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Trace fossils from the Desejosa Formation (Schist and Greywacke Complex, Douro Group, NE Portugal): new Cambrian age constraints

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ABSTRACT

Trace fossils from a new locality in the Desejosa Formation, Freixo de Espada à Cinta area, northeast Portugal, are described, including *Teichichnus rectus* and the first Cambrian record from Iberia of the ichnogenus *Rosselia*, identified as *R.* cf. *socialis*. A literary review of the Cambrian record of *Rosselia* reveals no occurrences older than Cambrian Age 3. The occurrence of *Rosselia* in the Desejosa Formation therefore adds evidence to that of earlier reports on trilobite remains from the upper part of the Desejosa Formation for a Cambrian age of this unit. Both *Rosselia* and *Teichichnus* are zindicative of the *Cruziana* ichnofacies, which is representative of a shallow-marine depositional environment, consistent with earlier interpretations for the depositional conditions of the upper part of the Desejosa Formation in this sector, and in the equivalent Cambrian units in Spain.

KEYWORDS Trace fossils. *Rosselia socialis. Teichichnus rectus.* Early Cambrian. Iberian Massif. Douro Group.

INTRODUCTION

Previous stratigraphic and paleontological studies (trace and body fossils) on the Spanish pre-Ordovician record of the Central Iberian Zone (CIZ) demonstrate that the age of the sequence is latest Ediacaran (Vidal *et al.*, 1994a, b; Cortijo *et al.*, 2010) to early Cambrian (*e.g.* Brasier *et al.*, 1979; Díez Balda, 1986; San José *et al.*, 1990; Gozalo *et al.*, 2003; Díez Balda *et al.*, 2004; Rodríguez Alonso *et al.*, 2004; Jensen *et al.*, 2010).

In Portugal, the pre-Ordovician stratigraphic units of the CIZ are grouped in the Schist and Graywacke Complex (Complexo Xisto-Grauváquico in Portuguese; Carrington da Costa, 1950; Teixeira, 1955) which has been classically divided into the Beiras and Douro groups (Sousa, 1982, 1984). The precise stratigraphic relationship between these two groups remains uncertain but recent studies suggest that at least portions of these units are time equivalent and they are late Ediacaran and Cambrian (*e.g.* Pereira *et al.*, 2006; Pereira *et al.*, 2012b). In the Caramulo-Buçaco region (Portugal) a succession attributed to the Beiras Group contains trace fossils identified as *Planolites* sp. and *Phycodes*? n. sp (Gámez Vintaned, personal communication in Medina *et al.*, 1998). The *Phycodes*-like morphology suggests an age younger than ca. 550Ma (*cf.* Jensen, 2003), consistent with the maximum depositional age of 549.6 ± 4.4Ma (U-Pb in detrital zircons; Pereira *et al.*, 2012b) from approximately the same stratigraphic interval. From the base, the Douro Group consists of the Bateiras, Ervedosa, Rio Pinhão, Pinhão, Desejosa and São Domingos formations. Sousa (1984) cited *Planolites* from the Pinhão Formation and suggested an age of less than 560Ma approximately. A younger age for the whole succession (<550Ma) can be expected if we adopt the correlation proposed by Sousa (1983b, 1984) of the carbonate-bearing Bateiras Formation with the *Cloudina*-rich units (Vidal *et al.*, 1994a) in the Salamanca province (Spain). Trace fossils have been reported as locally common in the Desejosa Formation (*e.g.* Coke, 2000; Coke *et al.*, 2000) though without published detail to date. At present time, evidence for a Cambrian (or younger) age for the upper part of the Desejosa Formation is based on poorly preserved indeterminable trilobites (Rebelo and Romano, 1986), and its geochemical profile is also consistent with Cambrian age (Dias da Silva *et al.*, 2011; Dias da Silva, 2014).

The first detailed documentation of trace fossils from the Desejosa Formation is here presented on the basis of material collected from a new trace fossil locality (Dias da Silva, 2014). These include *Teichichnus rectus* and some of the best preserved Cambrian material of *Rosselia* to date, providing important new age constraints on the Desejosa Formation, and also giving valuable information about the depositional setting of the Desejosa Formation. The regional stratigraphic implications of these new data are also discussed in the CIZ context.

GEOLOGICAL SETTING

The Iberian branch of the European Variscan Massif has been traditionally divided into several geological zones (Lotze, 1945; Julivert *et al.*, 1972). On historical grounds these divisions were based mainly on stratigraphic features, but tectonic, magmatic and metamorphic characteristics were also considered. The CIZ, in its current definition (Julivert *et al.*, 1972), is the most extensive zone in the Iberian Massif (Fig. 1).

It has been subdivided in several domains in Spain (Pérez-Estaún *et al.*, 2004) and Portugal (Dias *et al.*, 2006). One of its most outstanding stratigraphic features is the presence of a thick (>5km) and widespread basal metasedimentary unit known as the Schist and Greywacke Complex. It generally displays a (very) low metamorphic grade and little deformation, which allows the identification of the original lithologies and primary sedimentary structures thus suggesting a turbiditic nature for much of this sequence. The scarcity of lithological marker beds and fossil content has resulted in a poorly constrained age and an uncertain regional correlation. Several regional lithostratigraphic units have been established being recognized a general upward-shallowing environment from basinal and slope to platform deposits (*e.g.* Díez Balda, 1986; San José *et al.*, 1990; Vidal *et al.*, 1994a, b; Valladares *et al.*, 2002). The age of the oldest part of the Schist and Graywacke Complex remains poorly known, nevertheless the earlier suggestions of a "Riphean" age (>650Ma) were based on microfossils without age significance, and the entire succession is now thought to be Ediacaran and younger (*e.g.* Pereira *et al.*, 2012a,b).

The studied region is located next to the Douro River canyon which is the north-eastern border between Spain and Portugal for more than 100km, providing an impressive natural cross-section of the northern CIZ. Recent geological survey in this area has resulted in new stratigraphic and ichnologic data (Fig. 2; Dias da Silva, 2014). In the northern and central part of the canyon, sedimentary features of the older rocks are largely obliterated due to pervasive Variscan deformation which resulted in a high-temperature and low-pressure metamorphism (Escuder Viruete *et al.*, 1994, 2000; Dias da Silva, 2014). The southern sector, near Freixo de Espada à Cinta (Portugal), shows more favourable conditions with well-preserved sedimentary structures and trace fossils. The geological structure of this area is mainly composed of cartographic-scale upright folds belonging to the late Variscan regional event (Fig. 2). The Desejosa Formation is extensively exposed in the region and has been affected by only very low metamorphism and gentle deformation during the Variscan Orogeny, which has made it possible to build up a synthetic stratigraphic column of the infra-Ordovician rocks, unveil the tectonic structure, and position the trace fossils described here inside the sedimentary sequence (Fig. 2). The Desejosa Formation was first described by Sousa (1982, 1983b). It typically consists of millimetre- to centimetre-scale alternations of generally parallel-laminated lutites and fine-grained sandstone, resulting in a striped appearance. The most common sedimentary structures are graded bedding and load-structures. More rarely there are greywacke beds up to half a metre thickness. In the study area, the Desejosa Formation consists of a terrigenous sequence more than 300m thick, which displays thin beds of black slates and sandstones, the latter frequently showing

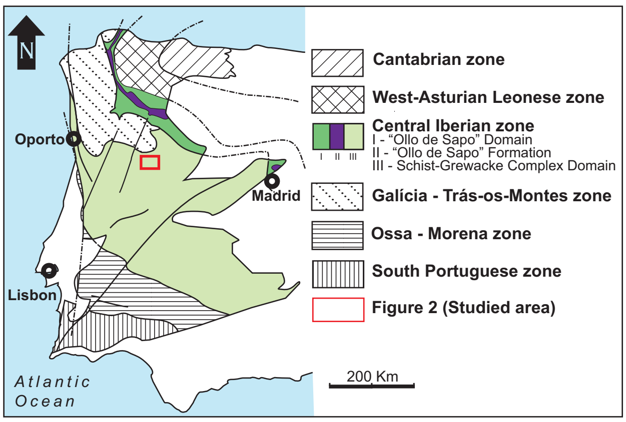

FIGURE 1. Location of the studied area in the Iberian Massif (adapted from Pérez-Estaún *et al.*, 2004).

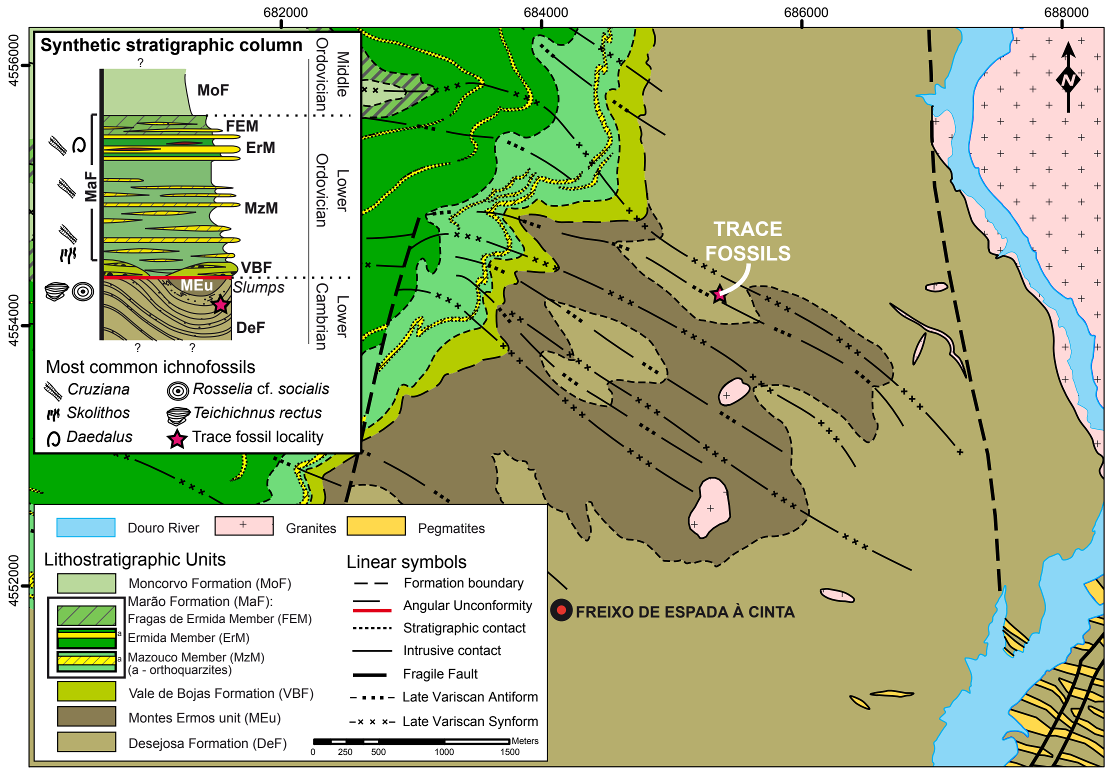

FIGURE 2. Schematic geological map of the eastern border of the Moncorvo Synform, near Freixo de Espada à Cinta (northeast Portugal) with the location of the studied trace fossils (star). In the top-left corner inset of the local synthetic stratigraphic column is displayed with the stratigraphic position of the site. Coordinate tags each 2000m (UTM-ED1950, 29N). Modified from Dias da Silva (2013) and form the 1:50.000 geologic map Nº 422 (Aldeadávila de la Ribera, Escuder Viruete *et al.*, 2000) of the Spanish National Geological Survey (IGME).

bioturbation and sedimentary structures. Some scarce and thin discontinuous beds of calc-silicate rocks and carbonates are referred in Ferreira da Silva and Ribeiro (1994). The uppermost beds (40m) present slump structures (Fig. 2, synthetic column), broken beds and microconglomeratic levels. The trace fossils described here were recently identified in the Freixo de Espada à Cinta area (Fig. 2) in a location that could be estimated at about 100m below the top of Desejosa Formation. The intensive bioturbation suggests a shallow depositional environment as was proposed for the upper part of the Douro group by Sousa (1982).

Concordantly overlying the Desejosa Formation, a new informal unit has been defined and mapped. It was first named Mazouco Formation (Dias da Silva *et al.*, 2011) after a small village which however is located out of the exposure. For this reason we propose to change the name to Montes Ermos unit, after a small hill located well inside the exposure of this lithostratigraphic unit (Dias da Silva, 2014). The Montes Ermos unit, with a thickness greater than 150m, is roofed by the Ordovician basal unconformity. It occupies the nucleus of a late Variscan first order synform also folding the Ordovician and Silurian age units (Moncorvo Synform, Fig. 2). In a small area (around Montes Ermos hill) it contains small cordierite blasts related to Variscan granitic stocks. This unit is made up of a monotonous sequence of grey fine-grained sandstone and siltstone beds ranging from 60 to 120cm. The boundaries between beds are marked by dark millimetre-thick layers displaying iron oxide when weathered. No fossils have been found in this unit.

The above described are the only lithostratigraphic units of the Schist and Graywacke Complex in the eastern portion of the Moncorvo Synform. The São Domingos, Pinhão and Rio Pinhão Formations as defined by Sousa (1984) were not identified here. The upper limit of the Douro Group is the regional angular unconformity known as Toledanic (*e.g.* Gutiérrez Marco *et al.*, 1990), underlying the Lower Ordovician stratigraphic units of the Vale de Bojas and Marão Formations (Sá *et al.*, 2005; Dias da Silva, 2014).

DESEJOSA FORMATION TRACE FOSSILS

A new ichnofossil locality in the Desejosa Formation was found about 3.5km NE of Freixo de Espada à Cinta village (Fig. 2). The trace fossils are observed on weathered bedding-planes (Figs. 3A; 5D-E) on both sides of a small valley with a moderately good geological exposure.

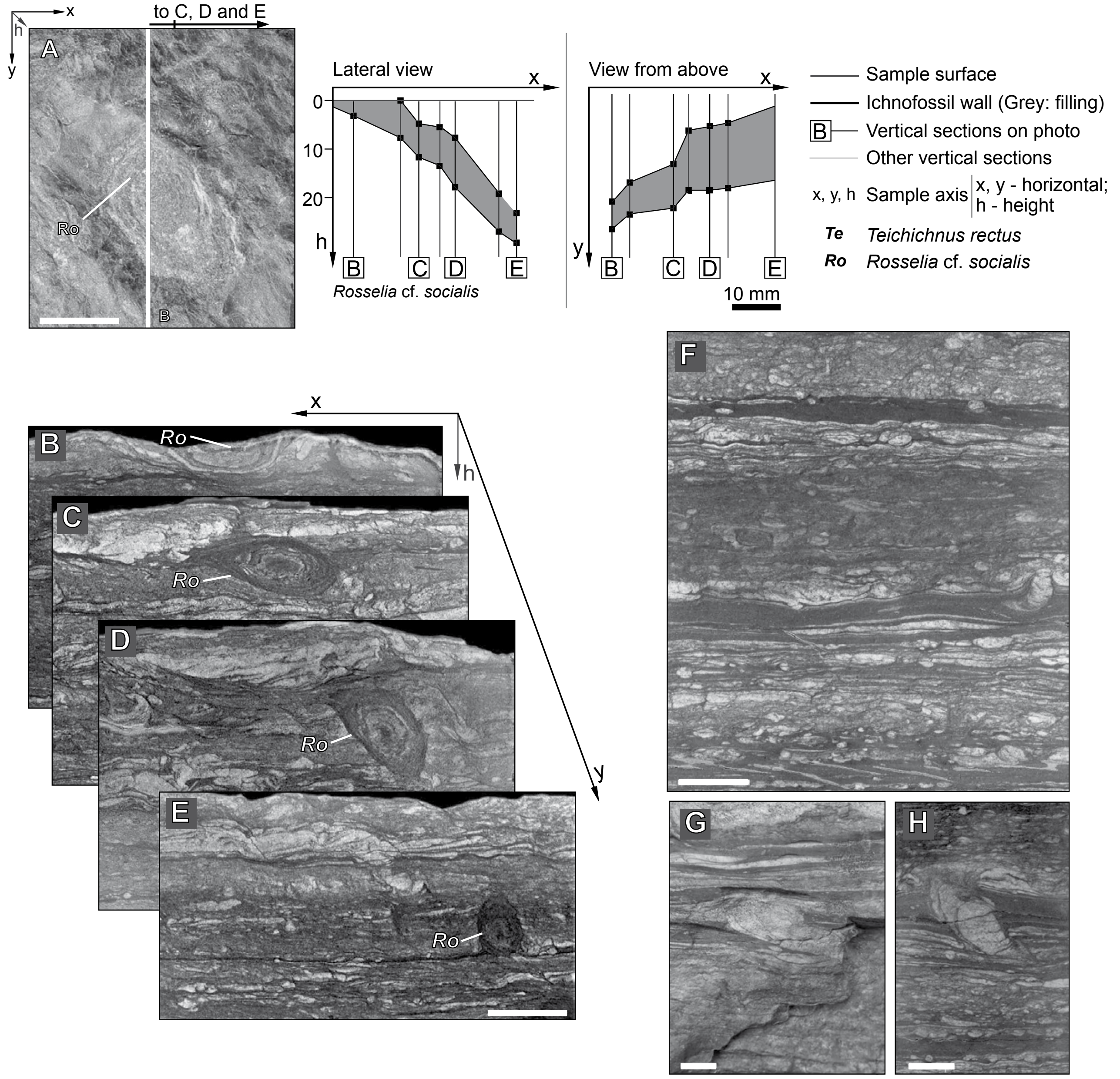

FIGURE 3. Trace fossils from the Desejosa Formation (locality in Fig. 2). A) Top view of *Rosselia* cf. *socialis* showing concentric lamellae. Diagrams show the vertical and horizontal track of this ichnogenus (lateral view and view from above, respectively) taken from the study of a sequence of seven vertical sections (represented by thin lines, including sections represented in the photos B to E); B-E) Vertical sections through the *Rosselia* cf. *socialis* represented in A; F) Typical example of bioturbation found in this locality; G-H) Inclined plug-shaped burrows (*Teichichnus rectus*?) showing lateral displacement. Scale bar represents 10mm in all the pictures.

Trace fossil description

In order to obtain 3D views of the ichnofossil, vertically oriented parallel sections were produced with a rock-saw to show the disruption of primary sedimentary bedding by burrowing animals, including oblique sand-filled plugs with evidence for lateral displacement or short plug-shaped burrows. Only two ichnogenera were noteworthy of a detailed description in the sectioned material, namely *Rosselia* Dahmer, 1937, and *Teichichnus* Seilacher, 1955 (illustrated trace fossil material is housed in the collections of Area de Paleontología, Universidad de Extremadura, Badajoz).

Ichnogenus *Rosselia* Dahmer, 1937

Rosselia cf. *socialis* Dahmer, 1937 (Figs. 3A-E; 4B, D-G; 5A, D-F)

Description. Trace fossils with a vertical or oblique orientation made up of irregularly spaced and wavy

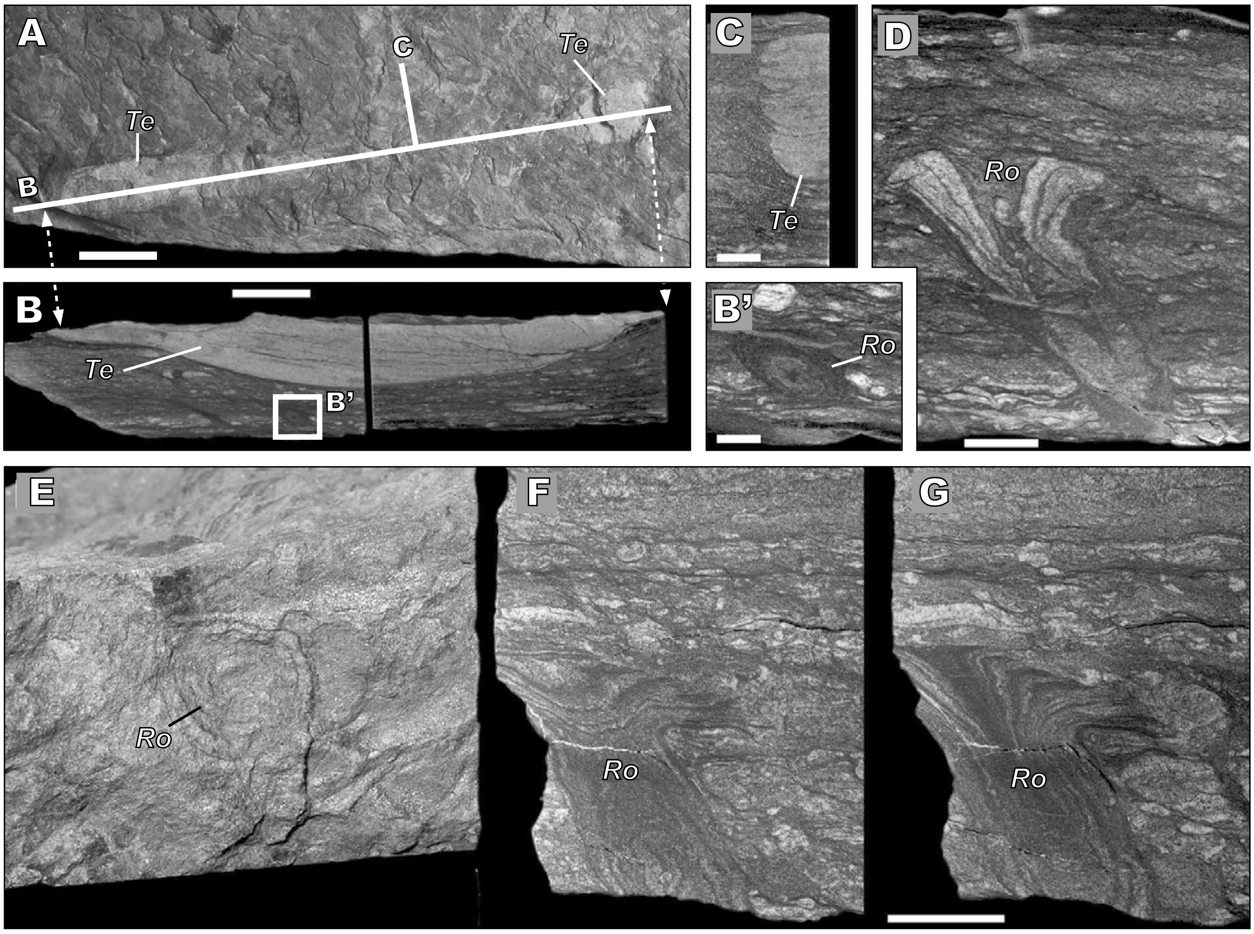

FIGURE 4. Trace fossils from the Desejosa Formation (locality in Fig. 2). A-C) Top (A) and lateral views (B and C) of a *Teichichnus rectus*. Scale bars in A and B represent 20mm. Scale bar in C represents 5mm; B' Close-up of *Rosselia* cf. *socialis* located left to centre in lower part of B. Scale bar represents 5mm; D) Vertical section showing a conical burrow with pronounced sand-dominated concentric lamination surrounding a broad central region (*Rosselia* cf. *socialis*). Scale bar represents 5mm; E-G) Top (E) and vertical sections (F and G) of a *Rosselia* cf. *socialis*. Scale bar represents 10mm. Legend as Figure 3.

alternations of dark (muddy) and light (micaceous siltstone) concentric laminae (Fig. 3D, G), or with pronounced siltstone laminae (Fig. 4D). Vertical sections show elongated cone-shaped burrows, some being approximately cylindrical, 10 to 20mm wide and up to 30mm long (representing incomplete specimens). The horizontal section presents ovate or circular shapes (Fig. 5E, F) with a narrow mud or sand-filled central shaft (Fig. 5F). In some cases it was possible to see signs of vertical repetition of the burrowing (Fig. 4G).

Discussion. The assignation of this material to *Rosselia* is based in the general conical-shaped burrows with concentric laminae that surround a central shaft (sandy or muddy). The relationship between *Rosselia* and *Cylindrichnus* has been discussed by numerous authors (*e.g*. Frey and Howard, 1985; Nara, 1995; Uchman and Krenmayr, 1995), leading to the differentiation of both genera with *Rosselia* presenting conical to irregularly bulbous concentric lamellae and *Cylindrichnus* showing vertical to horizontal cylindrical or sub-cylindrical burrows (Frey and Howard, 1985). However, recent studies suggest that the type material of *Cylindrichnus concentricus* consist of U-shaped or bow-shaped burrows (see Belaústegui and Gibert 2013, for dicussion), calling into question the identification of earlier reports of this ichnogenus. Vertical repetition in *Rosselia* probably represents examples of equilibrichnia (*cf*. Nara, 1997). Cretaceous and younger *Rosselia* typically have a spindle-shaped burrow-form, with conical forms as the result of erosional truncation (Nara, 1995). This is also seen in the type material of *Rosselia socialis* from the Devonian of Germany (Dahmer, 1937; Schlirf *et al*., 2002). In both cases the central portion of *Rosselia socialis* often is sand-filled. Another related form is *Asterosoma* von Otto, 1854, with concentrically layered horizontal or inclined burrows that radiate from a central point. *Asterosoma* has been described from the middle Cambrian of Jordan (Hofmann *et al*., 2012), but no evidence for a radiate arrangement has been observed in the Desejosa Formation material.

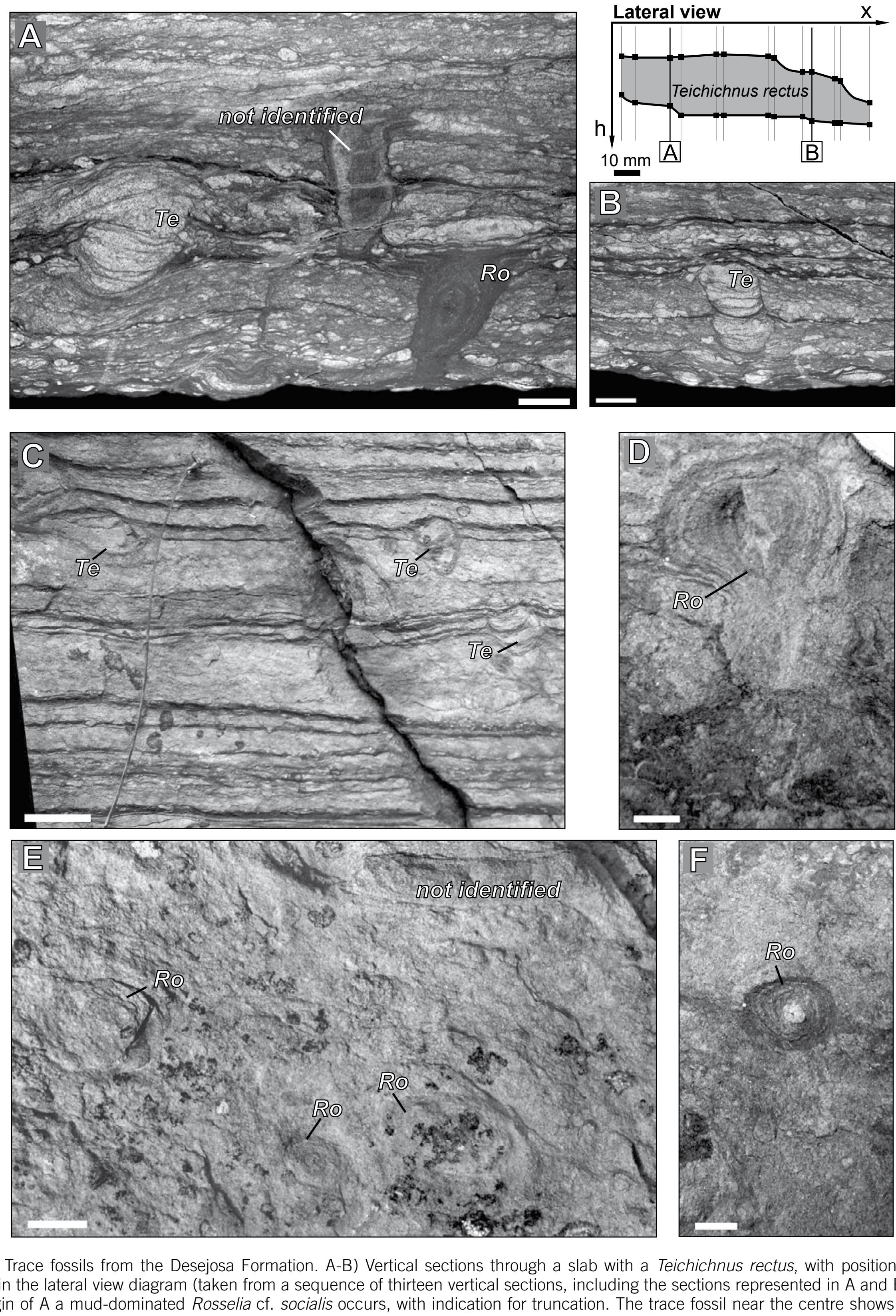

FIGURE 5. Trace fossils from the Desejosa Formation. A-B) Vertical sections through a slab with a *Teichichnus rectus*, with position of sections indicated in the lateral view diagram (taken from a sequence of thirteen vertical sections, including the sections represented in A and B). Near the right margin of A a mud-dominated *Rosselia* cf. *socialis* occurs, with indication for truncation. The trace fossil near the centre shows a sand-rich mantle surrounding a faintly developed concentric lamination. Scale bar in B represents 10mm (same scale as A); C) Field photograph showing bedding and several specimens of *Teichichnus rectus*. Scale bar represents 20mm; D) Field photograph of top bedding-plane view of a *Rosselia* cf. *socialis*. Scale bar represents 5mm; E) Field photograph of a weathered (and partly lichen-covered) top bedding-plane view with several poorly preserved *Rosselia* cf. *socialis*. Scale bar represents 10mm; F) Field photograph of top bedding-plane view of a *Rosselia* cf. *socialis* with a sand-filled central shaft. Scale bar represents 5mm. Legend as Figure 3.

The concentric lamellae observed in the Desejosa Formation materials are closely compared with the reports of *Rosselia socialis*, differing only in the predominantly mud-filled nature of the central shaft in this locality (only one specimen is sand filled; Fig. 5F). We consider that this difference is a reflection of the depositional conditions which created thin intercalations of sand, silt and mud beds, and therefore it does not present ichnotaxonomic significance. Well-developed specimens of *Rosselia socialis* are spindle-shaped, with conical forms being the result of erosional truncation. Because of the lack of evidence for spindle-shaped forms in the Desejosa Formation, this material is assigned to *Rosselia* cf. *socialis*. The *Rosselia* in Figure 4 D, F and G shows some similarity with burrows that Mata *et al.* (2012) interpreted as equilibrichnia behavior of sea anemones. Because the studied material always presents multiple concentric laminations with a mud or sandy central shaft and not a simple cylindrical burrow with a central shaft, the Desejosa material is better assigned to *Rosselia* than to plug-shaped burrows such as *Bergaueria*, *Conichnus*, or *Dolopichnus*.

The exact process by which the concentric lamination in *Rosselia* is formed is not well understood, although Cenozoic specimens, in particular, have been related to the feeding activity of terebellid polychaetes (*i.e.* Nara, 1995). However, the producers of Cambrian *Rosselia* are unknown as there exist no fossil evidence for Cambrian terebellids. In a model presented by Nara (1995) the organism was a surface detritus feeder that constructed the burrow walls from surface materials. On the other hand, Goldring (1996) distinguished between two mechanisms for the formation of concentrically laminated burrows, one made in response to the infilling sediment pushed aside by the producer, and a second produced by the addition of successive wall-layers by the living organism. With regard to the Desejosa material we consider it more likely that the burrow formed in response to sediment influx rather than the result of sediment manipulation from feeding activity.

Ichnogenus *Teichichnus* Seilacher, 1955

Teichichnus rectus Seilacher, 1955 (Figs. 4A-C, 5A-C).

Description. Retrusive spreiten-burrows with horizontal long axis. A specimen examined in a serially sectioned slab (Fig. 5A, B) has a spreite lamina that is 15cm long and 3.5cm high. The base of the lamina is gently inclined with a difference of close to 2cm between the preserved extremities. The spreiten are crudely developed but show a retrusive pattern (Figs. 4C; 5A, B), and spreite lamellae indicate a successive displacement along the horizontal axis (see sketch in Fig. 4).

Discussion. These trace fossils can be assigned to *Teichichnus* in being wall-like vertically oriented spreiten. The lamellae are somewhat irregular but the burrows can be compared with material that Pacześna (1996) attributed to *Teichichnus rectus* from the early and middle Cambrian of Poland. Axial displacement of the spreiten is also present in the type material of *Teichichnus rectus* material from the late early Cambrian Kussak Formation of Pakistan (Seilacher, 1955, plate 24, fig. 1).

DISCUSSION

The ichnogenus *Rosselia* has been typically reported from shallow-marine deposits (Uchman and Krenmayr, 1995) and its presence with *Teichichnus* is indicative of the Cruziana Ichnofacies, which is representative of a shallow-marine depositional environment between fair-weather and storm wave base, consistent with earlier interpretations of the depositional conditions of the upper part of the Desejosa Formation in this sector (Sousa, 1983a, b).

The age of the Douro Group has been problematic, being referred to as ante-Ordovician and probably late Precambrian to Cambrian in previous studies (Teixeira, 1955; Teixeira *et al.*, 1964; Teixeira, 1981; Sousa, 1982, 1983a, b, 1984; Rebelo and Romano, 1986; Ferreira da Silva and Ribeiro, 1994; Coke *et al.*, 1995; Coke and Gutiérrez-Marco, 2001; Pereira *et al.*, 2006). Brachiopods (including *Lingulella major*) from strata in the Serra do Marão area (Portugal) that were originally attributed to the Desejosa Formation by Teixeira *et al.* (1964), were considered the oldest skeletal fossils of Portugal (Teixeira, 1981). A more recent study was made by Coke and Gutiérrez-Marco (2001), who failed to recover additional brachiopods from the Desejosa Formation in the Marão area, and remarked on inconsistencies in the locality description provided in the reports of these specimens. Sá *et al.* (2002) reported on the recovery of some of the type material of *L. major*, until that time thought to be lost. They concluded that the rock matrix is identical to that of the Ordovician "Quartzitos sem Ferro" formation (Marão Formation in Sá *et al.*, 2003, 2005) cropping out in the same area.

The poorly preserved trilobites described by Rebelo and Romano (1986) are then the only fossil evidence for Phanerozoic age for the upper part of Desejosa Formation. This is now corroborated by the new discovery of trace fossils described here, as discussed below.

Trace fossils can be used to differentiate Phanerozoic and pre-Phanerozoic rocks, with some ichnogenera offering an additional age precision. The appearance of trace fossil genera through the Ediacaran-Cambrian boundary and into the Cambrian, led to an ichnofossil-based zonation (*e.g.* MacNaughton, 2007; Buatois and Mángano, 2011). The ichnotaxa described from the Desejosa Formation can be considered within this zonation. The ichnogenus *Teichichnus* is an indicator for Cambrian (or later) age (*e.g.* Crimes, 1987; McIlroy *et al.*, 1998). In Newfoundland the first appearance of *Teichichnus* belongs to the second Cambrian trace fossil-based zone – *Rusophycus avalonensis* Zone – and closely follows the appearance of *Rusophycus*. In the East European Platform, *Teichichnus* is common in the Lontova horizon, whereas there are no clear reports from the basal Cambrian Rovno horizon. The presence of *Teichichnus* point to an age of ca. 530Ma, or younger, with no additional precision.

The ichnogenus *Rosselia* is known from the early Cambrian to the Holocene (*e.g.* Nara and Haga, 2007), but early Palaeozoic examples are scarce, with the first appearance of this ichnogenus being poorly constrained. In order to assess the potential ichnostratigraphic implications of *Rosselia* we have undertaken a literature review of Cambrian occurrences of *Rosselia* and *Cylindrichnus* (Table I, Electronic Appendix available at www.geologica-acta.com). Direct comparison of the *Rosselia* found in the Desejosa Formation with the previously reported Cambrian localities is complicated by the general lack of cut material in those studies. Examples of early Cambrian *Rosselia* are frequently cited specimens from the Kussak Formation in Pakistan (Seilacher, 1955), being assigned to the Cambrian Stage 4. However, this author noted that the conical structure seemed to be connected to a vertical burrow and therefore this material could only be cautiously compared to *Rosselia*. Although Seilacher (1955) described *Rosselia* as abundant, we are not aware of any additional documentation of this material. Examples of *Rosselia* with sand-rich laminae were reported by Desjardins *et al.* (2010a, b) from the Lake Louise and St. Iran formations of the Gog Group, Alberta, Canada. These affected planar and hummocky cross-stratified sandstones with an upwards-flaring laminae and a cylindrical central shaft. The age of this group is constrained by acritarchs from the lower part of the St. Piran Formation that Downie (1982) compared to those of the Lükati horizon of the East European Platform (Cambrian Stage 3). Belaústegui and Gibert (2009) suggested that *Cylindrichnus operosus* (Orłowski, 1990) from the lower Cambrian of Poland is better assigned to *Rosselia*. Also, the *Cylindrichnus concentricus* reported from the middle Cambrian of Poland by Pacześna (1996) is comparable to the *Rosselia* described here. There exist no previous reports of *Rosselia* from the Cambrian of Iberia, although there are several reports of *Cylindrichnus* especially in the middle Cambrian. The previous, earliest descriptions of Iberian occurrences of *Rosselia* were made in the upper and middle part of the Early Ordovician (Floian) in the Serra do Brejo Formation in Figueiró dos Vinhos, Portugal (Cooper and Romano, 1982). This material is in a facies sandier than that of Desejosa Formation but it can be compared to the material described here. The *Rosselia* of Desejosa Formation represents some of the finest examples of Cambrian *Rosselia* ichnogenus with clearly defined concentric muddy laminae.

The presence of *Rosselia* cf. *socialis* in the upper part of the Desejosa Formation combined with the earlier findings of indeterminable trilobites in a similar stratigraphic position, means that this part of the succession cannot be older than Cambrian Age 3 (ca. 522Ma). However, the stratigraphic relationships in the Desejosa Formation between the *Rosselia* and the trilobite localities are not clear, due to the strongly erosive Toledanic Unconformity which is topping Desejosa Formation in Açoreira village (at 20 km to the west of this ichnofossil site), were Rebelo and Romano (1986) found the trilobite remains. At present, the upper age limit of the Douro Group has to be based on lithostratigraphic correlation to units within the Spanish part of the CIZ. Sousa (1983a, b, 1984) suggested that much of the Douro Group can be correlated with the Aldeatejada Formation (Díez Balda, 1986) in the Salamanca area and the Pusa Formation (San José, 1983) in the Toledo Mountains. Similarly, Pereira *et al.* (2006) approximated the top of the Douro Group to the upper part of the Pusa Formation and parts of the Azorejo Formation (San José *et al.*, 1974), which they positioned close to the transition of the Cordubian-Ovetian regional stages. A somewhat younger age for the upper part of the Pusa Formation was suggested by Jensen *et al.* (2010), placing it firmly within the Ovetian (Cambrian Stage 3). A circumstantial argument against a higher position of Desejosa Formation is the absence of prominent carbonate beds in the upper part of the Douro Group.

CONCLUSIONS

We present the first detailed description of discrete trace fossils from the Desejosa Formation on the basis of material from a new locality in the Freixo de Espada à Cinta area, Portugal. The most reliably identified forms are *Teichichnus rectus* and *Rosselia* cf. *socialis*, being the first report of the ichnogenus *Rosselia* from the Cambrian of Iberia, and some of the most conspicuous Cambrian examples of this ichnogenus to date.

A review of Cambrian occurrences of *Rosselia* and other vertical concentrically laminated burrows, show no record older than Cambrian Age 3. Together with the additional evidence of the previously described scarce remnants of unidentified trilobites, this demonstrates that the upper part of the Desejosa Formation is no older than Cambrian Age 3. Also the ichnogenera association (*Cruziana* Ichnofacies) described in this paper gives evidences of a shallow water depositional environment between fair-weather and storm wave base.

The Desejosa Formation is conformably overlain by a recently proposed lithostratigraphic unit, called Montes Ermos (Fig. 2). This is younger than the Cambrian Age 3 with no further precision. Nevertheless the absence of middle and late Cambrian rocks in the CIZ points to an age towards the later part of the early Cambrian. An upper age constraint for both formations is provided by the unconformably overlying Early Ordovician rocks.

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ELECTRONIC APPENDIX I

TABLE I. Cambrian occurrences of *Rosselia* and *Cylindrichnus*

Original attribution	Reference	Stratigraphy and location	Chronostratigraphy	Characteristics	Comment
Rosselia isp.	Desjardins *et al.*, 2010a, b	St Piran Fm., Gog Group, Alberta, Canada	Cambrian Stage 3, on acritarchs	Funnel-shaped concentric laminae, to 5 cm wide, sand-filled central tube	Abundant
	Mángano *et al.* 2013	Hanneh Mbr, Jordan	Cambrian Stage 5	-	-
	Aceñolaza and Nieva, 2003	Candelaria Fm., Argentina	Furongian-Lower Ord.	-	-
cf. *Rosellia* isp.	Seilacher, 1955	Kussak Fm. (Neobolus beds), Pakistan	Cambrian Stage 4	Nested laminae on top of cylindrical shaft	Seilacher (1955) thought attribution to *Rosselia,* doubtful
Rosselia socialis	Pickerill and Peel, 1990	Bastion Fm. (lower) , Greenland	Cambrian Stage 3 or 4	Funnel-shaped, 1.15 cm at top, 0.4 mm at base 2cm long (incomplete). Concentric laminae throughout	Three specimens
	Jensen, 1997	Mickwitzia sandstone mbr., File Haidar Fm., Sweden	Cambrian Stage 4	Conical to bulbuous, 25-47 mm wide, up to 30 mm long, central tube 3 mm	-
Cylindrichnus isp.	Pickerill and Peel, 1990	Bastion Fm. (lower) , Greenland	Cambrian Stage 3 or 4	Cylindrical 5.1 and 4.2 mm wide, with less than 1 mm thick laminae	Two specimens. Only observed in positive epirelief. Length unknown
Cylindrichnus operosus	Orłowski, 1990	Ocieseki Fm., Poland	Cambrian Stage 3 or 4	Subconical, up to 25 mm wide, with 7 mm wide and 9 cm long central tube	*Rosselia* – Belaustegui and Gibert (2009)
Cylindrichnus concentricus	Gámez Vintaned *et al.*, 2006	Pedroches Fm., Cordoba area, Spain.	Cambrian Stage 3 (Lower Ovetian)	Short, 2.4-3.5 mm wide. Sand-filled core surrounded by fine-grained concentric laminae	Two specimens
	Gámez Vintaned and Mayoral Alfaro, 1995	Valdemiedes Fm., Spain	Cambrian Stage 4 and ?5 (Mar. And Bilb.)	Cylindrical to subcylindrical, 7.6 to 13.7 mm in diameter	Associated with *Teichichnus* and *Sericichnus*
	Liñán *et al.*, 1995	Los Villares Fm., Cordoba area, Spain	Cambrian Stage 5 (Leonian)	Cylindrical, 1-6 mm wide, up to 40 cm long, mud-rich	-
	Gámez Vintaned *et al.*, 2000	Oville Fm., Spain	Cambrian Series 3	No published details	-
	Pacześna, 1996	Kostryzyn and Debki Fms, Poland	Cambrian Series 3 (oelandicus, parad.)	-	-