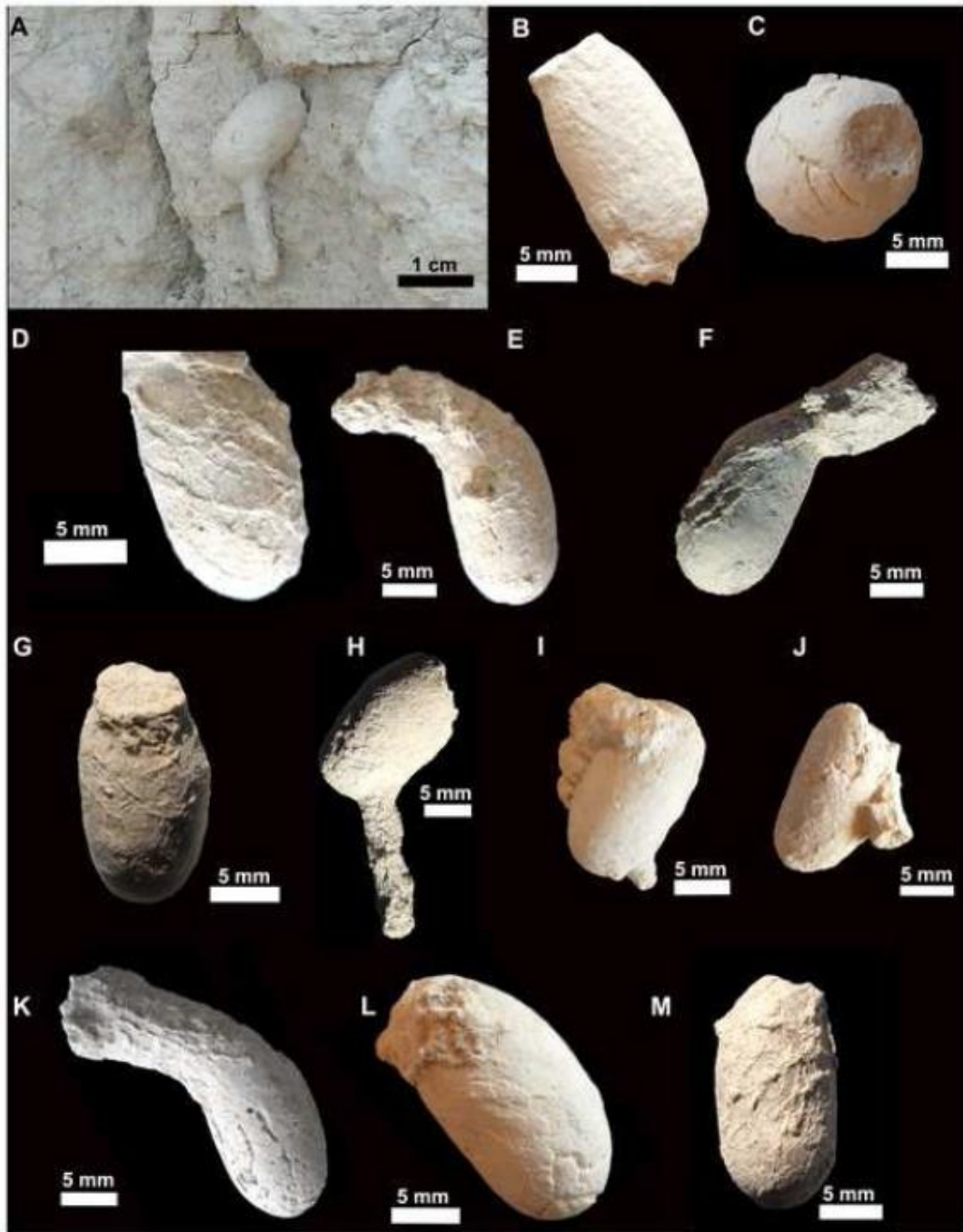


Figure 5

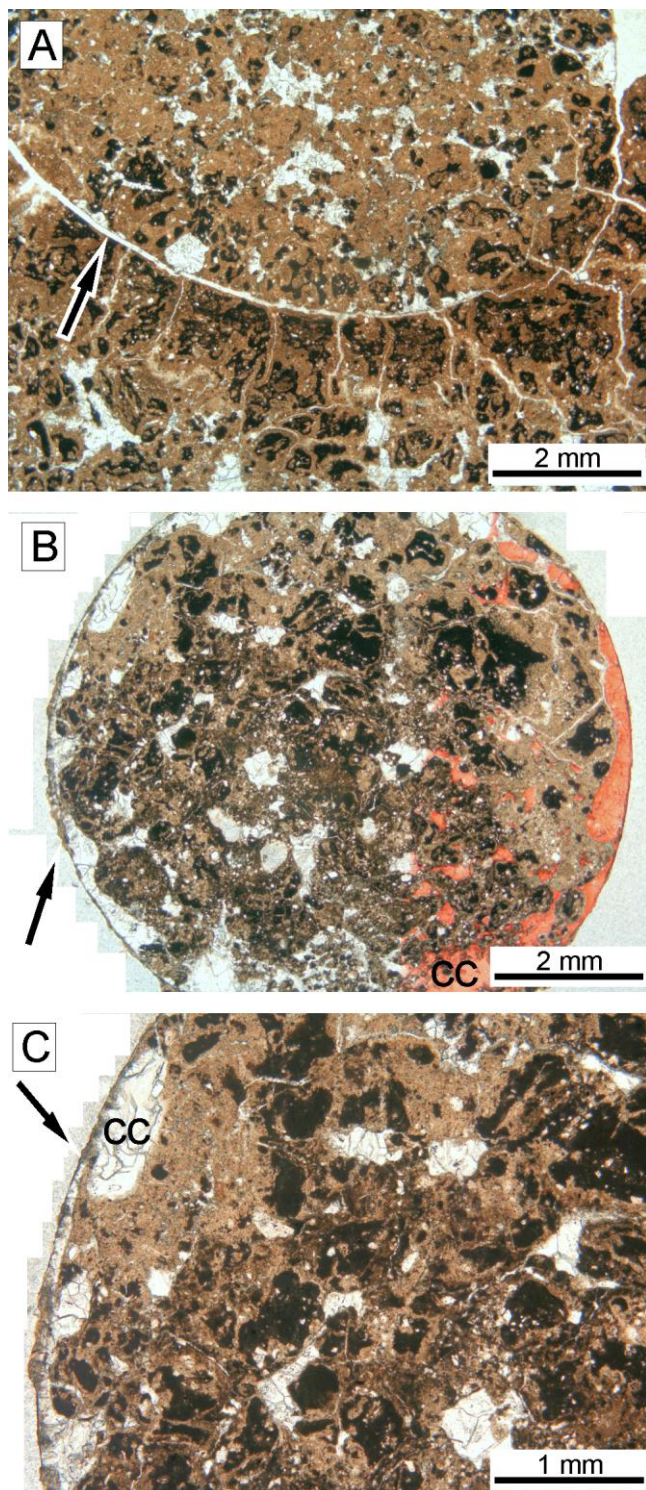


Figure 6

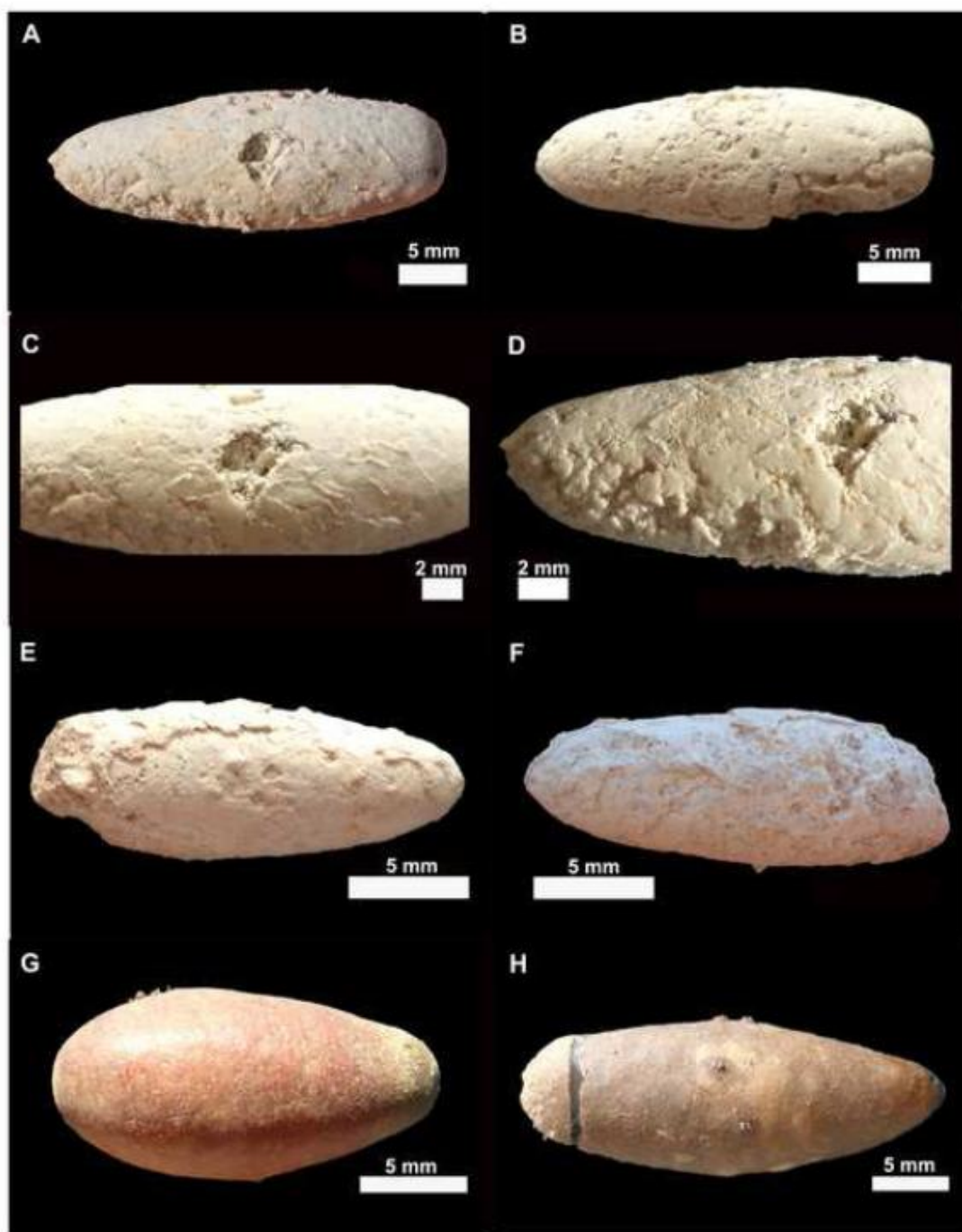


Figure 7

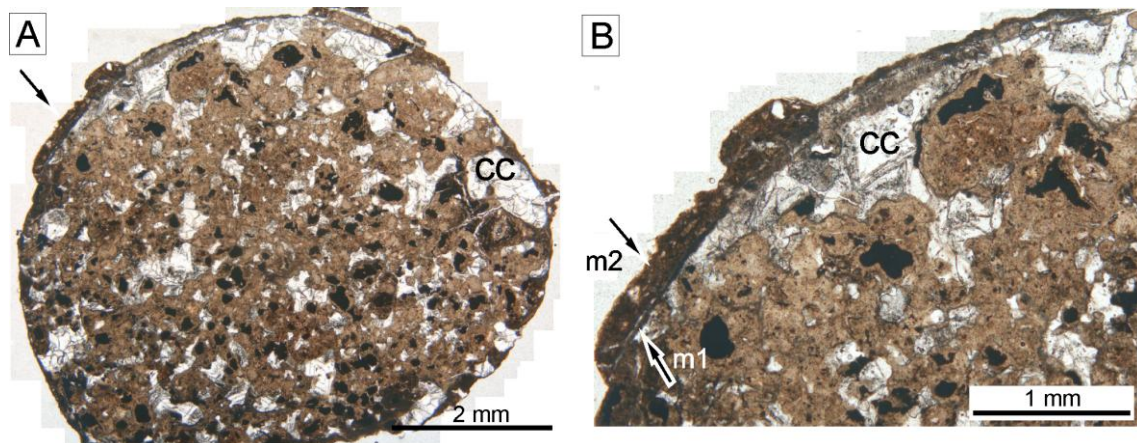


Figure 8

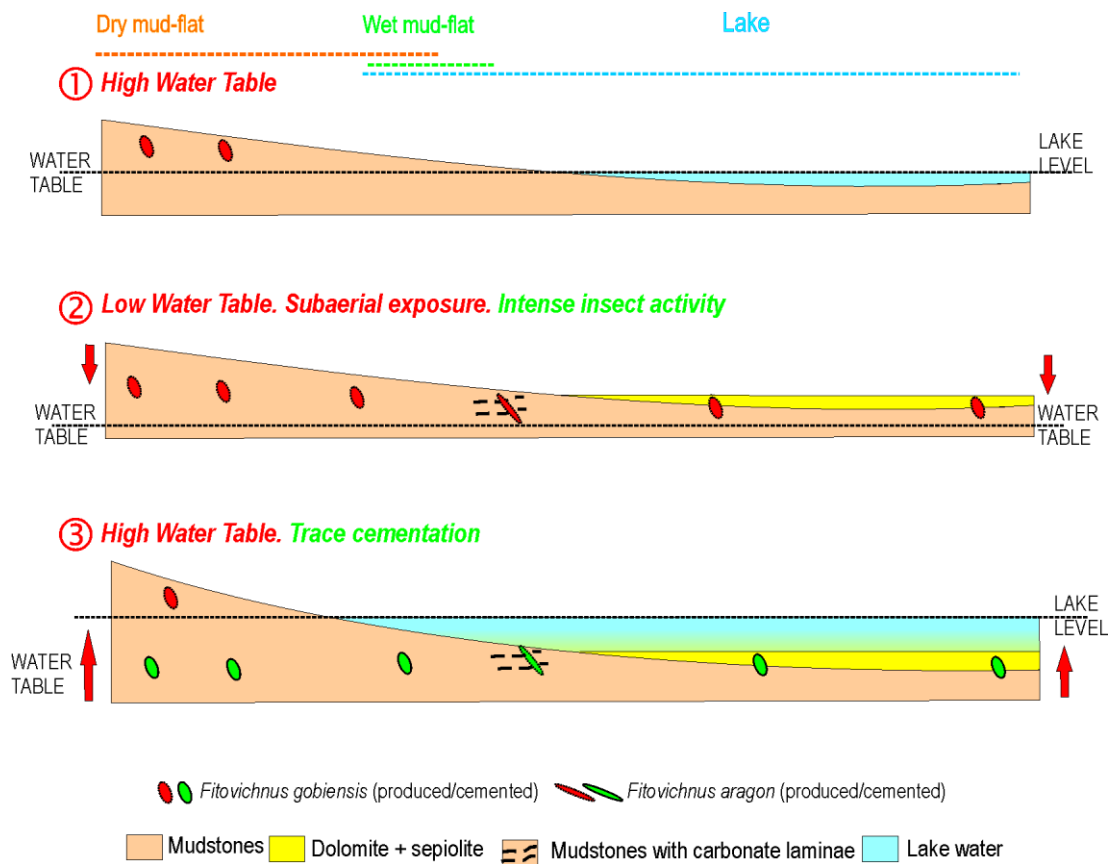


Figure 9

### Highlights

We analyze insect trace fossils of the continental mudflat of Calatayud-Daroca Basin

There are two ichnospecies: *Fictovichnus gobiensis* and *Fictovichnus aragon*, the later is new

There is a strong environmental and diagenetic control on insect traces preservation.

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