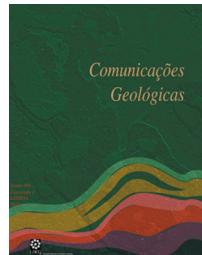


## The Ediacaran-Cambrian trace fossil record in the Central Iberian Zone, Iberian Peninsula

## O registo icnológico do Ediacariano-Câmbrico da Zona Centro-Ibérica, Península Ibérica

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**Abstract:** The record of late Ediacaran and lower Cambrian trace fossils in the Central Iberian Zone, Iberian Peninsula, is reviewed. The evolution in trace fossil morphologies is comparable to that documented worldwide, with domination of simple trace fossils such as *Gordia* and *Helminthoidichnites* in late Ediacaran rocks and the appearance of more complex trace fossil morphologies in Cambrian rocks, including *Treptichnus pedum*, *Rusophycus* and *Psammichnites*. There are possible latest Ediacaran treptichnids (but not *Treptichnus pedum*), although the precise placement of the Ediacaran-Cambrian boundary in the Central Iberian Zone on the basis of trace fossils is complicated by a general upward-shallowing trend that may confound environmental and evolutionary signals.

**Keywords:** Spain, Portugal, trace fossils, Cambrian, Ediacaran

**Resumo:** O registo de icnofósseis do Ediacariano superior e do Câmbrico inferior da Zona Centro-Ibérica é revisto. A evolução dos padrões icnológicos é comparável com aquela documentada um pouco por todo o mundo, com o domínio de icnofósseis simples tais como *Gordia* e *Helminthoidichnites* nas rochas do Ediacariano superior e o aparecimento de formas mais complexas nas rochas câmbricas, incluindo *Treptichnus pedum*, *Rusophycus* e *Psammichnites*. Existem possivelmente treptichnídeos ediacarianos (mas não *Treptichnus pedum*), embora o posicionamento preciso do limite Ediacariano-Câmbrico na Zona Centro-Ibérica, tendo como base os icnofósseis, é complicada pela tendência para a prevalência de fácies marinhas progressivamente menos profundas para o topo da sequência, o que poderá sobrepor sinais ambientais àqueles de significado evolutivo.

**Palavras-chave:** Espanha, Portugal, icnofósseis, Câmbrico, Ediacariano

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Buatois and Mángano, 2011). In successions dominated by siliciclastic rocks these ichnozones are important for identifying the Terreneuvian Series. In the area of the basal Cambrian GSSP, Burin Peninsula, Newfoundland, the *T. pedum* Ichnozone defines the base of the Cambrian, succeeding a late Ediacaran *Harlaniella podolica* Ichnozone (Narbonne *et al.*, 1987). The *H. podolica* Ichnozone contains simple horizontal trace fossils in addition to *Harlaniella* and *Palaeopascichnus*, enigmatic forms that probably are body fossils (Jensen, 2003; Ivantsov, 2013). Additional late Ediacaran trace fossil-based subdivision has been proposed, in particular with the latest Ediacaran appearance of treptichnids (but not *Treptichnus pedum*) (Jensen, 2003; Buatois and Mángano, 2011).

Trace fossils are of great importance for the biostratigraphy of the largely siliciclastic Ediacaran and basal Cambrian successions of the Iberian Peninsula (*e.g.* Liñán *et al.*, 1984). Three Iberian ichnozones spanning the Ediacaran-Cambrian transition have been proposed; in ascending order the *Torrowangea rosei*, *Treptichnus pedum*-*Monomorphichnus* and *Rusophycus avalonensis* ichnozones (Gámez Vintaned and Liñán, 1996, 2007; see also Fernández Remolar *et al.*, 2005). In its definition this zonation shows clear similarities with that developed globally. The most complete fossiliferous Ediacaran-Cambrian successions within the Iberian Peninsula are located in the Central Iberian Zone (CIZ) (*e.g.* Vidal *et al.*, 1994a, b). The purpose of this paper is a review, with no pretence of being comprehensive, of the late Ediacaran and basal Cambrian trace fossil record in the CIZ, and to discuss peculiarities and problems in the interpretation of this record. Some new trace fossil material is presented, in particular from the Río Alagón locality, which is included in the excursions of the ICHNIA 2016 – 4<sup>th</sup> International Congress on Ichnology.

### 2. The Central Iberian Zone

The CIZ, one of the tectonostratigraphic zones into which the Iberian Peninsula is divided, covers much of south-central Iberian Peninsula in a northwest-southeast stretching band (Fig. 1). It is bounded to the south by the Ossa Morena Zone; these two zones probably were genetically related during the Ediacaran-Cambrian transition, with the Ossa Morena Zone representing arcs and the Central Iberian Zone back-arc setting along the Gondwana margin (*e.g.* Eguíluz *et al.*, 2015). The southern part of the CIZ, with low levels of metamorphism, is characterized by a thick (>5 km) Ediacaran succession of mudrock, sandstone (generally greywacke) and conglomerate (generally with a muddy matrix), and by the Ordovician (Floian) up to 400 m thick quartz-arenite dominated

### 1. Introduction

The ecological and evolutionary radiation of bilaterian animals across the late Ediacaran to early Cambrian transition is strikingly demonstrated by the increase in size, diversity and complexity of trace fossils, and a moderate increase in the depth and intensity of sediment mixing (*e.g.* Buatois and Mángano, 2011; Carbone and Narbonne, 2014; Tarhan *et al.*, 2015). Although there remain some uncertainties in the exact timing and synchronicity of these events this has enabled the recognition of ichnozones, with the appearances of complex three-dimensional burrows and bilobed arthropod-type trace fossils characterizing respectively the *Treptichnus pedum* and *Rusophycus avalonensis* ichnozones (*e.g.* Narbonne *et al.*, 1987;

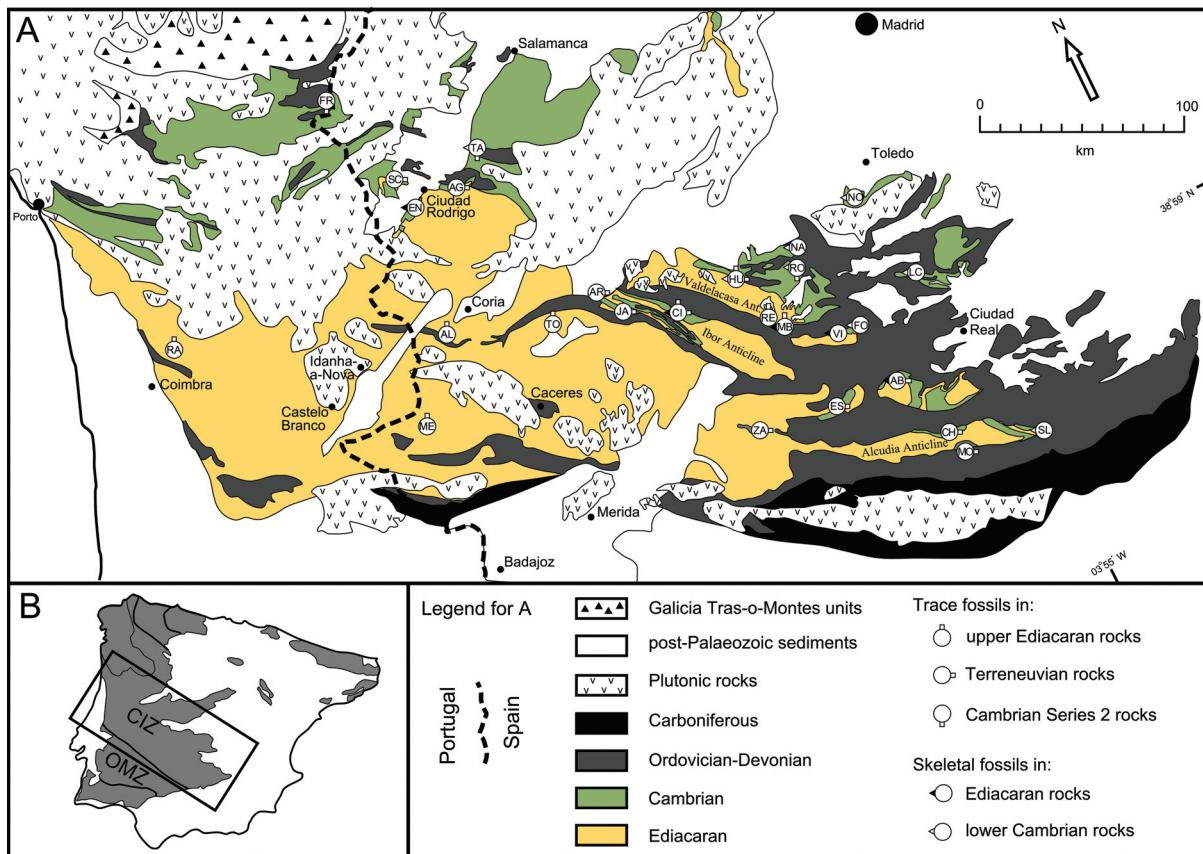


Fig. 1. Geological map of the southern part of the Central Iberian Zone (modified from Rodriguez-Fernández, 2004) with principal localities with late Ediacaran and early Cambrian trace fossils and metazoan fossils. Taxa identifications are those published, unless otherwise indicated. AB – Abenojar Anticline, *Cloudina* in lower carbonates, Zhuravlev et al. (2012), and trace fossils in higher siliciclastic units, *Planolites-Palaephycus*, possible *Belorhaphe* and *Phycodes*, García-Hidalgo (1993b). AG – Río Agadón, west of Monsagro, *Psammichnites* isp, not figured, Rodríguez Alonso et al. (1995). AL – Río Alagón, south of Coria, trace fossils described by Liñán and Palacios (1987), and this paper. AR – Arrocampo-Almaraz Dam, trace fossils including treptichnids and *Treptichnus pedum*, García-Hidalgo (1993a), Fernández Remolar et al. (2005), this paper. CH – Cabezarribias-Hinojosa, trace fossils include *Monomorphichnus* and *Bergaueria*, García-Hidalgo (1993b), Pierren Pidal (2000), Fernández Remolar et al. (2005). CI – Área de Castañar de Ibor, *Cloudina* and simple trace fossils in lower and middle part of the Ibor Group, Cambrian-type trace fossils in an overlying siliciclastic series, García-Hidalgo (1985), Vidal et al. (1994b), Fernández Remolar et al. (2005). EN – Carbonates west of La Encina with probable *Cloudina*, Vidal et al. (1994b), Rodríguez Alonso et al. (1995). ES – Río Esteras area, *Planolites* and *Taphrhelminthopsis* in Unit AE1, Pierren Pidal (2000, p. 169). FO – Fontanarejo, sponge fossils in the Pusa Formation, Reitner et al. (2012). FR – Freixo de Espada à Cinta area, *Rosellia cf. socialis* and *Teichichnus* in the Desejosa Formation, Dias da Silva et al. (2014). HU – Sections along Río Huso and abandoned railway in the area of La Nava de Ricomalillo, with late Ediacaran and Cambrian shelly fossils and carbonaceous compressions, late Ediacaran and Cambrian trace fossils, Brasier et al. (1979), Palacios (1989), Vidal et al. (1994a, b), Martí Mus et al. (2008), Jensen et al. (2007). JA – East of Jaraicejo, trace fossil including *Phycodes pedum* and *Monomorphichnus*, Monteserín López and Pérez Rojas (1987). LC – Área de Los Cortijos, with late early Cambrian trilobites, e.g. Gil Cid et al. (2011). MB – Membrillar olistostrome with *Cloudina*, and simple trace fossils in Cijara Formation, Cortijo et al. (2010). ME – Possible trace fossil near Membriño, Vidal et al. (1994a). MO – Río Montoro area, *Taphrhelminthopsis circularis*, Pierren Pidal (2000), Fernández Remolar et al. (2005). NA – Área de Navalucillos, trilobites and archaeocyathia of upper part of Cambrian Stage 3, e.g. Gil Cid et al. (2011), Menéndez (2014). NO – Área de Noez, with late early Cambrian trilobites, e.g. Gil Cid et al. (2011). RA – Raiva section, *Phycodes*? n. isp., and *Planolites*, Medina et al. (1998). RE – Área de Río Esterilla with simple trace fossils and treptichnids in the Cijara Formation, Jensen et al. (2007), this paper. RO – Área de Robledo del Buey-Los Alares-Gevora, with trace fossils, including *Psammichnites gigas*, *Dactyloïdites*, trilobites and small shelly fossils, Moreno et al. (1976), Jensen et al. (2010). SC – Área de Saelices el Chico, *Planolites*, *Phycodes*?, and cf. *Torrowangea* reported but not figured by Martín Herrero et al. (1990). Rodríguez Alonso (1986, Fig. 3) figures trace fossils from nearby Río Azaba that need closer examination for identification. SL – San Lorenzo de Calatrava, small shelly fossils (*Anabarella*), Vidal et al. (1999). TA – Tamames Sandstone Formation, south of Tamames, trace fossils including *Rusophycus* and *Astropolichnus*, and trilobites, e.g. Díez Balda (1986), Rodríguez Alonso et al. (1995), Liñán et al. (2015). TO – North of Torrejon el Rubio, *Torrowangea* aff. *rosei*, Liñán and Palacios (1987). VI – Villarta de los Montes, *Cloudina* and *Sinotubulites*, Cortijo et al. (2010; 2015).

Fig. 1. Mapa geológico do borgo meridional da Zona Centro-Ibérica (modificado de Rodriguez-Fernández, 2004) com a localização dos principais sectores com icnofósseis e fósseis de metazoários do Ediacariano superior e Câmbriano inferior. Identificação dos taxa em acordo com a bibliografia, a não ser que seja indicado outro modo. AB – Anticlinial de Abenojar, *Cloudina* nos carbonatos inferiores, Zhuravlev et al. (2012), e icnofósseis nas unidades silicicísticas mais altas, *Planolites-Palaephycus*, possivelmente *Belorhaphe* e *Phycodes*, García-Hidalgo (1993b). AG – Río Agadón, a oeste de Monsagro, *Psammichnites* isp, não figurado, Rodríguez Alonso et al. (1995). AL – Río Alagón, a sul de Coria, icnofósseis descritos por Liñán & Palacios (1987), e este artigo. AR – Barragem de Arrocampo-Almaraz, icnofósseis incluindo treptichnides e *Treptichnus pedum*, García-Hidalgo (1993a), Fernández Remolar et al. (2005), este artigo. CH – Cabezarribias-Hinojosa, icnofósseis incluindo *Monomorphichnus* e *Bergaueria*, García-Hidalgo (1993b), Pierren Pidal (2000), Fernández Remolar et al. (2005). CI – Castañar de Ibor, *Cloudina* e icnofósseis simples na parte inferior e média do Grupo Ibor Group, icnofósseis indicadores do Câmbriano nas séries silicicísticas suprajacentes, García-Hidalgo (1985), Vidal et al. (1994b), Fernández Remolar et al. (2005). EN – Carbonatos a ocidente de La Encina com *Cloudina* provável, Vidal et al. (1994b), Rodríguez Alonso et al. (1995). ES – sector de Río Esteras, *Planolites* e *Taphrhelminthopsis* na Unidade AE1, Pierren Pidal (2000, p. 169). FO – Fontanarejo, esponjas fósseis na Formação Pusa, Reitner et al. (2012). FR – sector de Freixo de Espada à Cinta, *Rosellia cf. socialis* e *Teichichnus* na Formação do Desejosa, Dias da Silva et al. (2014). HU – Secções ao longo do Río Huso e na linha de caminho-de-ferro abandonada na área de La Nava de Ricomalillo, Ediacariano superior e fósseis de concha do Câmbriano e compressões carbonáceas, icnofósseis do Ediacariano superior e Câmbriano, Brasier et al. (1979), Palacios (1989), Vidal et al. (1994a, b), Martí Mus et al. (2008), Jensen et al. (2007). JA – Leste de Jaraicejo, icnofósseis incluindo *Phycodes pedum* e *Monomorphichnus*, Monteserín López e Pérez Rojas (1987). LC – sector Los Cortijos, com trilobites do Câmbriano inferior tardio, e.g., Gil Cid et al. (2011). MB – Olistostrome de Membrillar com *Cloudina* e icnofósseis simples na Formação Cijara, Cortijo et al. (2010). ME – Possível icnofóssil perto de Membriño, Vidal et al. (1994a). MO – sector de Río Montoro, *Taphrhelminthopsis circularis*, Pierren Pidal (2000), Fernández Remolar et al. (2005). NA – Área de Navalucillos, trilobites e Archaeocyatha da parte superior do Câmbriano Andar 3, e.g. Gil Cid et al. (2011), Menéndez (2014). NO – sector de Noez, com trilobites do Câmbriano inferior tardio, Gil Cid et al. (2011). RA – secção de Raiva, *Phycodes*? n. isp., e *Planolites*, Medina et al. (1998). RE – sector Rio Esterilla com icnofósseis simples e treptichnides na Formação Cijara; Jensen et al. (2007), este trabalho. RO – sector de Robledo del Buey-Los Alares-Gevora, com icnofósseis, incluindo *Psammichnites gigas*, *Dactyloïdites*, trilobites e pequenos fósseis de concha, Moreno et al. (1976), Jensen et al. (2010). SC – sector de Saelices el Chico, *Planolites*, *Phycodes*?, e cf. *Torrowangea* reportados mas não figurados por Martín Herrero et al. (1990). Rodriguez Alonso (1986, Fig. 3) figura icnofósseis encontrados perto do rio Azaba que necessitam de um exame mais detalhado para identificação. SL – San Lorenzo de Calatrava, pequenos fósseis de concha (*Anabarella*), Vidal et al. (1999). TA – Formação Arenítica de Tamames Sandstone, a sul de Tamames, icnofósseis incluindo *Rusophycus* e *Astropolichnus*, assim como trilobites, e.g., Díez Balda (1986), Rodríguez Alonso et al. (1995). TO – Norte de Torrejon el Rubio, *Torrowangea* aff. *rosei*, Liñán and Palacios (1987). VI – Villarta de los Montes, *Cloudina* e *Sinotubulites*, Cortijo et al. (2010; 2015).

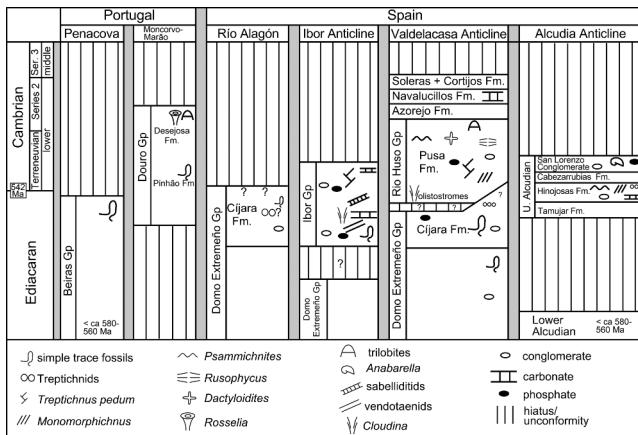


Fig. 2. Simplified tentative correlation of Ediacaran and lower Cambrian stratigraphy in selected regions of the Central Iberian Zone. The occurrences of selected biostratigraphically significant trace fossils and body fossils are shown.

Fig. 2. Tentativa de correlação simplificada da estratigrafia do Ediacarano e Câmbriico inferior em regiões selecionadas da Zona Centro-Ibérica. São mostradas as ocorrências de icnofósseis e somatofósseis, selecionadas pelo seu significado bioestratigráfico.

**Armorican Quartzite Formation.** The Armorican Quartzite, preserved in tight Variscan synclines, forms ranges that dominate the landscape. Separating the largely turbiditic Ediacaran rocks and the trace fossil-rich Armorican Quartzite are mainly fine-grained siliciclastic terminal Ediacaran and lower Cambrian shelf and basin deposits, and a locally *Skolithos*-rich shallow-water succession of poorly constrained but probable early Ordovician age. The number and duration of depositional breaks and unconformities in this succession have been debated, but it is generally agreed the more complete terminal Ediacaran-lower Cambrian successions are located towards the north, where carbonates with the terminal Ediacaran tubular fossil *Cloudina* provide an important reference level (Figs. 1, 2; Vidal *et al.*, 1994b; Cortijo *et al.*, 2015). Recently detrital zircon studies (*e.g.* Pereira *et al.*, 2012a, b; Talavera *et al.*, 2012, 2015) are contributing to additional age constraints on the Ediacaran-Cambrian succession in the CIZ.

### 3. Trace fossils in the Central Iberian Zone

In the following, selected types of trace fossils are briefly discussed.

#### 3.1 Unbranched simple essentially horizontal trace fossils

The most common trace fossils in late Ediacaran strata of the CIZ are simple horizontal meandering to irregularly winding trace fossils. Forms of this simple morphology can have a non-trace fossil origin (Jensen *et al.*, 2006, 2007; Cohen *et al.*, 2009). In the following discussion this highly problematic issue will not be further considered and it will be assumed that among the presented material at least some are genuine trace fossils.

Simple horizontal winding or looping trace fossils can typically be attributed to *Helminthoidichnites* or *Gordia*. Schlirf *et al.* (2001, p. 82) diagnosed *Helminthoidichnites* as “Relatively thin, horizontal, irregularly meandering winding trails with occasional loops”. In *Gordia* loops are prominent and the pattern of movement is more random (Hofmann, 1990). Transitions from one ichnogenus to another may be observed; in such cases the dominant form may take precedence in the naming, or it can be treated as a compound trace fossil, in which case different portions of a continuous trace receive a different name.

There are examples of both *Gordia* (Figs. 3A, 4A, 5A,B), and *Helminthoidichnites* (Fig. 3B) in the late Ediacaran Domo Extremeño

Group (Fig. 2). Rare specimens from the upper part of the Cijara Formation are developed as regular spiral loops (Fig. 4B). These are more regular than “pseudo-spirals” described from the Ingta Formation, Canada (Carbone and Narbonne, 2014), but similar trace fossils have been described from the basal Cambrian Khmelnitsky Formation, Ukraine, as *Planispiralichnus rarus* Menasova, 2003, (see Ivantsov *et al.*, 2015, pl. 7, Fig 4). Although the ichnogeneric assignment warrants consideration, the ichnospecies may prove to be applicable to this Cijara Formation material.

*Torrowangea rosei* are sinuous to randomly meandering cylindrical trace fossils with irregularly spaced transverse constrictions (Webby, 1970). In some material attributed to *Torrowangea* the constrictions apparently result from the adjoining of pods of sediment (*e.g.* Walter *et al.*, 1989), whereas in other material they appear to reflect peristalsis (Narbonne and Aitken, 1990). Although *Torrowangea rosei* has been reported from several latest Ediacaran and Cambrian units in Spain (*e.g.* Liñán and Palacios, 1987), the nature and origin of the transverse constrictions in this material generally is not obvious. In material regarded as possible *Torrowangea* from the upper part of the Cijara Formation, the irregular transverse constrictions may alternatively have originated from incomplete sediment fill of the trace fossil, or from postdepositional deformation (Figs. 3C, 6D). A further possibility is that irregular constrictions represent basal portions of vertical probes (compare Figs. 6C and Fig. 4E).

#### 3.2 Branching trace fossils including *Treptichnus pedum*

Trace fossils with repeated vertical or oblique probes are biostratigraphically important as they are common only in Cambrian strata. They may be preserved as series of pimples along bedding- or splitting-planes. In such cases the three-dimensional arrangement

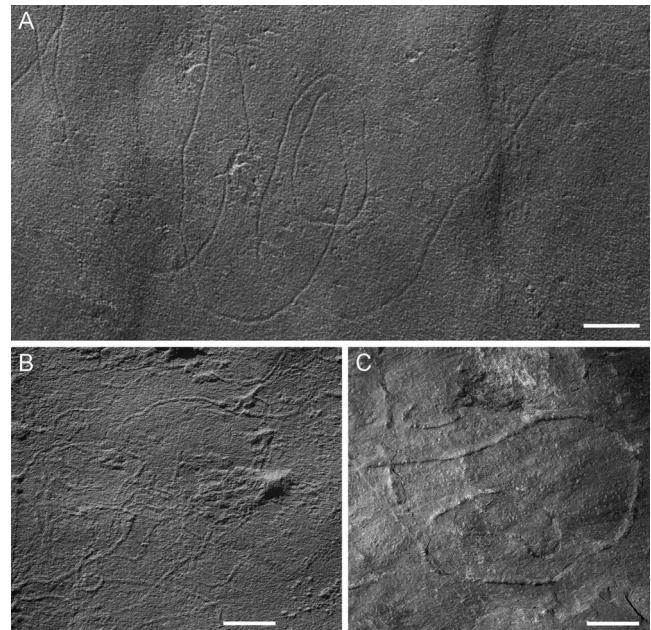


Fig. 3. Trace fossils from the upper part of the Domo Extremeño Group in the Río Huso section. A – *Gordia marina*, preservada em hiporrelevo negativo. UExP682Fe3:001. B – *Helminthoidichnites tenuis*, preservado como cristais a muro da camada. UExP682Fe2:001. C – Icnofóssil com constricções pouco desenvolvidas e irregularmente espaçadas, possivelmente *Torrowangea rosei*. Fotografia de campo. Escala gráfica de 20 mm.

Fig. 3. Icnofósseis da parte superior do Grupo Domo Extremeño na secção do Río Huso. A – *Gordia marina* preservada em hiporrelevo negativo. UExP682Fe3:001. B – *Helminthoidichnites tenuis* preservado como cristais a muro da camada. UExP682Fe2:001. C – Icnofóssil com constricções pouco desenvolvidas e irregularmente espaçadas, possivelmente *Torrowangea rosei*. Fotografia de campo. Escala gráfica de 20 mm.

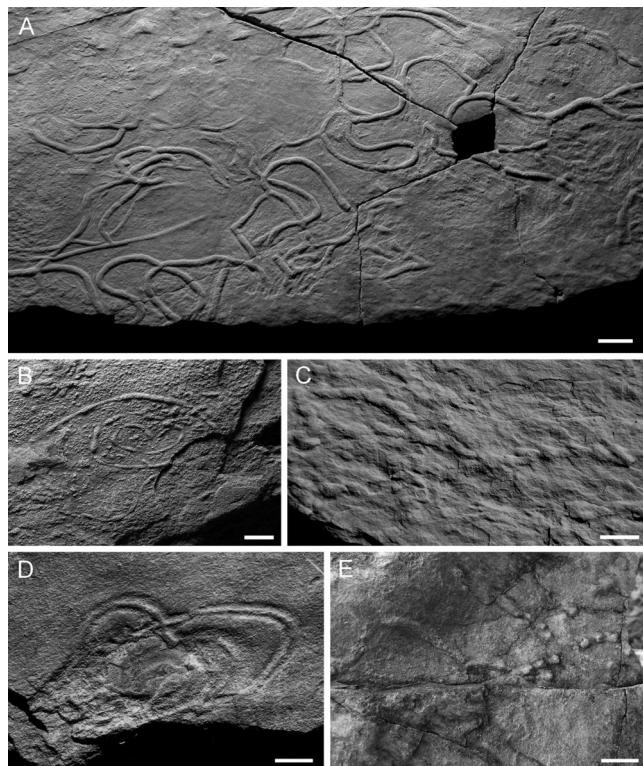


Fig. 4. Trace fossils from the Central Iberian Zone. A – *Gordia marina* from the Cijara Formation, Río Estenilla section. UExP708Es1:002. Scale bar is 10 mm. B – A spiral trace fossil from the Cijara Formation, Río Estenilla. This could be a portion of a *Gordia marina*, but alternative naming is possible (see text). UExP708Es1:001. Scale bar is 5 mm. C – *Treptichnus pedum* from the upper part of the Ibor Group (or AS 4 of García-Hidalgo, 1985). Arrocampo-Almaraz Dam. UExP652Ar1:001. Scale bar is 10 mm. D – Looping bilobed trace fossil preserved in negative epirelief. This is probably a *Psammichnites circularis*. “Upper Conglomeratic Series”, Río Esteras area. Image courtesy of Agustín Pieren Pidal. Scale bar is 10 mm. E – Field photograph of bed base with series of inclined probes grading into a band-like trace. This probably is a *Treptichnus pedum*. Sierra de la Zarzuela area. Scale bar is 20 mm.

Fig. 4. Icnofósseis da Zona Centro-Ibérica. A – *Gordia marina* da Formação Cijara, secção do Rio Estenilla. UExP708Es1:002. Escala gráfica de 10 mm. B – Icnofóssil espiralado da Formação de Cijara, Rio Estenilla. Esta poderia ser uma porção de *Gordia marina*, mas é possível dar uma designação alternativa (ver texto). UExP708Es1:001. Escala gráfica de 5 mm. C – *Treptichnus pedum* proveniente da parte superior do Grupo Ibor (ou AS 4 de García-Hidalgo 1985). UExP652Ar1:001. Escala gráfica de 10 mm. D – Icnofóssil bilobado desenvolvendo um “looping” em epirrelevo negativo. Será provavelmente um *Psammichnites circularis*. “Série Conglomerática Superior”, área do Rio Esteras. A imagem é cortesia de Agustín Pieren Pidal. Escala gráfica de 10 mm. E – Fotografia de campo de base de camada com séries de prospecções inclinadas dando origem a uma estrutura em forma de banda. Tal é provavelmente *Treptichnus pedum*. Sector de Sierra de la Zarzuela. Escala gráfica de 20 mm.

and interconnection of burrow segments is unknown although it can be generally assumed that there was some form of basal master burrow (Fig. 4E). Trace fossils of this type have been reported as *Hormosiroidea* from several basal Cambrian units in the CIZ, including the Hinojosas Formation of the Alcudia Anticline (García-Hidalgo, 1993a, b). *Treptichnus pedum* occurs in the upper part of the Ibor Group (Fig. 4C), and the lower, but not lowest, part of the Pusa Formation (e.g. Vidal *et al.*, 1994b; Gámez Vintaned and Liñán, 2007). Burrow systems possibly akin to *Treptichnus* and *Phycodes* also occur in the upper part of the Domo Extremeño Group. Some of these have been described from the CIZ as *Phycodes*? n. sp. (Liñán and Palacios, 1987). In the Cijara Formation series of individual probes have been found (Jensen *et al.*, 2007, Fig. 2b), or thin burrows arranged in a zigzag pattern (Jensen *et al.*, 2007, Fig. 2c, d). These may be examples of latest Ediacaran treptichnids

(*cf.* Jensen, 2003). Other discontinuous trace fossils from the Cijara Formation (Figs. 5C,D, 6B) may also be treptichnids but the preservation do not allow a confident assignment. Probably comparable trace fossils also occur deeper in the Domo Extremeño Group (Vidal *et al.*, 1994b, Fig. 17e, f).

### 3.3 Bilobed trace fossils including *Psammichnites*

These are often large trace fossils with a unilobed or bilobed lower part, an internal zone of sediment displacement, and an upwards-convex bilobed top part transected by a straight or sinusoidal furrow. An irregular circling motion often is present. Generally only some of these features are visible in a single specimen, and they probably were not all originally present in each specimen; the type material of *Psammichnites gigas* from the lower Cambrian of southern Sweden only clearly shows the zone of sediment displacement. Trace fossils of this type include *Plagiogmus arcuatus* and *Didymaulichnus miettensis*, and all or some of the Cambrian reports of “*Taphrhelminthopsis circularis*”. Large forms of this type of trace fossil first appear in the *Rusophycus avalonensis* Ichnozone, but smaller, and possibly related forms are found in older strata (see Jensen, 2003).

Spectacular material of *Psammichnites gigas* from the upper part of the Río Huso Group has been figured in several of Seilacher’s papers (e.g. Seilacher, 2007). Pieren Pidal (2000, 2009) reported the occurrences of relatively small trace fossils of this type, probably attributable to *Psammichnites circularis* (*Taphrhelminthopsis circularis* of Fernández Remolar *et al.*, 2005), from several localities in the southeastern part of the study area (Alcudia Anticline etc.). Circling trace fossils from units corresponding to the Hinojosas Formation in the Río Montoro area (MO in Fig. 1) (Pieren Pidal, 2000, Figs. 109, 110) are preserved in bilobed positive hyporelief (Pieren Pidal, personal communication 2016). Similar looping bilobed trace fossil about 5 mm wide preserved in negative epirelief occur in the Río Esteras region (ES in Fig. 1) (Fig. 4D; Pieren Pidal, 2000, Figs. 131, 132; Pieren Pidal, 2009, Fig. 4). Pieren Pidal’s (2000) lithostratigraphical correlation places the Montoro and Esteras occurrences at similar stratigraphical levels.

### 3.4 Arthropod-type trace fossils including *Rusophycus*

These are trace fossils with clear evidence for imprints of arthropod-type limbs. The earliest *Rusophycus* in the CIZ occurs in the Tamames Sandstone Formation (Díez Balda, 1986), and the upper part of the Pusa Formation (Jensen *et al.*, 2010), in both instances below the first regional records of trilobites. *Monomorphichnus* are sets of subequally spaced simple or paired ridges formed by the passive or active raking of the sediment and may have been also produced by arthropods, although caution is required as similar structures may have other origins. An early occurrence of *Monomorphichnus* in the CIZ comes from the lower part of the Pusa Formation (Brasier *et al.*, 1979). *Monomorphichnus* has also been reported from the Hinojosas Formation in the Alcudia Anticline (García-Hidalgo, 1993b; Fernández Remolar *et al.*, 2005). The temporal relationships between the Pusa and Hinojosas formations are not well understood (see below).

### 3.5 Other trace fossils

Other noteworthy trace fossils from the lower Cambrian of the CIZ are *Astropolichnus hispanicus*, a plug-shaped trace fossil with a restricted palaeogeographical range (Pillola *et al.*, 1995), and the star-shaped trace fossil *Dactyloidites*, known from the upper part of the Pusa Formation and the Tamames Sandstone Formation (Diez Balda, 1986; Jensen *et al.*, 2010).

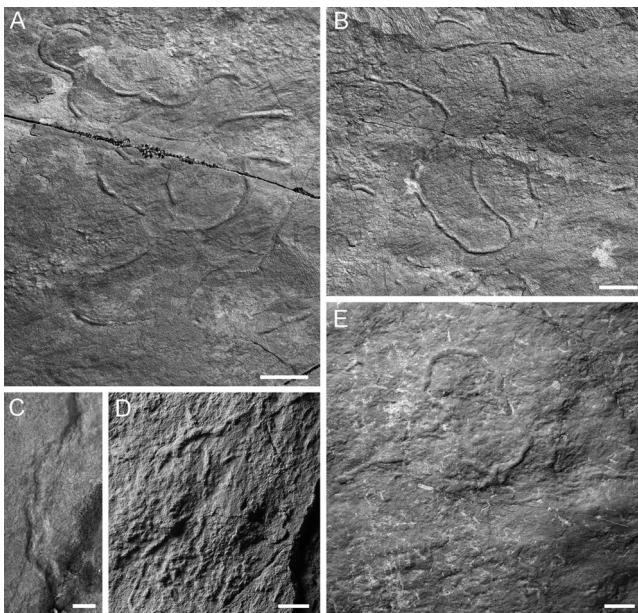


Fig. 5. Trace fossils from the Río Alagón section. A, B – Field photographs of *Gordia marina* from a lower bedding plane in the upper part of the succession. Scale bars in A and B are 10 mm. C, D – Trace fossils with incipient branching. This material is too poorly preserved for confident identification to ichnogenus but could be *Treptichnus*. C, field photograph, D, UEx621Al1:001. Scale bars in C and D are 5 mm. E – Field photograph of bed base with trace fossil with possible transverse constrictions. Irregular nature of bed base likely represent poorly preserved trace fossils. Scale bar is 10 mm.

Fig. 5. Icnofósseis da secção do Río Alagón. A, B – Fotografias de campo de *Gordia marina* a muro de camada da parte superior da sucessão. Escalas gráficas em A e B com 10 mm. C, D – Icnofósseis com ramificações incipientes. Este material está mal preservado para uma atribuição clara a um icnogénero, mas poderá ser *Treptichnus*. C, fotografia de campo, D, UEx621Al1:001. Escalas gráficas em C e D com 5 mm. E – Fotografia de campo de muro de camada com icnofóssil evidenciando constrições transversas. A natureza irregular do muro da camada possivelmente representa icnofósseis pouco preservados. Escala gráfica de 10 mm.

#### 4. Temporal distribution of trace fossils in the Central Iberian Zone

Despite extensive search trace fossils have not been confidently identified within the vast expanses of outcrop of the Domo Extremeño Group in the southern regions of the Central Iberian Zone. The only exception is a single occurrence of a possible simple trace fossil from the Membrio area (ME in Fig. 1; Vidal *et al.*, 1994a), although non-trace fossil interpretations of this form cannot be excluded. The most intensively studied sections with regards to the evolution of traces fossils in the CIZ are located along the northern flank of the Valdelacasa Anticline (Palacios, 1989; Vidal *et al.*, 1994a, b). Here the lower part of the succession comprises the Domo Extremeño Group, dominated by greywacke turbidites, mudrock and matrix-rich conglomerate. At the top of the Domo Extremeño Group is locally found a unit with thinner and cleaner sandstone beds (Member 2 of the Cijara Formation of Palacios, 1989). The overlying Río Huso Group is dominated by siltstone and mudstone. Phosphates are locally present as rinds and particularly in channel conglomerates have attracted economic exploitation. Overall, this represents a shallowing-upwards succession, a factor that has to be taken into consideration in interpreting the fossil record. Metazoan body fossils in the Río Huso Group include chancellorids and helcionellids in the middle part of the Pusa Formation and trilobites in the upper part (Jensen *et al.*, 2010). The Domo Extremeño Group yields simple unbranched trace fossils, but possible more complex forms have also been reported (Vidal *et al.*,

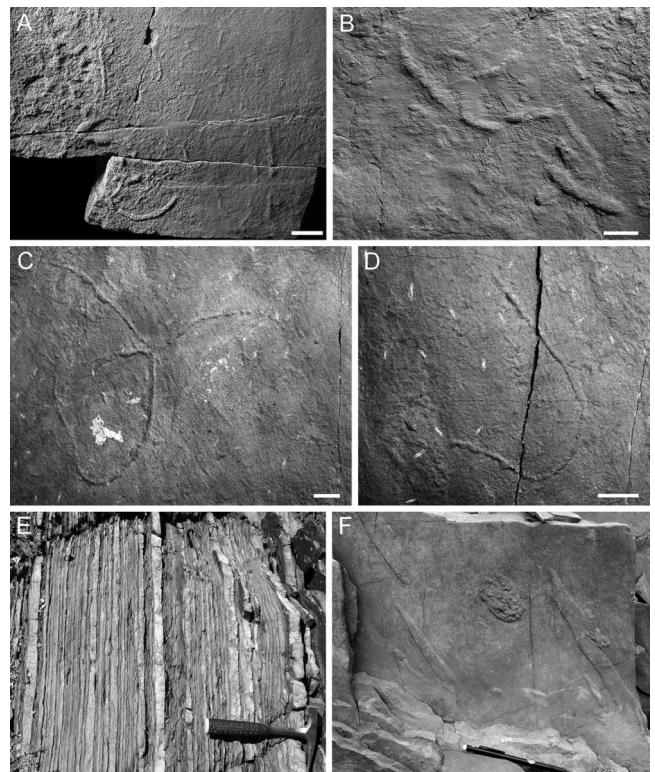


Fig. 6. Trace fossils and sedimentary structures from the Río Alagón section. A – Simple trace fossil on bed sole. Finest discernible traces are about 0.2 mm in diameter. UEx621Al1:002. Scale bar is 5 mm. B – Trace fossils on bed sole with possible change of level, either being short U-shaped traces or parts of a more complex burrow system. UEx621Al1:003. Scale bar is 5 mm. C – Field photograph of looping trace fossil. Towards the right the trace becomes discontinuous. Scale bar is 10 mm. D – Trace fossils with corrugations of uncertain origin, on same bedding plane as C. Scale bar is 10 mm. E – Alternation of sandstone and mudstone typical for the upper part of the section. Top is to the left. Hammer is 28 cm long. F – Bed sole with sedimentary structures that probably are sharp-pointed flute marks. Pencil is 14 cm.

Fig. 6. Icnofósseis e estruturas sedimentares da secção de Rio Alagon. A – Icnofósseis simples na base da camada. Os icnofósseis discerníveis mais finos medem cerca de 0.2 mm de diâmetro. UEx621Al1:002. Escala gráfica de 5 mm. B – Icnofósseis a muro com possível mudança de nível, podendo ser formas em U pouco desenvolvidas ou parte de um sistema de galerias mais complexo. UEx621Al1:003. Escala gráfica de 5 mm. C – Fotografia de campo de um icnofóssil desenvolvendo um “loop”. Para a direita a estrutura torna-se descontínua. Escala de 10 mm. D – Icnofósseis com enrugamentos de origem incerta, no mesmo plano de estratificação que em C. Escala de 10 mm. E – Alternâncias de arenitos e argilitos típicas da parte superior da secção. O topo é para a esquerda. Martelo com 28 cm de comprimento. F – Muro de camada com estruturas sedimentares que deverão ser “flute marks” de bordo afilado. Lápis com 14 cm.

1994b, Fig. 17e, f; Jensen *et al.*, 2007, Fig. 2c, d). The youngest detrital zircon ages from the Domo Extremeño Group (underlying the Cijara Formation) are 550 +/- 6 Ma (Talavera *et al.*, 2012). Although there are reports of Ediacara-type taxa in the Domo Extremeño Group, as *Nimbia occlusa* (Vidal *et al.*, 1994b, Fig. 15f) and *Tirasiana* (Liñán *et al.*, 2009, Fig. 1.9a), these relate to simple structures for which a range of alternative interpretations must be considered.

A section through the Pusa Formation along an abandoned railway south of La Nava de Ricomalillo, typically referred to as the Río Huso section (HU in Fig. 1), has figured as a reference section for the Ediacaran-Cambrian transition in the CIZ (Brasier *et al.*, 1979; Liñán *et al.*, 1984, 2006; Gámez Vintaned and Liñán, 2007). Trace fossils from this section have been listed, figured or briefly described by Brasier *et al.* (1979), Palacios (1989), Vidal *et al.* (1994a, b), Gámez Vintaned (1996) and Gámez Vintaned and Liñán (2007). Brasier *et al.* (1979) noted that this section yields

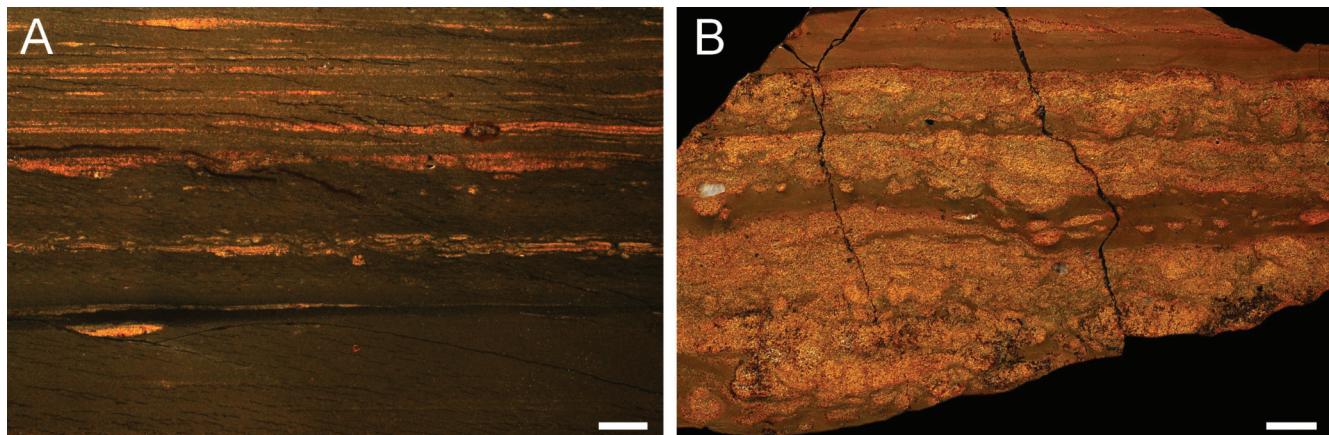


Fig. 7. Ichnofabric in vertically cut slabs from the Central Iberian Zone. A – Mudrock-dominated slab with thin siltstone lamina from the mid-part of the Pusa Formation, Río Huso section, a few meters above the proposed Ediacaran-Cambrian boundary level of some workers. Bioturbation is seen as minor disruption of siltstone lamina and small siltstone-filled burrows (ichnofabric index 2). Dark band is phosphate impregnation. UExP682Fe1:004. Scale bar is 5 mm. B – Sandstone-dominated slab from the Hinojosa Formation, east of Cabezarrubias. The disruption of the sandstone levels is prominent, but do not obliterate the beds (ichnofabric index 3). UExP836Ca1:001. Scale bar is 10 mm.

Fig. 7. Ichnofábrica em secções verticais provenientes da Zona Centro-Iberica. A – Nível onde predominam pelitos com finas laminações siltíticas da parte intermédia da Formação Pusa, poucos metros acima do limite Ediacarano-Câmbrico proposto por alguns autores na secção de Río Huso. A bioturbação corresponde a um distúrbio pouco significativo das laminações siltíticas e a pequenas escavações preenchidas por siltito (icnofábrica índice 2). O nível negro corresponde a uma impregnação de fosfatos. UExP682Fe1:004. Escala gráfica de 5 mm. B – Nível arenítico da Formação Hinojosa, a leste de Cabezarrubias. A perturbação dos níveis areníticos é notória, mas não oblitera a textura primária das camadas (icnofábrica índice 3). UExP836Ca1:001. Escala com 10 mm.

fossils of a mixed Ediacaran–Cambrian characteristics; Cambrian-type trace fossils such as *Treptichnus* and *Monomorphaichnus*, occurring with disc-shaped carbonaceous compressions similar to *Beltanelliformis*, a taxon not generally known from the Cambrian (see also Vidal *et al.*, 1994b, Jensen *et al.*, 2007). Although it has been suggested that an interval in this section can be readily correlated with the basal Cambrian GSSP (*e.g.* Liñán *et al.*, 2006), there remain some uncertainties. First, outcrop of the basal part of the Pusa Formation is of inferior quality for trace fossil identification to that in the proposed boundary section. Second, both *Monomorphaichnus* (Brasier *et al.*, 1979; but see Vidal *et al.*, 1994b, p. 745-746) and *Treptichnus* (Jensen *et al.*, 2007) have been reported from lower stratigraphical levels of the Pusa Formation in this area. It may also be noted that trace fossils in the lower part of the Pusa Formation are of small dimensions (Fig. 7A), possibly from low levels of sea-floor oxygenation in the dark, locally phosphate-rich, mudrock-dominated lower and middle parts of the Pusa Formation. The occurrence of the terminal Ediacaran index fossil *Cloudina* in carbonate olistoliths in the Fuentes olistostrome, at the base of the Río Huso Group, provides additional biostratigraphic age constraints on the succession. However, different interpretations have been advanced on the time of emplacement of the carbonate olistoliths from their source area in the Ibor Group. If essentially contemporaneous with carbonate deposition (*e.g.* Vidal *et al.*, 1994b), then the base of the Cambrian is restricted to the lower part of the Pusa Formation (*e.g.* Jensen *et al.*, 2007). On the other hand, if the olistoliths were incorporated at a later stage, related to sea-level drop, the base of the Cambrian could be placed at the base of the olistostromic unit (*e.g.* Fuenlabrada *et al.*, in press), or even in the Cijara Formation. Although the Río Huso section remains highly important its precise correlation with the basal Cambrian GSSP, and other regions in the CIZ, remains uncertain.

Ediacaran-Cambrian boundary successions can also be sought in the platform successions in the Ibor and Abenojar anticlines with *in situ* *Cloudina*-bearing carbonates, as well as higher carbonate levels, in the Abenojar Anticline with possible Cambrian small shelly fossils (Fernández Remolar *et al.*, 2005, pl. 2, Figs. 4-6). In the northwestern termination of the Ibor Anticline, along the Arrocampo-Almaraz dam (AR in Fig. 1), García-Hidalgo (1985,

1993a) described trace fossils in a siliciclastic interval between two carbonate levels. This interval yields *Treptichnus pedum* (Fig. 4C). Similarly, sections in the area of Sierra de la Zarzuela yield Cambrian-type trace fossils (Fig. 4E; Pieren Pidal, 2000) in siliciclastics enclosed by carbonate levels. These areas hold great promise for further characterization of the Ediacaran-Cambrian transition in the CIZ.

From the Alcudia Anticline trace fossils of probable Terrenuvian age have been reported from the Hinojosa Formation, including *Monomorphaichnus*, *Psammichnites circularis*, and treptichnids (as *Hormosiroidea cf. canadensis*) (García-Hidalgo, 1993b; Pieren Pidal, 2000, 2009; Fernández Remolar *et al.*, 2005). The extent of bioturbation can be prominent in this unit (Fig. 7B). From the overlying Cabezarrubias Formation have been reported *Planolites* and *Bergaueria aff. langi* (García-Hidalgo, 1993b; Fernández Remolar *et al.*, 2005). Trace fossils are not known from the Ediacaran part of the succession in the Alcudia Anticline, possibly because of a more significant depositional break in this area (Talavera *et al.*, 2015).

Little is known of Ediacaran and basal Cambrian trace fossils from Portugal. Medina *et al.* (1998) recorded *Phycodes?* n. sp and *Planolites* from the Beiras Group in the area of Penacova, and Pereira *et al.* (2012a, Fig. 1) added *Torrowangea rosei*. Pereira *et al.* (2012a) established a maximum depositional age for the Beiras Group from detrital zircons in this area to be 578-560 Ma, with a youngest detrital zircon of 549.6 +/- 4.4 Ma. Further north in Portugal *Planolites* has been reported, but not figured, from the Pinhão Formation, a unit poorly constrained but probably Cambrian in age (see Dias da Silva *et al.*, 2014, for discussion).

## 5. The Río Alagón section

The interest of the Río Alagón section is the possibility to examine a trace fossil-bearing succession of late Ediacaran- ?early Terrenuvian age exposed along the Alagón River (Río Alagón), some 30 km south of Coria (AL in Fig. 1). The section is accessed by a dirt-road that exits to the west off road CC-70, some 100 m south of Cachorrilla (exit at UTM (WGS 84) coordinates 699185, 4420679) (Fig. 8). This dirt-road terminates at a location suitable for parking with a pleasant view to the west of the Armorican

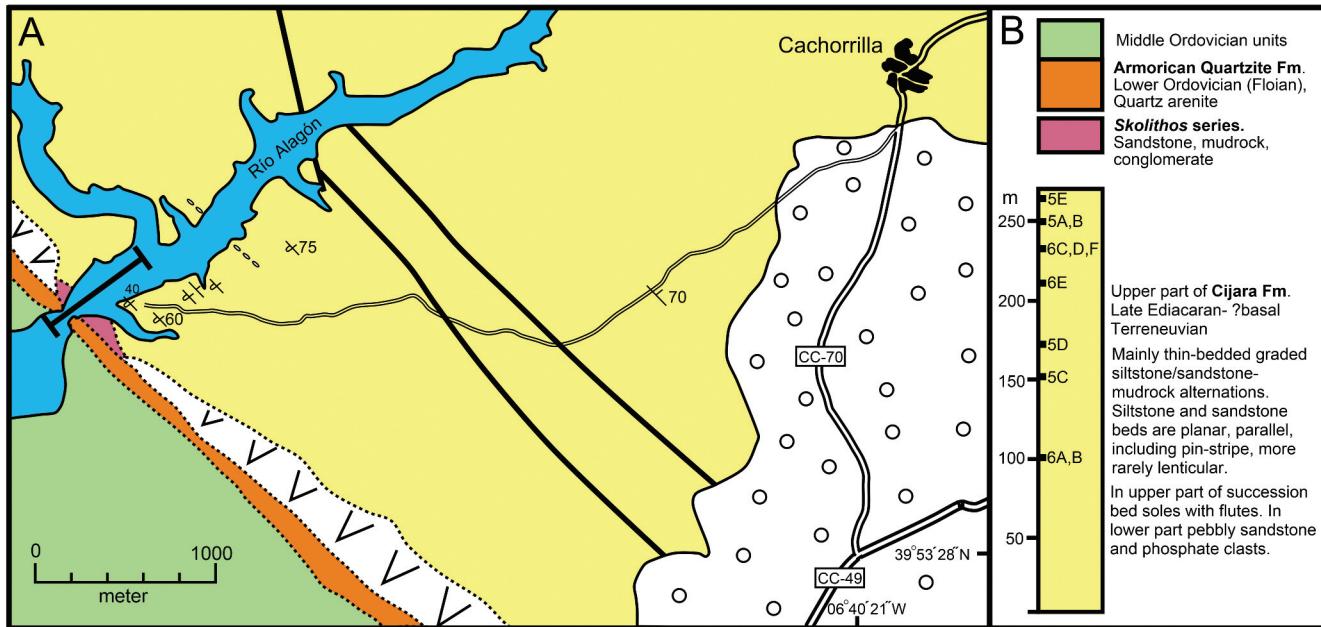


Fig. 8. A – Geological map of northern flank of Penha Garcia-Cañaveral Syncline, along Río Alagón, southwest of Coria. B – Simplified stratigraphic succession along double-barred line in A.

Fig. 8. A – Mapa geológico do flanco norte do Sinclinal de Penha Garcia-Cañaveral, no Río Alagón, a sudoeste de Coria. B – Sucessão estratigráfica simplificada no transepto A.

Quartzite Formation of the northern flank of the Penha Garcia-Cañaveral Syncline. By lithostratigraphical correlation Palacios (1989) attributed the alternations of thin-bedded sandstone and mudrock in the upper part of the succession to Member 2 of the Cíjara Formation. The contact to the Armorian Quartzite Formation is largely covered. Bascone Alvira *et al.* (1987) interpreted a coarse sandy unit at the contact with the Armorian Quartzite to be continuous with the underlying succession but, as suggested by Gil Toja and Pardo Alonso (1991), it more likely belongs to a series of conglomerates, sandstone and mudrock, with a wide distribution along the southern part of the CIZ, where it is known under a variety of names, and with dramatic differences in thickness. This series, which is better developed along the southern flank of the syncline, formed in fault-bounded basins, with both non-marine and shallow-marine sediments, locally with abundant *Skolithos* (e.g. McDougall *et al.*, 1987). The age of this *Skolithos* series has remained poorly known, often placed in a broad late Cambrian to early Ordovician span. Recently Sá *et al.* (2014) suggested this series to be as high as the uppermost Tremadocian to lower Floian.

Trace fossils from the Río Alagón section were described by Liñán and Palacios (1987), who identified *Torrowangea* aff. *rosei* and *Phycodes* ? n. sp. An ongoing study has revealed additional material, some of which is figured here (Figs. 5, 6). The Río Alagón section presents many of the problems typical for the interpretation of CIZ trace fossil associations.

- Trace fossil identification. A certain amount of cleavage limits the quality of observation in the fine-grained material but trace fossils can be reasonably studied on sandstone bed soles, in cases with sub-millimetre traces preserved (Fig. 6A). However, the moderate quality of preservation raises problems in the interpretation of the trace morphology, such as that of possible *Torrowangea* and treptichnids (see above).
- Depositional setting. The simplicity of the trace fossil association could reflect depositional environment rather than age of the strata. Although *Treptichnus pedum* appears to have had a relatively broad environmental distribution (Buatois *et al.*, 2013), lower Cambrian deep water trace fossil associations were

of low diversity (e.g. Buatois and Mángano, 2011). Bedding in the upper part of the Cíjara Formation has been interpreted as resulting from turbidity currents (Bascone Alvira *et al.*, 1987), and flutes on bed soles (Fig. 6F) are consistent, if not diagnostic, with this. However, the depositional setting of the Cíjara Formation is still poorly understood and could represent distal platform sediments.

- Age of the rocks. A late Ediacaran age for the upper part of the Cíjara Formation is suggested by the simple morphology of the trace fossils and the absence of typical Cambrian trace fossils, although possible *Treptichnus*-type trace fossils (Fig. 5C,D) raises questions, in particular when taking into consideration the above discussed preservational and environmental factors. Besides trace fossils the only fossils found in this succession are organic-walled microfossils of likely bacterial origin (Liñán and Palacios, 1987; Palacios, 1989). This includes *Palaeogomphosphaeridium cauriensis*, also described from the Cíjara Formation elsewhere in the CIZ, although probably of limited biostratigraphical value.

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