



## Ichnological analysis at the Fonte Coberta section (Lusitanian Basin, Portugal): Approaching depositional environment during the Toarcian oceanic anoxic event (T-OAE)

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Miguez-Salas, O., Rodríguez-Tovar, F.J. & Duarte, L.V. 2018. Ichnological analysis at the Fonte Coberta section (Lusitanian Basin, Portugal): Approaching depositional environment during the Toarcian oceanic anoxic event (T-OAE). [Análisis icnológico de la sección Fonte Coberta (Cuenca Lusitánica, Portugal): una aproximación al ambiente de depósito durante el evento anóxico del Toarciense (T-OAE)]. *Spanish Journal of Palaeontology*, 33 (2), 261-276.

Manuscript received 20 December 2017

Manuscript accepted 22 March 2018

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### ABSTRACT

The Toarcian Oceanic Anoxic Event (T-OAE) is commonly related with an extended marine mass extinction and global oceanic anoxic conditions. However, recently it has been demonstrated that local palaeotopography/palaeogeography can determinate the absence of anoxic conditions, being other limiting environmental parameters of higher significance. The detailed study of the Fonte Coberta section (Lusitanian Basin, Portugal) shows significant changes in the macrobenthic community at the lower Toarcian (Levisoni Zone) sediments during the event. In the study section, this interval presents a high degree of bioturbation with a relatively abundant and moderately diverse trace fossil assemblage dominated by *Thalassinoides*, with punctual *Spongeliomorpha*. The ichnotaxonomical study conducted on this trace fossil assemblage has allowed the recognition of a single species of *Thalassinoides*, *T. suevicus* Rieth, with two different morphotypes (I and II), as well the differentiation of *Spongeliomorpha* aff. *iberica* Saporta. The distribution of these ichnospecies, including the differentiated morphogroups,

### RESUMEN

El evento anóxico oceánico del Toarciense (T-OAE en inglés) se relaciona comúnmente con una extinción en masa en el medio marino y condiciones anóxicas oceánicas globales. Sin embargo, recientemente se ha demostrado que la compleja paleotopografía/paleogeografía local puede determinar la ausencia de condiciones anóxicas, siendo otros parámetros ambientales de mayor importancia. El estudio detallado de los sedimentos del Toarciense inferior (Zona Levisoni), en la sección de Fonte Coberta (Cuenca Lusitánica, Portugal), muestra cambios significativos en la comunidad macrobentónica durante el evento. En la sección de estudio, este intervalo presenta un alto grado de bioturbación con una asociación de trazas fósiles relativamente abundante y moderadamente diversa, con predominio de *Thalassinoides* y aparición puntual de *Spongeliomorpha*. El estudio iconotaxonomico ha permitido el reconocimiento de una única icnoespecie de *Thalassinoides*, *T. suevicus* Rieth, con dos morfotipos diferentes (I y II), así como la diferenciación de *Spongeliomorpha* aff. *iberica* Saporta. La distribución de

along the studied interval, corresponding to the T-OAE, allows refining depositional conditions as changes in the substrate consistency related to variations in relative sea level. Ichnological analysis reveals as a proxy to improve sequence stratigraphy characterization for the Lusitanian Basin during the T-OAE.

**Keywords:** Trace fossils, *Thalassinoides suevicus*, T-OAE, sequence stratigraphy, Portugal.

estas icnoespecies, incluidos los morfogrupos diferenciados, a lo largo del intervalo estudiado, correspondiente al T-OAE, permite detallar las condiciones de depósito, observándose cambios en la consistencia del sustrato relacionados con las variaciones en el nivel relativo del mar. De esta manera se pone de manifiesto que el análisis icnológico puede ser un valioso indicador a la hora de mejorar la propuesta secuencial de la Cuenca Lusitánica durante el T-OAE.

**Palabras clave:** Trazas fósiles, *Thalassinoides suevicus*, T-OAE, estratigrafía secuencial, Portugal.

## 1. INTRODUCTION

In recent years, several studies have proven the potential of trace fossils to improve understanding of mass-extinction events (e.g., Twitchett & Barras, 2004; Beatty *et al.*, 2008; Fraiser & Bottjer, 2009; Knaust, 2010; Hofmann *et al.*, 2011; Buatois *et al.*, 2013; Labandeira *et al.*, 2016), because of trace fossils represent the response of trace makers to palaeoenvironmental conditions. Nevertheless most of the ichnological studies are focused on major extinction events, such as the end-Permian (Knaust, 2010; Mata & Bottjer, 2011) or the end-Cretaceous (Rodríguez-Tovar & Uchman, 2004a, 2004b, 2006, 2008; Rodríguez-Tovar *et al.*, 2004, 2006, 2010, 2011, 2016; Rodríguez-Tovar, 2005; Kędzierski *et al.*, 2011; Alegret *et al.*, 2015; Monaco *et al.*, 2015; Labandeira *et al.*, 2016; Łaska *et al.*, 2017), while others minor extinction events as the Toarcian Oceanic Anoxic Event (T-OAE) has been comparatively scarcely studied from an ichnological point of view (Rodríguez-Tovar & Uchman, 2010; Rodríguez-Tovar & Reolid, 2013; Reolid *et al.*, 2014, 2015; Miguez-Salas *et al.*, 2017; Rodríguez-Tovar *et al.*, 2017).

The T-OAE is considered a global event and one of the most extreme palaeoenvironmental perturbations of the Jurassic, as evidenced by a significant global mass extinction event (Pálffy & Smith, 2000; Gómez *et al.*, 2008; Wignall & Bond, 2008; Mattioli *et al.*, 2009; Danise *et al.*, 2015). The T-OAE is characterized by common black shale deposits that reflect the widespread development of poor oxygenation in the oceans, warming in tropical and subtropical seas (~5-8°C; Gómez *et al.*, 2008), biotic turnovers and negative carbon isotope excursions (CIE) (e.g., Jenkyns, 1988; Hesselbo *et al.*, 2007; Suan *et al.*, 2008, 2011; Littler *et al.*, 2010; Izumi *et al.*, 2012). This event had a significant impact on the marine biota, including benthic and pelagic groups (Hallam, 1996; Wignall *et al.*, 2005; Rodríguez-Tovar & Uchman, 2010; Comas-Rengifo *et al.*, 2013; Rita *et al.*, 2016; Baeza-Carratalá *et al.*, 2017; Correia *et al.*, 2017b). The negative CIEs suggest an input of <sup>13</sup>C-depleted carbon into the atmosphere-ocean system. Two main hypotheses have

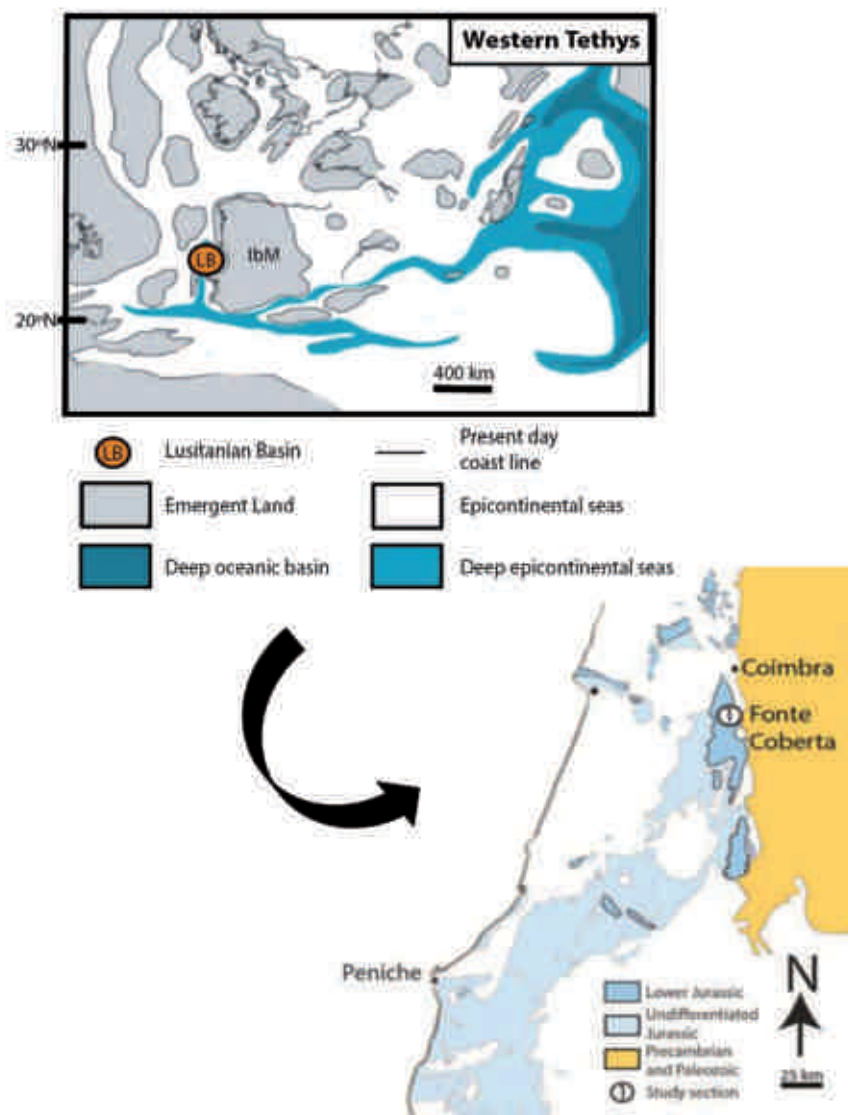
been proposed to explain this <sup>13</sup>C-depleted carbon release and the important environmental changes involved: 1) tectonic extensional mechanisms, which would release methane hydrate in marine sediments (Hesselbo *et al.*, 2000), inducing anoxic conditions, ocean acidification and possibly determining variations in the thermohaline currents (Bjerrum *et al.*, 2001; Trecalli *et al.*, 2012); and 2) the volcanic episode Karoo-Ferrar, which began in the Pliensbachian (lowermost Jurassic) and produced a big thermogenic methane emissions (McElwain *et al.*, 2005; Svensen *et al.*, 2007). These two mechanisms created greenhouse conditions (Pálffy & Smith, 2000). However, global anoxic conditions can be locally absent due to a strong palaeogeographical control (i.e., McArthur *et al.*, 2008; Rodríguez-Tovar & Uchman, 2010; Rodríguez-Tovar & Reolid, 2013; Danise *et al.*, 2015), being other environmental parameters of higher influence on biota (e.g., temperature, salinity, or nutrients availability, among others).

The Lusitanian Basin (LB, Portugal) presents a complex record of the T-OAE; the event significantly affected the marine biota (e.g., Barrón *et al.*, 2013; Cabral *et al.*, 2013; Ferreira *et al.*, 2015; Rita *et al.*, 2016; Baeza-Carratalá *et al.*, 2017; Correia *et al.*, 2017a; Miguez-Salas *et al.*, 2017, among others), but the common black shales registered in other European basins (Jenkyns *et al.*, 2001; Röhl *et al.*, 2002; van Breugel *et al.*, 2006), are absent here (Hesselbo *et al.*, 2007; Pittet *et al.*, 2014). In the proximal Rabaçal area, abundant bioturbation is registered associated to the T-OAE in a context of absence of black shales (Miguez-Salas *et al.*, 2017). This record can be influenced by the relative sea-level changes, controlled by tectonics, including the uplift of the emerged areas during the T-OAE, displaying a main role in the control of palaeoenvironmental conditions (Duarte, 1997, 2007; Kullberg *et al.*, 2001; Hesselbo *et al.*, 2007). As pointed out by Pittet *et al.* (2014) the occurrence of complex palaeotopographies and palaeogeography at the onset of the T-OAE might constitute a pivotal controlling factor in modulating the development of anoxic conditions in epicontinental basins.

Previous ichnological studies of the T-OAE at the Fonte Coberta section revealed a comparatively minor influence of the oxygenation on the macrobenthic trace maker community, being other parameters, as nutrient availability, or substrate consistency of major importance (Miguez-Salas *et al.*, 2017; Rodríguez-Tovar *et al.*, 2017). Here we present a new detailed ichnotaxonomical study of the lower Levisoni Zone (lower Toarcian) in the Fonte Coberta section, with differentiation at sub-ichnospecies level (morphotypes). This ichnological analysis allows interpret the depositional context affecting the registered response of the macrobenthic tracemaker community and then the minor incidence of the T-OAE event.

## 2. GEOLOGICAL SETTING. THE FONTE COBERTA SECTION

The Fonte Coberta section is located 15 km south of Coimbra (northwest Portugal, Rabaçal area; 40°03'34.3"N - 8°27'34.2"W; Fig. 1) on the northeastern part of the LB, corresponding to the mid-distal part of a carbonate homoclinal ramp that dip to the northwest (Duarte, 1997). The lower Toarcian sediments from this section belong to the lower part of the São Gião Formation (Polymorphum and Levisoni zones), corresponding to three main members, which from the bottom to the top are (Fig. 2):

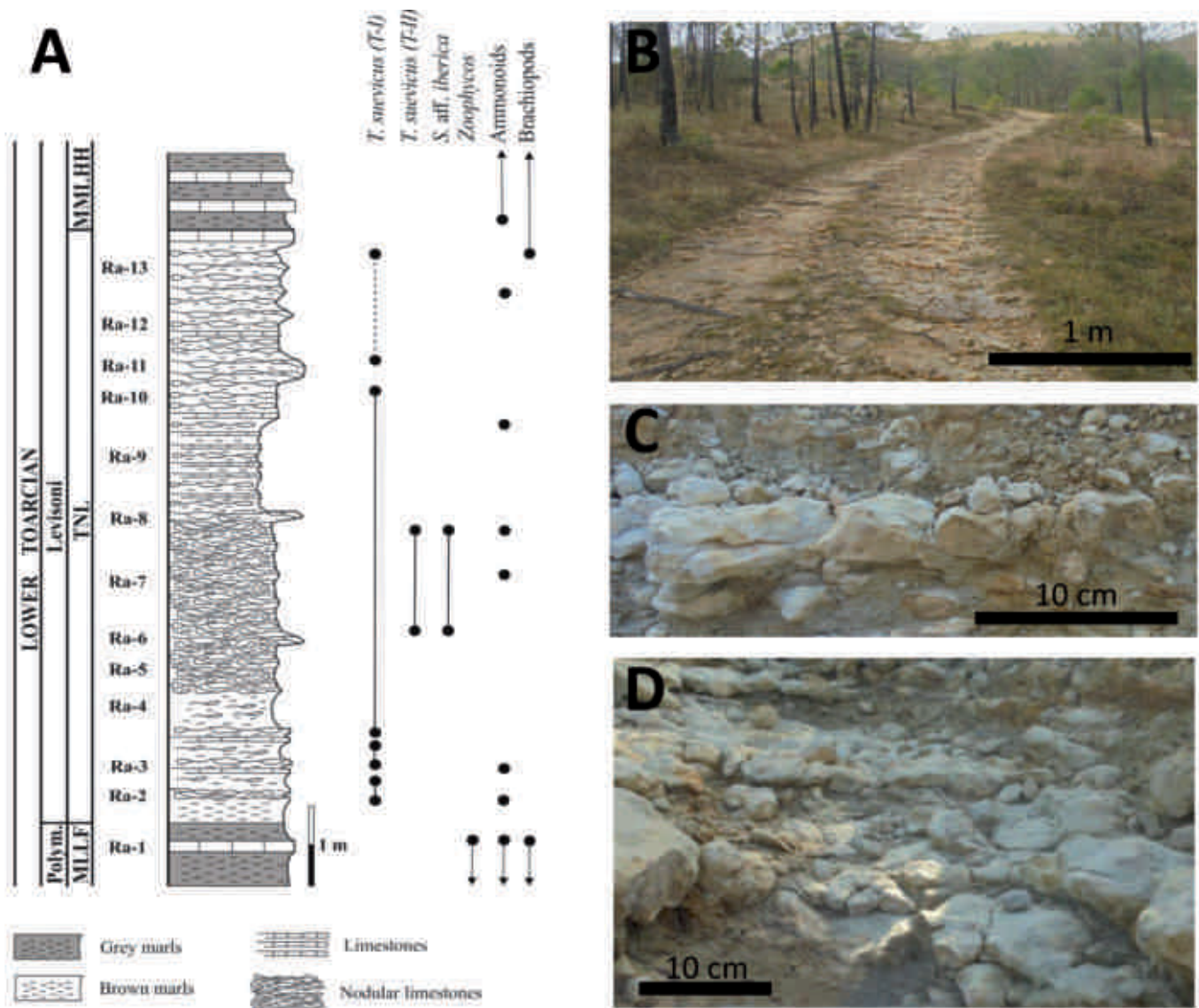


**Figure 1.** Palaeogeographical representation of the western Tethys with the position of the Lusitanian Basin (LB) during the early Jurassic (based on Dera *et al.*, 2010 and Ferreira *et al.*, 2015) and geological setting (modified from Duarte, 2007); IbM, Iberian Massif.

1) marly limestones with *Leptaena* fauna (MLLF); 2) thin nodular limestone (TNL); and, 3) marls and marly limestones with *Hildaites* and *Hildoceras* (MMLHH) (Duarte & Soares, 2002; Duarte *et al.*, 2004; Duarte, 2007). Our study is focused on the 7-meter-thick TNL member, which is characterized by light brown marl-limestone alternations with highly bioturbated limestone layers that cause its nodular aspect. The base of this member corresponds to the boundary between Polymorphum and Levisoni ammonite zones (base of T-OAE) and marks one of the most important palaeontological and sedimentological changes observed in the whole Lower

Jurassic (see Duarte, 1997; Miguez-Salas *et al.*, 2017), including the extinction of the previously well-represented brachiopods community, a decreased in the abundance of ammonoids and the disappearance of the previous record of *Zoophycos* (Duarte, 1997; Comas-Rengifo *et al.*, 2013) (Fig. 2a).

In terms of sedimentological features, the beginning of the TNL at the Fonte Coberta section is marked by a change in the coloration of the marls, from grayish in the MLLF member to brownish in the TNL member (intervals Ra-2 and Ra-3) (Fig. 2a); besides the thickness of the marls is thinner (centimetrical) than in the previous member.



**Figure 2.** a) Lithological column of the Fonte Coberta section showing distribution of ammonoids, brachiopods, *Zoophycos*, *T. suevicus* (type I and II) and *S. aff. iberica*. MLLF = Marly limestones with *Leptaena* facies member; TNL = Thin nodular limestones member; MMLHH = Marly limestones with *Hildaites* and *Hildoceras* member (modified from Miguez-Salas *et al.*, 2017). b) Outcrop view of the TNL member in the Fonte Coberta section. c-d) Close-up views of middle part of the TNL member (Ra 6 and 7).

The nodular limestone levels, mainly observed from intervals Ra-5 to Ra-8, record an increase in abundance of bioturbation from beds Ra-2 to Ra-7. Intervals from Ra-6 to Ra-8 present scarce marly inter-bedding and a more calcareous character (conspicuous appearance). From interval Ra-9 to the end of Ra-10 a progressive diminution of the nodularity, together with an increase in thickness of the clay levels, is observed (Miguez-Salas *et al.*, 2017). Finally, at the top of the TNL member (from Ra-11 to Ra-13), the section returns to more grayish marly facies, with a clear increase in macroinvertebrates (especially brachiopods and ammonoids with dominance of *Hildaites* and *Hildoceras*, see Comas-Rengifo *et al.*, 2013).

### 3. RESULTS. TRACE FOSSIL ANALYSIS

Trace fossil features, including ichnofabrics, were re-examined in detail from bottom to top of the TNL member. The trace-fossil assemblage reveals significant changes in abundance and diversity throughout the section. The abundance increases from the base until the middle part of the TNL member and then decreases progressively to the top of the member. Ichnotaxonomic diversity changes run parallel to the trace-fossil abundance. Ichnotaxonomical analysis allows ichnospecies characterization, and even intra-specific differentiation, into the previously recognized ichnogenera *Thalassinoides* and *Spongeliomorpha*.

Ichnogenus *Thalassinoides* Ehrenberg, 1944

Type species *Thalassinoides callianassae* (Ehrenberg) from the Burdigalian Stage of the Vienna basin (Ehrenberg, 1944, p. 358).

**Diagnosis.** The ichnogenus *Thalassinoides* Ehrenberg (1944) comprises cylindrical to elliptical burrows systems with regular branching, which form a three-dimensional polygonal network with both horizontal and vertical elements connected to the surface; external surfaces of the burrow are usually smooth.

**Palaeoecological remarks of *Thalassinoides*.** The record of *Thalassinoides* has been associated to a number of palaeoenvironmental conditions (Rodríguez-Tovar *et al.*, 2008). As a general interpretation, an abundant record of *Thalassinoides* can be considered as indicative of well-oxygenated environments (Bromley & Frey, 1974; Kern & Warne, 1974; Ekdale & Bromley, 1984; Bromley, 1990). Occasionally, *Thalassinoides* has been also registered in salinity or temperature stressed environments (e.g., Howard & Frey, 1975; MacEachern & Gingras, 2007; Dashtgard *et al.*, 2008; Gingras *et al.*, 2011). *Thalassinoides* occurs from softgrounds to firmgrounds and in some cases are

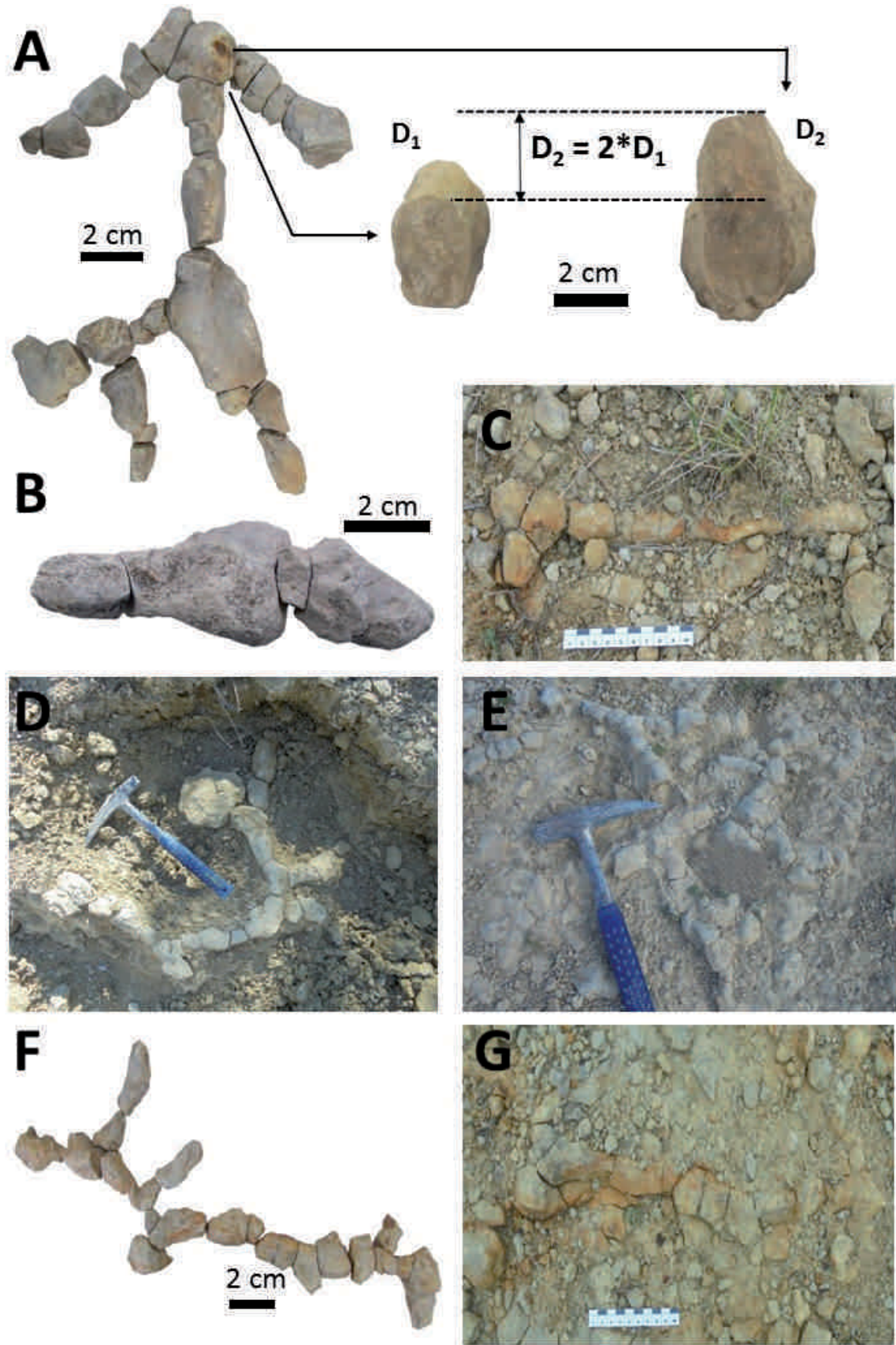
recorded in association with the first stages of hardground surfaces (Ekdale & Bromley, 1984; Ekdale, 1992; Myrow, 1995; Pemberton *et al.*, 2004).

**Ichnospecies of *Thalassinoides*.** The species accepted to the ichnogenus *Thalassinoides* are: *T. saxonicus* (Geinitz, 1842), *T. ornatus* (Kennedy, 1967), *T. paradoxicus* (Woodward, 1830), *T. suevicus* (Rieth, 1932), *T. horizontalis* (Myrow, 1995), *T. bacae* (Ekdale & Bromley, 2003) and *T. sifangpoensis* Wang, 2004. Other proposed ichnospecies that are no longer accepted or whose validity is questioned are *T. tandoni* (Badve & Ghare, 1978) and *T. foedus* (Mikuláš, 1990) (Fürsich, 1973; Keighley & Pickerill, 1997; Rodríguez-Tovar *et al.*, 2008; Yanin & Baraboshkin, 2013).

*Thalassinoides saxonicus* is characterized by its large tunnels with diameters between 5 and 20 cm (Kennedy, 1967). *T. ornatus* refers to smaller ovate (0.8×1.6 cm to 1×2.2 cm), horizontal to gently inclined burrows (Kennedy, 1967). *T. paradoxicus* corresponds to burrows where branches form complex boxwork systems, usually with T-shaped bifurcations, and highly irregular in size and geometry (Kennedy, 1967; Howard & Frey, 1984; Frey & Howard, 1985). *T. suevicus* is a predominantly horizontal structure with dominant Y-shaped bifurcations that may contain enlargements at the branching point (Howard & Frey, 1984). *T. horizontalis* is a strictly horizontal form with relative small diameter as well as a diagenetically wall lining. *T. bacae* refers to irregularly anastomosing, horizontal tunnel mazes with highly variable branching angles and numerous vertical shafts (Ekdale & Bromley, 2003). *T. sifangpoensis* is a small netting burrow system, the sizes of the net being 3 mm × 5 mm–5 mm × 8 mm and the diameters of burrow 0.5–1.0 mm (Wang, 2004).

**Description.** The studied specimens of *Thalassinoides* appears on the limestone layers from the bottom to the top of the TNL member (Figs 2b-d). They are well preserved, although their lateral continuity is short. The structures show a dominant horizontal development, with irregular branches, and the near absence of vertical components (Figs 3-4).

The burrow systems are cylindrical or subcylindrical in cross-section with diameters that varies between 1.5 and 6 cm (Table 1). The main feature of the studied specimens is a higher frequency of Y-shaped than T-shaped bifurcations. In the case of Y-shaped bifurcations, a big swelling at their junctions is common (Fig. 3a), which is comparatively less developed in the T-shaped forms (Fig. 4a). The angle of Y-shaped bifurcations is normally between 55°-80° (Figs 3d-g). Locally short dead-end chambers seem to be observed (Fig. 3a). External surfaces of burrow casts are usually smooth. In some cases, wall burrow peaks are observed; according to Nickell & Atkinson (1995) this could be related to irrigation offshoots (Figs 4a-b; dashed



**Figure 3.** Specimens of *T. suevicus* from the outcrop in Fonte Coberta section and after laboratory cleaning and digital treatment. **a)** *T. suevicus* type I where can be appreciated a big increase at branching point and possibly short dead-end chambers **b-c)** Specimens of *T. suevicus* type I. **d-e)** Specimens of *T. suevicus* type II. **f-g)** Specimens of *T. suevicus* type I.

	Average diameter (cm)	Length (cm)	Minimum diameter (cm)	Maximum diameter (cm)	Increase at branching point (cm)	Bifurcation angle
2-Th1	2.3	18	2	3	0.7	60°
3-Th1	2.2	55	1.9	3	0.8	75°
3-Th2	2.1	34	1.8	2.6	0.5	80°/60°
3-Th3	2	46	1.8	2.8	0.8	65°
3-Th4	1.9	22	1.5	2.1	x	x
3-Th5	2.4	24	2.2	3	0.6	73°
4-Th1	1.8	36	1.5	2.4	0.6	66°
5-Th1	2.3	51	1.9	2.7	0.4	58°/72°
5-Th2	2	32	1.6	2.8	0.8	x
5-Th3	2.3	24.3	2	2.6	0.3	77°
5-Th4	2.4	55	2	3	x	55°
5-Th5	2	18	1.7	2.7	0.7	80°
5-Th6	2	15.5	1.6	2.3	x	x
5-Th7	2	32	1.7	2.5	0.5	62°
6-Th1	2.8	40	2.3	3.7	0.9	76°/65°
6-Th2	2.2	16	1.8	2.7	x	x
6-Th3	4.5	79	3.1	6	1.5	68°
7-Th1	2.2	52	1.9	2.5	0.3	59°
7-Th2	2.3	17	1.8	2.8	0.5	55°/67°
7-Th3	2.5	16.5	2	4	1.5	x
7-Th4	2.3	31	2	2.8	0.5	73°
7-Th5	3	35	2.7	4	1	79°
11-Th1	2.2	19	1.9	3.2	1	63°
13-Th1	2.4	12	2	3	x	x

**Table 1.** *Thalassinoides* measurements. In grey *T. suevicus* type II.

line). The tubular wall lining is usually missing or poorly preserved (Fig. 4d), only in few occasions inside the burrow a lining can be distinguished (Fig. 4d). Specimens with smaller diameters (1.5 to 2.5 cm) present an exclusive horizontal development and lack of vertical offshoots, constant burrow diameter, and preferential T-shaped bifurcations where vertical swellings at bifurcation points are notably absent (Figs 4c-f).

**Ichnotaxonomical classification.** According to the ichnological features above indicated, most of the studied specimens in the Fonte Coberta section belong to *Thalassinoides suevicus*. However, observed variations allow a more detailed characterization into the ichnospecies level. Traditionally different types of *T. suevicus* were described according to the range of sizes. Fürsich (1998) recognized three types: small (type C, 0.3–0.7 cm wide), intermediate (type B, 1–2 cm), and large (type A, 2.5–4 cm) structures. Monaco & Garassino (2001) and Monaco & Giannetti (2002) proposed a new four-type size classification from smaller to larger diameter: type I (2–4 cm), type II (4–7 cm), type III (9–10 cm), and type IV (14–16 cm), always considering an enlargement at branching points.

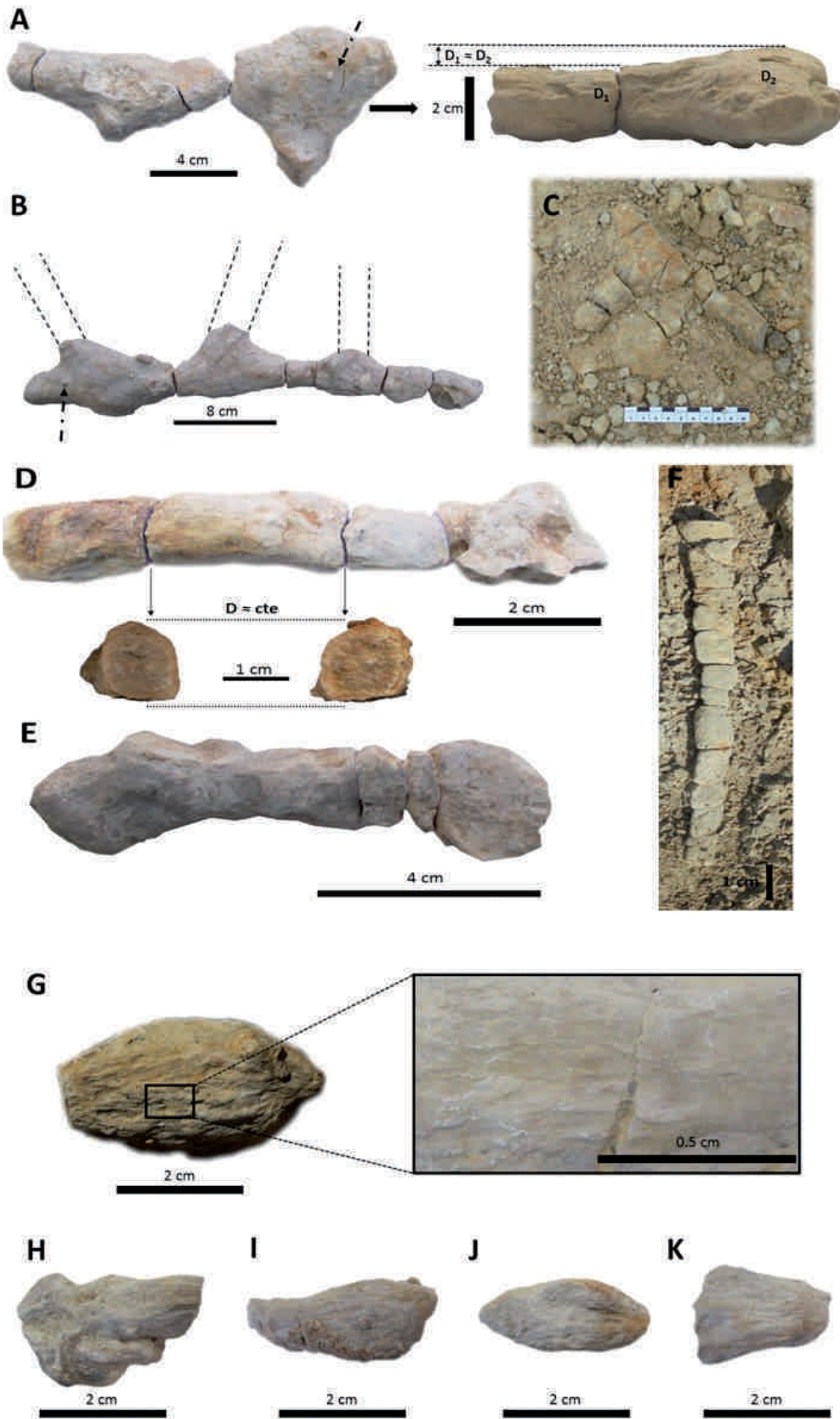
Most of the collected specimens of *T. suevicus* could be assigned to type I (Figs 3a-c, 4a-f; Table 1), based on

size diameter, together with the presence of features similar to those observed in type I by Giannetti *et al.* (2007), as the branches tend to be circular in section, the turning chambers are not particularly developed, and the mazes are developed only on the horizontal plane. Moreover, when these burrows are tiered with the other forms of *Thalassinoides*, they occupy the upper tier. The specimens of *T. suevicus* with larger diameter are less common in the studied section and can be assigned to type II, also showing features resembling those observed by Giannetti *et al.* (2007), e.g., development of turning chambers, long branches forming geometrical mazes, and smooth external surface without lining (Figs 3d, g; Table 1).

Ichnogenus *Spongeliomorpha* Saporta, 1887

Type ichnospecies *Spongeliomorpha iberica* Saporta, 1887.

**Diagnosis.** Cylindrical to subcylindrical burrow systems with predominant horizontal elements, which shows Y or T-shaped bifurcations. Burrow terminations are conical, tapered or hemispherical but uninflated. Burrow walls are unlined and ornamented with deep ridges, which are longitudinal, oblique or transverse to the main axis of the trace *sensu* Melchor *et al.* (2009).



**Figure 4.** a) Specimens of *T. suevicus* type I with T-shaped bifurcation that present less vertical swelling at the bifurcation point, identification of possible exhalation shaft (dashed arrow). b) *T. suevicus* type I with combined T and Y shaped bifurcation and possible exhalation shaft (dashed arrow). c-f) Specimens of *T. suevicus* type I. g-k) Specimens of *S. aff. iberica* from the Fonte Coberta section.



### Palaeoecological remarks of *Spongeliomorpha*.

This ichnogenus is commonly interpreted as the domicile structure of crustaceans in firm or semi-consolidated substrates as the scratch marks produced by locomotory organs reveals (Frey *et al.*, 1984). *Spongeliomorpha* is a facies-crossing form that appears on a wide range of environments, from shallow to deep-marine, as well as fresh-water settings. This trace fossil is recorded over different environmental parameters like oxygenation, salinity, temperature, etc. (Frey *et al.*, 1984; Buatois & Mángano, 1998, 2011; Uchman, 1998). The main control on the formation of extensive *Spongeliomorpha* horizons seems to be the substrate consistency (Muñiz & Mayoral, 2001; Ekdale & de Gibert, 2010; de Gibert & Ekdale, 2010).

**Ichnospecies of *Spongeliomorpha*.** In the revision of Muñiz & Mayoral (2001), they report various ichnospecies following the ichnotaxobases proposed by Calzada (1981) and added the orientation of the scratch traces with respect to the burrow axis as an important criterion for the ichnospecies differentiation. Recently, Melchor *et al.* (2009) report that some of them did not belong to the ichnogenus because they do not fit the diagnostic features. Thus, Melchor *et al.* (2009) consider that the remaining ichnospecies that belong to *Spongeliomorpha* are: *S. iberica*, with scratch marks forming a reticulate pattern or longitudinal “Y”-shaped bioglyph and ridges (de Gibert & Ekdale, 2010); *S. chevronensis* Muñiz & Mayoral, 2001, exhibiting ridges oblique to the main axis of the burrow; *S. sicula* D’Alessandro & Bromley, 1995, characterised by longitudinal ridges and striated, vertical chambers (also considered *Spongeliomorpha* isp. nov. aff. *sicula* by Lewy & Goldring, 2006); and *S. carlsbergi* (Bromley & Asgaard, 1979), which shows dominantly oblique to transverse surface ridges.

**Description.** The studied specimens appear on the limestone layers (Ra-7) (Fig. 2a), showing a variable preservation (Figs 4g-k). Structures present an exclusive horizontal development, but not well-extended cylindrical or subcylindrical burrow systems are observed; only individual burrow segments are recorded. Thus, elements like Y or T-shaped bifurcations are not observed. Cross-sections are subcircular to ovate and width of the tunnel varies from 15 to 22 mm. Some conical burrow terminations are recorded (Fig. 4g). Burrow walls are clearly unlined, showing deep asymmetrical longitudinal ridges that run parallel or subparallel to the main burrow axis, also some longitudinal “Y”-shaped bioglyphs are appreciated (Fig. 4g).

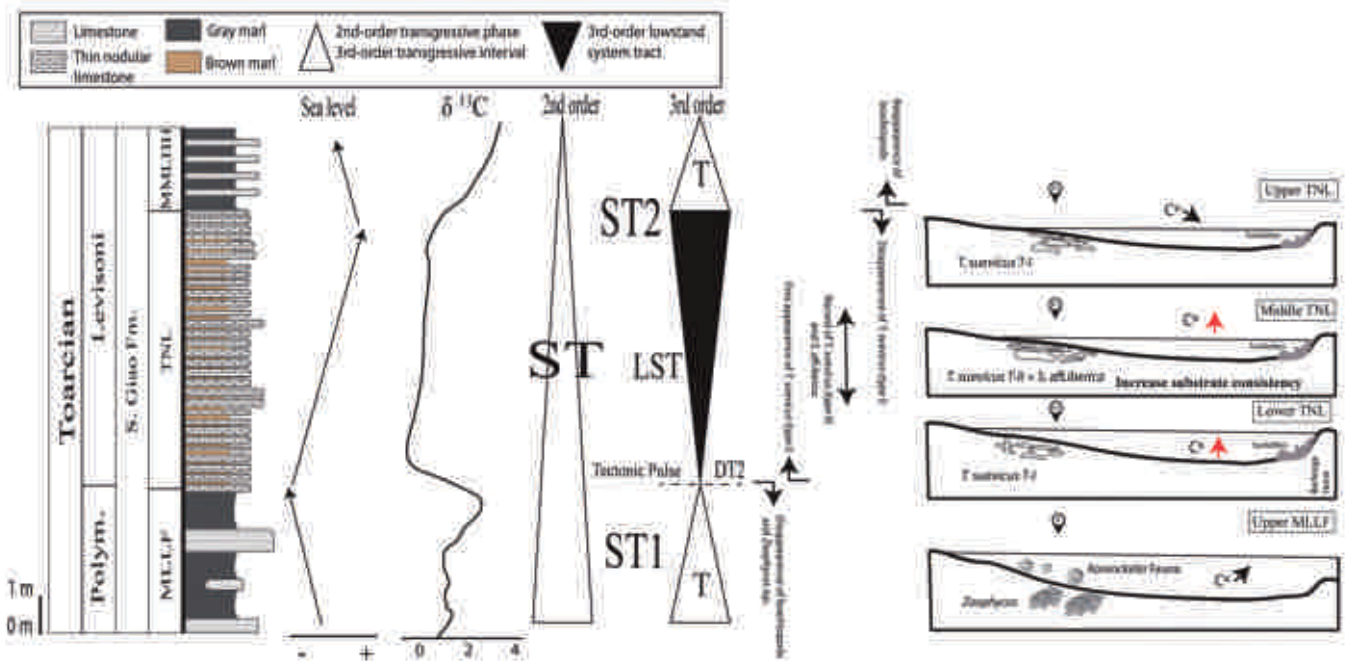
**Ichnotaxonomical classification.** According to the features mentioned above, the ichnotaxobases proposed by Muñiz & Mayoral (2001) and the emended ichnotaxonomical diagnosis proposed by Melchor *et al.* (2009), we can tentatively assign the specimens to *S. aff. iberica*.

## 4. DISCUSSION

### 4.1. Sequence stratigraphy at the Lusitanian Basin

During the last years, detailed sedimentological researches allowed a significant improvement in the sequence stratigraphy framework for the Toarcian of the Lusitanian Basin (e.g., Duarte *et al.*, 2001, 2004, 2007; Duarte, 2007; Pittet *et al.*, 2014). The lower Toarcian succession belongs to a second-order depositional sequence (ST), which is dated from the earliest Toarcian to the early Aalenian and includes the whole São Gião Formation (Duarte, 2007). Into this lower Toarcian part of the second order sequence, the Polymorphum and Levisoni zones of the Rabaçal area are organized into two third-order depositional sequences (ST1 and ST2) separated by discontinuity DT2 (Duarte *et al.*, 2004; Duarte, 2007) (Fig. 5). This boundary between the Polymorphum and Levisoni zones is also associated to an important tectonic activity (Duarte, 1995, 1997; Kullberg *et al.*, 2001; Duarte *et al.*, 2004). The ST1, corresponding to the Polymorphum Zone, is interpreted as a transgressive system tract where isotopic data record an increased trend of  $\delta^{13}\text{C}$  that reach maximum values around +2.6 ‰ just below DT2 (Duarte, 1997; Duarte *et al.*, 2004). This phase is correlated with the deposition of MLLF member, which is the most argillaceous marl/marly limestone (micrite to biomicrite/wackestone) succession of the entire Toarcian (Duarte & Soares, 2002). This member is represented by well developed brachiopod species such as *Koninckella liasina*, *Nannirhynchia pygmaea*, and *Pseudokingena deslongchampsii* that characterize “*Koninckella* Fauna”, which is characteristic of relatively deep zones (Vörös, 2002; Comas-Rengifo *et al.*, 2013).

The transgressive system tract associated with the MLLF is capped by DT2 that coincides with Polymorphum/Levisoni boundary (Fig. 5). This discontinuity is related to important sedimentological changes observed at basin scale. In fact, the basal Levisoni Zone is characterized by strong facies variation that includes chocolate marls in northern sections, calcarenites–calcisiltites with storm influence, and turbidites at Peniche (Wright & Wilson, 1984; Duarte, 1997; Duarte *et al.*, 2004; Suan *et al.*, 2010; Pittet *et al.*, 2014; Rodrigues *et al.*, 2016). These changes in lithology and the variable depositional environments have been attributed to the pre-existing basin morphology with marked topographies (Pittet *et al.*, 2014) as a consequence of regional tectonic pulses (Kullberg *et al.*, 2001), directly related with the Berlenga uplift (see Wright & Wilson, 1984; Duarte, 1997, 2007; Duarte *et al.*, 2004). In terms of sequence stratigraphy interpretation, as the result of this tectonic event, the infill of the base of Levisoni Zone has been interpreted as a lowstand (Duarte *et al.*, 2004, 2007), induced by a rapid relative sea level fall. This lowstand system tract ends on top of the TNL member by the record



**Figure 5.** Summary stratigraphic and sedimentological chart of the lower Toarcian succession at LB: lithostratigraphy, sequence stratigraphy (second and third-order sequences), sedimentary characteristics, carbon-isotopic record and schematic palaeoenvironmental succession based on ichnotaxonomical interpretation (modified from Duarte *et al.*, 2004; Duarte, 2007; Rodrigues *et al.*, 2016). DT2 = 3rd-order sequence boundary; ST = 2nd-order depositional sequence; ST1 and ST2 = 3rd-order depositional sequences; T = transgressive interval; LST = 3rd-order lowstand system tract; FC = Fonte Coberta Section.

of a new transgressive event materialised by decimetric to metric marl-limestone alternations of the MMLH member (Duarte *et al.*, 2004, 2007).

#### 4.2. Ichnological record and sequence stratigraphy framework

Ichnological analysis shows to be very useful in sequence stratigraphy analysis by both, the recognition and interpretation of genetically related sedimentary packages, and the characterization of several-order discontinuities of sequence stratigraphy significance (Rodríguez-Tovar, 2010, for a review). Stratigraphic evolution of trace fossil assemblages, mainly related to changes in substrate consistence associated to variations in the rate of sedimentation induced by changes in the relative sea level, allowed characterization of third-order system tracts (Rodríguez-Tovar & Nieto, 2013; Nieto *et al.*, 2014). On the other hand, presence of particular ichnotaxa, as *Diplocraterion* or *Rhynchonellium*, was used as useful maker in sequence stratigraphy by the recognition of several-order discontinuity surfaces (Olóriz & Rodríguez-Tovar, 2000; Rodríguez-Tovar *et al.*, 2007; Rodríguez-Tovar & Pérez-Valera, 2008).

In the case study, in a context of a trace fossil assemblage dominated by *Thalassinoides suevicus*, it

is especially interesting the coincidence in the same beds at the middle part of the TNL member (Ra-7) of *Thalassinoides suevicus* type II and *S. aff. iberica*. As indicated above, *Spongeliomorpha* is mainly interpreted as related to firm or semi-consolidated substrates, while *Thalassinoides* is common in softgrounds, although occurs in a range of substrate consistencies, including firmgrounds and in the first stages of hardgrounds development (Ekdale & Bromley, 1984; Rodríguez-Tovar *et al.*, 2008; El-Sabbagh *et al.*, 2017). The presence of *T. suevicus* type II, with larger diameter than *T. suevicus* type I, showing long branches forming geometrical mazes, could be related with larger trace makers that bioturbated more consolidate substrates. Thus, the dominant presence of *T. suevicus* type I can be interpreted as revealing a generalized context of soft, but fairly cohesive substrate conditions, punctuated by the occasional increase in substrate consistency favouring bioturbation by *Thalassinoides suevicus* type II and *S. aff. iberica* trace makers. This agrees with the observed changes in lithofacies features. The generalized nodular limestones show a significant change from the lower part of TNL member, with thinner limestone layers and some thick brown marls intervals, characterized by exclusiveness of *T. suevicus* type I, to the middle of TNL member, with thicker limestones layers and thinner marly inter-beds (Ra-6 to Ra-8), where *T. suevicus* type II and *S. aff. iberica* are observed.

The interpreted variations in substrate consistency revealed by the record of *Thalassinoides suevicus* type II and *S. aff. iberica*, could be associated to: 1) minor-order erosions that could determine the exhumation of concealed firmgrounds, or 2) changes in the rate of sedimentation during the proposed lowstand system tract; a decrease of sedimentation rate allowed a higher compaction of the sediment on the sea floor and then development of firmgrounds conditions.

Firmground *Glossifungites* ichnofacies are commonly recorded in association with major stratigraphic surfaces (Pemberton *et al.*, 2004, and references therein). In the study case, the only appearance of two ichnogenera (*Thalassinoides* and *Spongeliomorpha*) cannot allow us a reliable assignation to the *Glossifungites* ichnofacies, although some erosive surfaces can be observed in the base of the limestone layers. The firmground ichnogenus *Spongeliomorpha* has been commonly associated to flooding (transgressive) events (de Gibert & Robles, 2005), but de Gibert & Ekdale (2010) also report the appearance of *S. aff. iberica* in shallow water facies in an erosional regressive context. Furthermore, firmground assemblages with coeval appearance of *Thalassinoides* and *Spongeliomorpha* have been identified previously in lowstand conditions (see MacEachern *et al.*, 1992; Pemberton & MacEachern, 1995).

On the other hand, lithological changes into the TNL member, from Ra-6 to Ra-8, represented by scarce marly inter-bedding and a more calcareous character can be related with decreasing in sedimentation rate. During these periods a higher compaction of the sediment on the sea floor took place, allowing the development of firmground conditions. Besides, recent studies shows that slower sedimentation rate allowed the formation of extensive and bigger *T. suevicus* burrow systems (Abdel Fattah *et al.*, 2010; Whicher *et al.*, 2016; El-Sabbagh *et al.*, 2017). For a more precise evaluation of these two alternative hypotheses, further studies are necessary in more sections from proximal to distal parts of the ramp along the LB.

## 5. CONCLUSIONS

Detailed ichnological study conducted on the Fonte Coberta section at the Lusitanian Basin, shows that during the Toarcian oceanic anoxic event the marly-calcareous succession suffers a high endobenthic activity as reflected the abundance of bioturbation, revealing favourable palaeoecological conditions for trace makers, including oxygen availability. The low impact of environmental conditions associated with the anoxic event, can be the consequence of local conditions determined by a strong palaeotopographic/palaeogeographic control. Ichnological analysis shows the occurrence of horizontal structures, with differentiation of two ichnogenus: 1) dominant

*Thalassinoides*, with exclusiveness of the ichnospecies *T. suevicus*, and the differentiation of morphotypes I and II, characterized by a predominant horizontal development and more frequent Y-shaped than T-shaped bifurcations, and 2) frequent *Spongeliomorpha*, tentatively assigned to *S. aff. iberica*, where asymmetrical longitudinal ridges and some “Y” shaped bioglyphs are the main features. The coeval appearance of *T. suevicus* type II and *S. aff. iberica* along the studied interval, together with the associated lithological changes (scarce marly inter-bedding and a more calcareous character of lithofacies), are interpreted as reflecting increase in the substrate consistency during development of a third order lowstand system tract. The exhumation of concealed firmgrounds due to erosional phases is the most plausible explanation, although decrease in the sedimentation rates cannot be discarded.

## ACKNOWLEDGEMENTS

We thank reviewers Drs. Mayoral (Univ. Huelva) and Reolid (Univ. Jaén), for their valuable suggestions and comments on the manuscript. Also, we sincerely acknowledge the associate editor G. Jiménez-Moreno. The study has been funded by project CGL2015-66835-P (Secretaría de Estado de I+D+I, Spain), Research Group RNM-178 (Junta de Andalucía), and Scientific Excellence Unit UCE-2016-05 (Universidad de Granada). The research of Míguez-Salas is funded through a pre-doctoral grant from the Ministerio de Educación, Cultura y Deporte and a research grant from the Spanish Society of Palaeontology.

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