

## BIOEROSION SCARS OF ACORN BARNACLES FROM THE SOUTHWESTERN IBERIAN PENINSULA, UPPER NEOGENE

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**Abstract.** New etching trace fossils produced by the attachment of balanid barnacles on fossil molluscs, mainly bivalves, from the Upper Miocene of Cacela (southern Portugal) and Lower Pliocene of Huelva (southwestern Spain) are described. These traces are named as *Anellusichnus* n. igen. due to the ring-like shape of the scars. Two ichnospecies are recognized: *A. circularis* n. isp., consisting in a circular scar defined by a discoloured area or by a circular to subcircular trench and *A. undulatus* n. isp. that has a sinuous perimeter reflecting the undulate pathway of the furrow and a flat shelf etched into the substrate. Within the outer furrow both can display a cluster of circular, oval or subpolygonal concentric lines. *A. undulatus* n. isp. shows several morphologies that correspond to different ontogenetic stages.

**Riassunto.** Sono descritte nuove tracce fossili di dissoluzione dovute alla fissazione di cirripedi su molluschi, soprattutto bivalvi, nel Miocene superiore di Cacela (Portogallo meridionale) e nel Pliocene inferiore di Huelva (Spagna sudoccidentale). Queste tracce vengono denominate *Anellusichnus* n. igen., per la forma ad anello delle incisioni. Sono distinte due ichnospecie: *A. circularis* n. isp., che consiste in una incisione circolare delimitata da un'area decolorata o da un solco circolare o subcircolare. *A. undulatus* n. isp., che ha perimetro sinuoso, connesso con la traccia ondulata del solco a base piatta, inciso nel substrato. Nell'ambito del solco esterno entrambe le ichnospecie mostrano un insieme di linee concentriche circolari, ovali o subpoligonali. *A. undulatus* n. isp. presenta diverse morfologie, che corrispondono a diversi stadi ontogenetici.

### Introduction

Attachment scars produced by cirripeds in general and balanids in particular are of frequent occurrence

in exoskeletons from both invertebrates (bivalves, gastropods and limulid arthropods, among others) and vertebrates (turtles, whales). Although such scars have been known in the fossil record for several decades they have never been systematically studied in paleoichnological terms. The earliest findings on molluscs (*Astarte basterotti* Nyst; *Polinices* sp.) were reported by Boekschoten (1967) from the Belgian Pliocene. Subsequently, Miller & Brown (1979), reported on the circular trace fossils left by balanids on molluscs from the Pleistocene in Dare County (North Carolina) and classified them into three different categories depending on their preservation state; the specimens, however, were still not regarded as ichnotaxa. Brande (1982) reported the finding of oval, discoloured trace fossils of a dentate boundary on bivalves from the Pleistocene in Simon's Bluff (South Carolina) which he ascribed to the attachment of balanids. A few years later, Mayoral (1986) found similar trace fossils on molluscs from the Lower Pliocene in the Guadalquivir Basin in Huelva (Spain) and, based on the fact that they were closely bound to remains of the basal plates, also ascribed them to the attachment of balanomorphs. Additional subsequent findings were made by González-Delgado et al. (1995) in fossils from the same area and age. Balanid attachments, particularly of *Balanus concavus* (Bronn) and *B. trigonus* Darwin, have also been encountered in materials from the Pliocene in the Alt Empordà Basin (specifically, in Girona, Spain) (Martinell et al. 2000), but their trace fossils, however, were not described.

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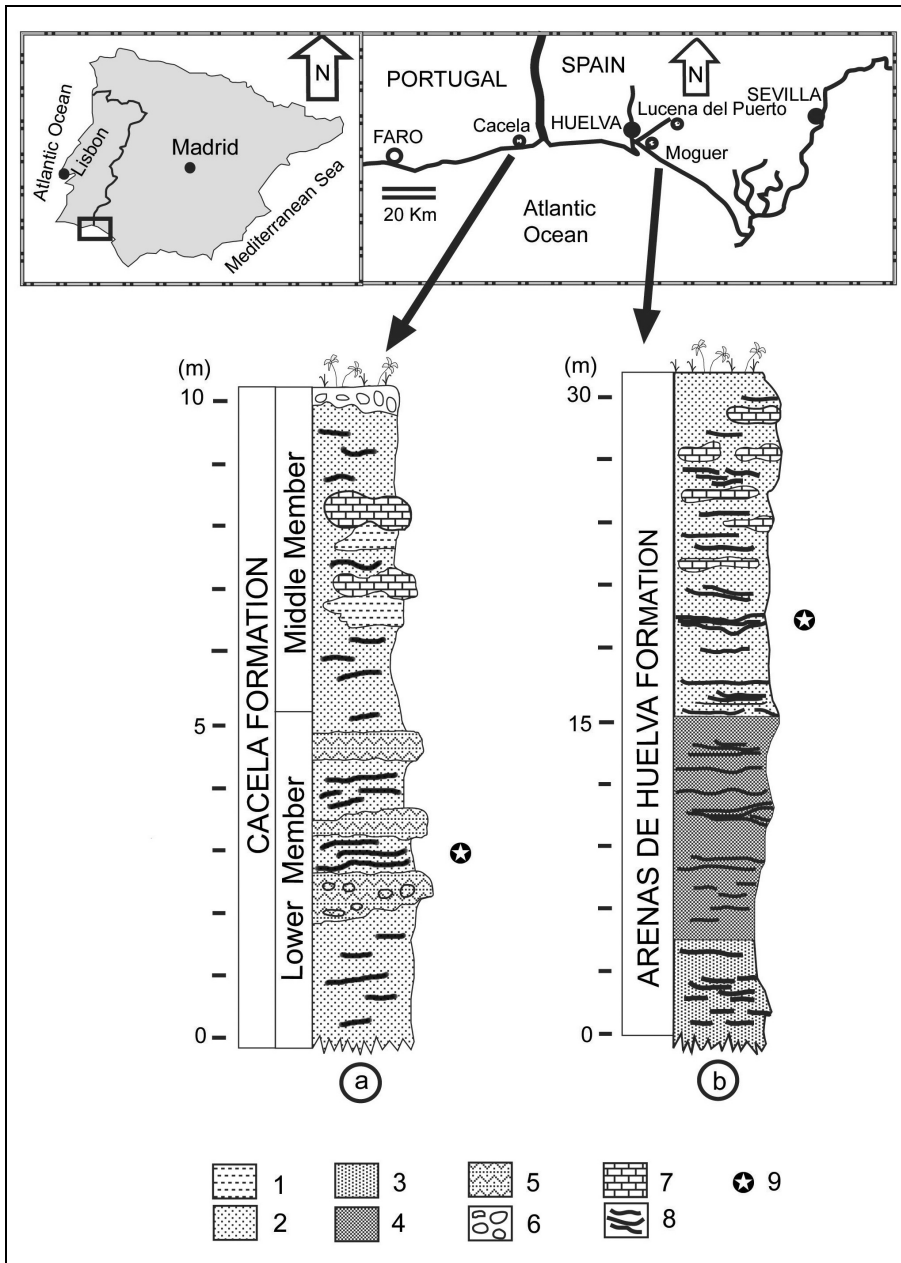


Fig. 1 - Geographical location of the studied areas and simplified lithological logs. a: Upper Miocene, Cacela (Portugal) (Cachão 1995). b: Lower Pliocene, Moguer-Lucena del Puerto (Huelva, Spain) (Mayoral 1986). Lithologic legend: 1. Lutites. 2. Fine sands. 3. Silty sands. 4. Glauconitic sands. 5. Fossiliferous carbonate sands. 6. Conglomerates. 7. Calcareous concretions. 8. Fossiliferous horizons. 9. Horizon yielding the studied material.

Morphologically similar structures were produced by verrucid cirripeds, which have been known since nineteenth century. Thus, Darwin (1854) reported and even illustrated the earliest attachment scars from these organisms, which he found in both contemporary shells and Neogene fossils. Also, Baluk (1975) found attachment scars of verrucids on *Lemintina arenaria* (Linné) from the Lower Tortonian in the Korytinica Basin (Poland). Radwanski (1977) reported similar findings on ostreids from the Miocene in Nawodzice (Poland), as well as in contemporary gastropods on the southern coast of England, and so did Martinell & Domènech (1982) in molluscs from the Holocene in Girona (Spain). More recently, these scars have been examined ichnologically and assigned to *Centrichnus concentricus* (Bromley & Martinell 1991; Bromley 1992, 1994). Therefore, existing studies on attachment scars left by

balanids provide more or less extensive descriptions of the traces but, unlike studies on *Centrichnus*, have failed to consider their high ichnological value. For this reason, and because the scars are very common, a parataxonomic study aimed at unifying identification criteria and establishing the palaeoecological significance of the scars is given.

The studied material was obtained from various sites in the southwest of the Iberian Peninsula. The oldest specimens, from the Late Miocene, were collected in the southeast of Portugal in the neighbourhood of Cacela Velha, located in the area spanned by the Ría Formosa Natural Park. The others, from the Lower Pliocene, were obtained from various locations in the southwestern sector of the Guadalquivir Basin, specifically from Moguer and Lucena del Puerto in Huelva (Spain) (Fig. 1).

## Stratigraphy

The Cacela site shows only two of the three members that characterize the Cacela Formation in the Algarve region (*sensu* Cachão et al. 1998). The series is constituted by the lowest member, consisting of 5-6 m of fossiliferous conglomerates and fine sands, which is representative of a shallow infralitoral environment. The middle member, consisting of 5-13 m thickness, represented by fine sands and lutites forming a succession of orange-yellow silt with intercalation of pelitic levels that are grey in colour and 50 cm in thickness. The outcrop lies within the lowest member of this formation (Fig. 1a).

Calcareous nannoplankton data (Cachão 1995) for the lowest member of the Formation, estimate the age of the sediments between 8.2 (FAD's for *Discoaster berggrenni* and *D. quinqueramus*) and 7.5 Ma (LAD for *Minylita convalis*), which corresponds to the Upper

Tortonian (Late Miocene). These estimates are consistent with data obtained by planktonic foraminifers (Le-goinha 2001).

In the Spanish sector, the stratigraphic series of the Arenas de Huelva Formation, typical of a shallow infralitoral marine environment, consists of 10 to 30 m thickness of yellowish-brown fine sand that is silty in its lower interval and exhibits a glauconitic horizon at the lower part (Fig. 1b). According to Civis et al. (1987), the age of this formation is Lower Pliocene (Tabianian, upper portion of the biozone of *Globorotalia margaritae* and part of the biozone of *G. puncticulata*) (Sierro 1985; Civis et al. 1987; González-Regalado 1986).

## Material

The studied structures from the Late Miocene occurred mainly on the inner side of shallow infaunal bivalves, namely *Megacardita jouanneti* Basterot, *Callista (C.) italica* (Defrance), *Circomphalus foliaceolamellosus* (Dillwyn) and *Glycymeris bimaculata* (Poli), all from the lower member of the Cacela Formation. Those from the Lower Pliocene were found on epifaunal bivalves including *Chlamys (Flexopecten) flexuosa* (Poli), *Crassadoma multistriata* (Poli), *Pecten (P.) cf. planariae* Simonelli, *Amusium cristatum* (Bronn), *Ostrea (O.) edulis* Linné and gastropods such as *Neverita josephimia* Risso from the Arenas de Huelva Formation. These kinds of structures were seen in recent ostreids and pectinids shells (Holocene) in the southwestern atlantic coast of Spain.

An overall 232 bioerosive structures from the Miocene and 60 from the Pliocene were examined and measured. The Miocene material describes in this work is deposited in the collections of University of Algarve (Portugal) with RC references and the Pliocene one, in the Geological Museum of the University of Seville (Spain), with PN references.

## Systematic Paleichnology

### *Anellusichnus* n. igen.

**Derivatio nominis.** From the Latin *anellus* (ring), after its ring-shaped structure.

**Type ichnospecies.** *Anellusichnus undulatus* Santos, Mayoral & Muñiz (this paper).

**Diagnosis.** Surface traces of circular or subcircular to oval - subpolygonal shape. In the simplest case, the boundary is revealed merely by a colour difference in the substrate or, more often, by the presence of a shallow, ring-shaped furrow following a curved, rectilinear or festooned pathway. Within this outer furrow, as a rule, additional structures occur consisting of very faint, circular, oval or subpolygonal concentric striations.

**Stratigraphic range.** Late Tortonian (Late Miocene) - Holocene

### *Anellusichnus circularis* n. igen., n. isp.

Figs 2 a-b; Pl.1, figs a-f

1967 Barnacles ring-shaped furrows Boekschoten, p. 327, text-fig. 18.

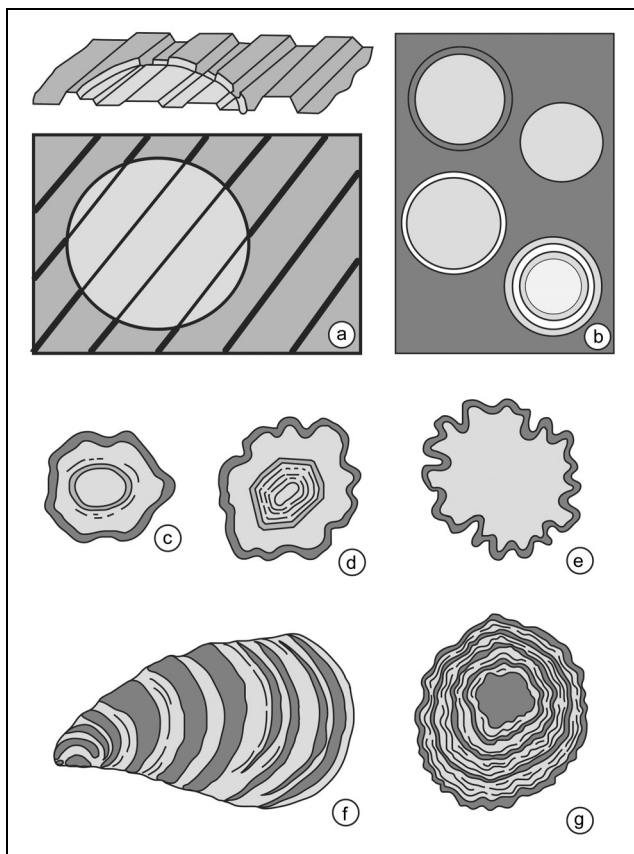


Fig. 2a-b. - Sketches of *Anellusichnus circularis* n. igen., n. isp., showing different states of conservation. a. Circular scar reducing primary ornamentation of the substrate. b. Circular, discoloured scars with and without outer furrow and with concentric interior lines. c-e. Sketches of *Anellusichnus undulatus* n. igen., n. isp. c. early ontogenetic state, with subpolygonal, outer furrow. d-e. late ontogenetic states, with typical, undulating furrow. f-g. Sketches of *Centrichnus*. f. *C. eccentricus*. g. *C. concentricus*. Scale of grey colours means deeping in the substrate. Light grey: shallower, dark grey: deeper.

1979 Balanid attachment scars Miller & Brown, pp 208-210, text-fig. 1A.

1986 Balanomorphous cirriped marks Mayoral, p. 295, text-pl. XIX, figs 6, 7.

**Derivatio nominis.** From the Latin *circularis* (circular), after the ring-shaped groove.

**Locus typicus:** Lucena del Puerto (Huelva, Spain).

**Stratum typicum:** Arenas de Huelva Formation (Huelva, Spain).

**Holotype.** PN-205.

**Paratypes.** PN-206 to PN-210; PN-826/1 to PN-826/6, PN-828.

**Diagnosis.** Circular or subcircular in shape and exposed by a discoloured zone that differs in preservation state from the neighbouring surfaces or a very shallow ring-shaped furrow with a curved pathway. The inside is smooth or exhibits concentric circular etched rings.

**Description.** Superficially etched, circular or subcircular trace fossils, either clustered or in isolation. When the boundary is exposed by a colour change in the substrate, usually is discoloured and the inner zone differs in preservation state from those around it, which is less well preserved. (Fig. 2 b). Otherwise, the colour difference is restricted to the outer ring, which is normally fairly wide (0.7 - 2.8 mm) (Pl.1, figs c and f.). If the trace fossil involves some ornamental structure, this exhibits a more gentle relief (Fig. 2 a, Pl. 1, figs a-b). If it is bounded by a furrow, this is typically very shallow (Pl.1, fig. e) and follows a curved pathway. When the trace fossils are less than 8 mm in diameter, the thickness of the furrow is 20 - 40 times smaller than its diameter, or exceptionally, in some Miocene records, it is only 6 times smaller at most. On the other hand, if the diameter exceeds 12 mm, then the furrow is only 15 times smaller. As a rule, the diameter of the trace fossil ranged from less than 1 mm to 30 mm with a average of 10 mm. In some cases, two or three series of subcircular concentric lines are observed in the inner zone (Fig. 2 b). When the basal calcareous plate is apparent, the furrow may or may not be present depending on the particular *Balanus* species. Thus, in *Balanus* (*B.*) *spongicola* (Brown), which possesses a thin, porous basal plate, the furrow is usually present around the plate (Pl. 1, fig. e). On the other hand, in *Balanus* (*B.*) *amphitrite* (Darwin), which possesses a somewhat thicker plate, the furrow is either absent or not so apparent.

**Range.** Late Tortonian (Late Miocene) - Holocene.

**Remarks.** One of the oldest findings of attachment scars from *Balanus concavus* (Bronn) corresponds to the first fossil example reported and illustrated by Lister (1687) in North America on the bivalve *Chesapeake madisonius* (Say), from the Pliocene Yorktown Formation (Virginia). However, closer inspection of the scars suggests that they cannot correspond to balanomorph attachments as they are not circular or subpolygonal, but rather drop- or teardrop-shaped. They are thus more likely to correspond to some gastropod

with an attaching habit, for exemple *Crepidula*. These scars have also been encountered in similar fossils of the same age from the southwest of the Iberian Peninsula (Santos et al. 2001; Santos et al. 2003).

The characteristics of *A. circularis* coincide with those reported by Boekschoten (1967), who found ring-shaped scars on some mollusc shells. The scars had the form of shallow furrows that occasionally contained many other, concentric furrows inside. This author even found several ring systems on the same side of a specimen. Similarly, Miller & Brown (1979) encountered three different types of scars on shells ranging from discoloured zones, or circular spots with 1 - 3 mm in diameter, in some cases clustered or in concentric arrangements to circular or subcircular patches where the shell surface was less markedly weathered. The latter were bounded by a furrow 0.1 - 0.3 mm wide and occurred either clustered or in isolation. Mayoral (1986) also identified shallow depressions with a circular boundary occasionally bounded by a furrow. This author related such depressions to those previously found by Miller & Brown (1979) and ascribed them to the attachment of balanomorphous cirripeds (Pl. 1, fig. f).

The differences among types are insubstantial and restricted to preservation state and/or the degree of ontogenetic development. Thus, they differ from *Anellusichnus undulatus* in that this ichnospecies exhibits a well-defined boundary consisting of a shallow furrow of subpolygonal or markedly festooned geometry. Only the smallest forms of *A. circularis* might be close to those of *A. undulatus* at their early stages, however, their boundaries are distinctly different. The differences from *Centrichnus concentricus* (Bromley & Martinell 1991) are quite marked, in fact, this exhibits a round-shaped central depression surrounded by a shallow platform excavated in the substrate. The platform possesses an oval, crenulate perimeter and occasionally exhibits an inner pattern of concentric and also crenulate rings (Fig. 2g).

#### **Anellusichnus undulatus** n. igen., n. isp.

Figs 2 c-e, Pl. 1, figs g-j, Pl. 2, figs a-f

2001 Attachment scars from balanomorphous cirripeds Santos et al., pp 474-479, text-fig. 1C, figs 8-14, 1-17.

**Derivatio nominis.** From the Latin *undulatus* (undulate), after the wavy pathway followed by the furrow forming the ring.

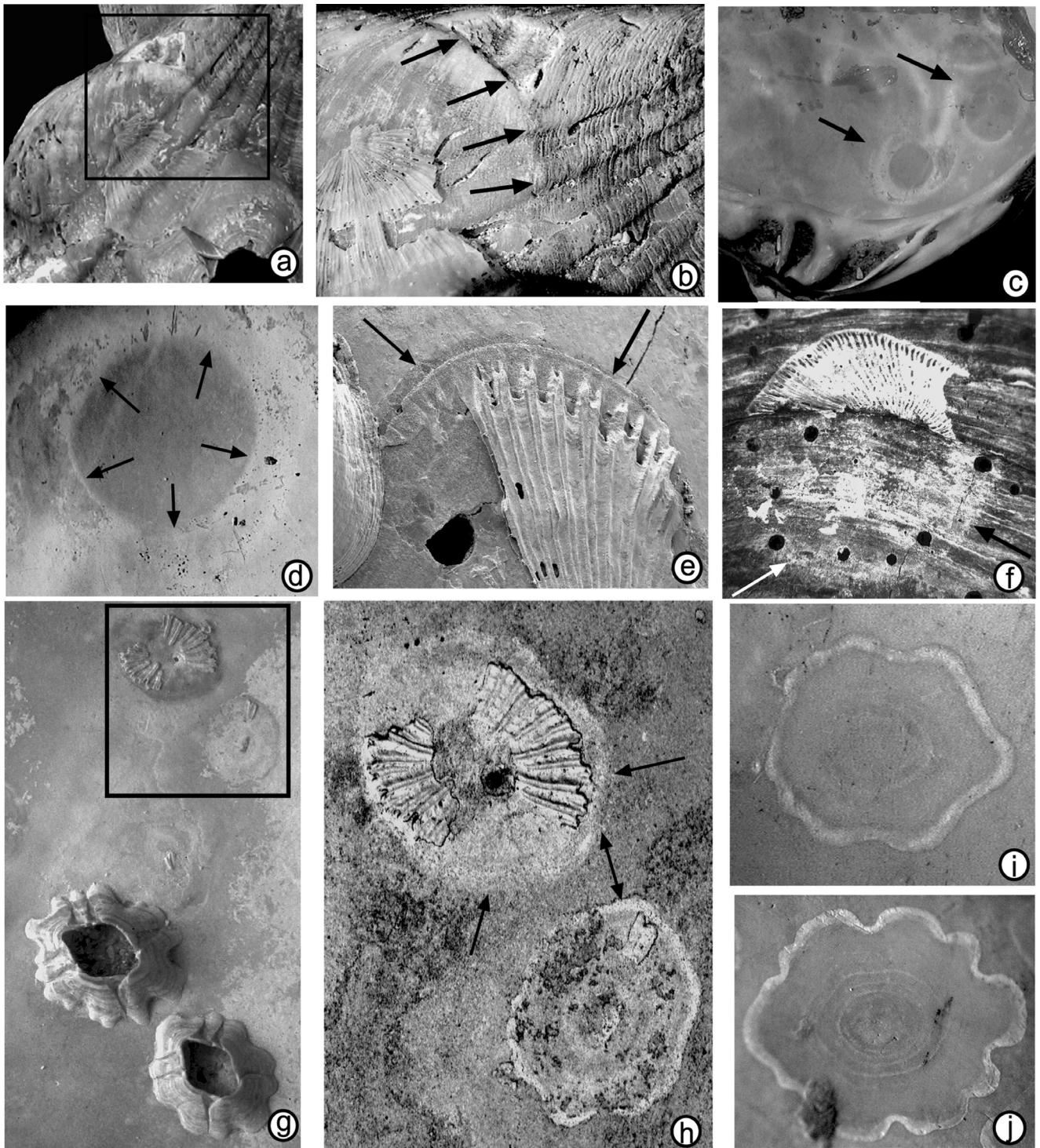
**Locus typicus.** Ribeira de Cacela (Portugal).

**Stratum typicum.** Lower member of the Cacela Formation.

**Holotype.** RC-9/1.

**Paratypes.** RC-9/2 to RC-9/16; RC-10/1 to RC-10/5; and RC-12-13.

**Diagnosis.** Oval to subpolygonal trace fossil in the form of a well-defined outer furrow following a curved to rectilinear pathway at the initial ontogenetic stages and a markedly festooned pathway at the later ones. The inner zone usually exhibits fine, concentric grooves of subovoid to subpolygonal shape. In some cases, these grooves are at least as deep as the outer furrow.



## PLATE 1

- a-f. - *Anellusichnus circularis* n. igen., n. isp.. a-b. on *Pecten* (*P.*) cf. *planariae* Simonelli and *Balanus* (*B.*) *spongicola* Brown. Holotype PN-205. a. General view. b. Close-up of the trace showing the circular discoloured area (arrows). This area exhibits minor ornamentation and preserves remains of the basal plate. c. Trace exhibiting a relatively width ring. Paratype RC-11. Cacela Velha; Cacela Formation, x1. d. Detail of the former trace showing the width discolored area, x4.2. e. Trace showing the typical circular furrow (arrows). Basal plates of *Balanus* (*B.*) *spongicola* are superimposed. Paratype PN-826/1. Specimens a-b and e-f from Lucena del Puerto; Huelva Sands Formation, a: x0.4, b: x0.2, e: x30. f. Trace displaying the typical circular discoloured area with remains of a basal plate. *Entobia* borings are superimposed. Paratype PN-209, x3.
- g-h. - *Anellusichnus undulatus* n. igen., n. isp.. g. Tests of *Balanus* (*B.*) aff. *crenatus* Bruguière with containing remains of the basal plates. Paratypes RC-10/1-3, x5; h. Close-up of the former picture showing the trace (arrows) with remains of the basal plates. Paratypes RC-10/1-2, x3; i. Expression of the trace corresponding to the first stages of the incrustation. Paratype RC-9/3, x28.5; j. Late ontogenetic phase. Paratype RC-9/2, x15.8. All specimens from Cacela Velha; Cacela Formation.



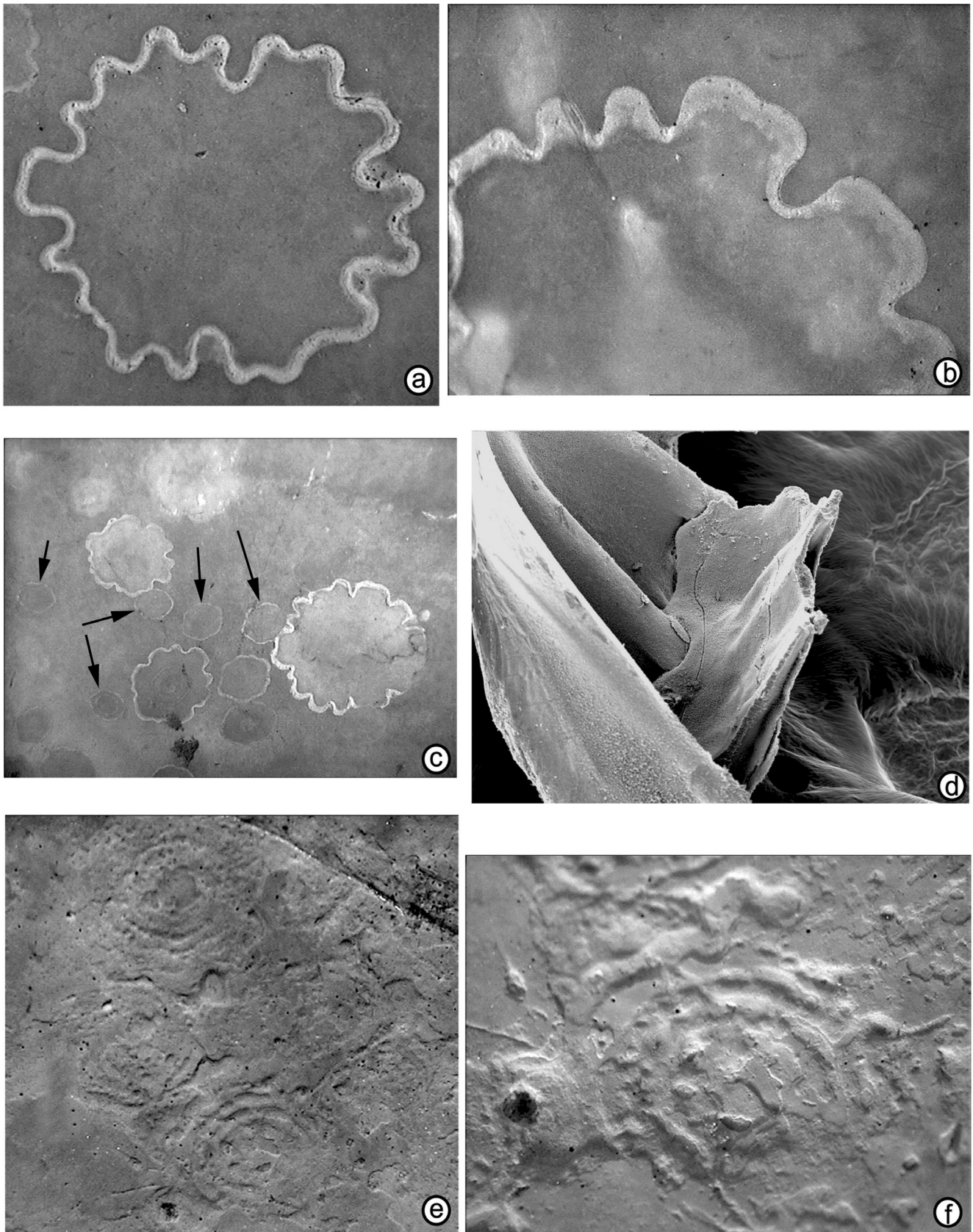


PLATE 2

a-f. - *Anellusichnus undulatus* n. igen., n. isp.. a. Typical morphology exhibiting the characteristic undulating furrow. Last ontogenetic phase. Holotype RC-9/1, x14.5; b. Close-up of the undulating furrow, x34; c. Group of traces in several ontogenetic phases. Arrows shows early subhexagonal phases. Paratypes RC-9/2-11, x6; d. *Balanus* (*B.*) aff. *crenatus* observed by S.E.M, showing the joint zone between the basal plate and the undulating wall of the test. Paratype RC-13, x1000; e-f. Traces showing a preservation consisting of small, concentric ridges and furrows. e. Paratype RC-12, x8.5; f. Close-up of the former specimen, x10. All specimens from Cacela Velha; Cacela Formation.

**Description.** The structures identified consist of a series of scars, whether isolated or in small groups, which range from 1 to 8.5 mm in diameter. The boundaries of the scar vary in shape. Thus, small scars have subhexagonal boundaries (Fig. 2 c, Pl. 1, fig. i, Pl. 2, fig. c) while larger scars have subrounded or subovoid boundaries (Fig. 2 e; Pl. 1, fig. j, Pl. 2, figs. a, and c). The former are simpler 1 to 2 mm in diameter. They exhibit poorly and scarce defined concentric lines of oval to subrhomboid shape in the inner zone (Figs. 2 c-d, Pl. 1, figs i-j). The latter are more complex and vary from 4 to 9.5 mm in diameter; and exhibit a very special morphology, with a ribbon-shaped furrow following a wavy pathway that results in a very typical festooned structure consisting of very tight folds at well-defined intervals (Fig. 2 e, Pl. 1, fig. j, Pl. 2, figs a-c). This pathway corresponds to a shallow furrow excavated in the substrate surface (Pl. 2, fig. d), the furrow has a flat bottom and is 0.05 – 4 mm wide. The zone inside this perimeter occasionally exhibits some, usually very soft, concentric lines arranged similarly to the previous lines (Fig. 2 d, Pl. 1, fig. j). In some specimens, the surface features are furrows that are as well defined as that constituting the outer boundary (Pl. 2, figs. e-f). In a few specimens, additionally to the trace, calcareous remains of plates appear in the vicinity of the concentric lines that exhibit simple or double radial structures running from the centre of the scar to its periphery (Pl. 1, figs g-h).

**Range:** Late Tortonian (Late Miocene).

**Remarks.** The characteristics of *A. undulatus* are somewhat similar to those of the ichnotaxa *Centrichnus eccentricus* and *C. concentricus* found both in Recent and fossil materials (Bromley & Martinell 1991; Bromley 1999). However, *C. eccentricus* and *C. concentricus* differ substantially in their general structure and dimensions between 10 to 8.5 mm, respectively. *Centrichnus eccentricus* is a scar having a compact, teardrop-shaped boundary enclosing arched, concave lines ending in a truncation (Fig. 2 f). By contrast, *A. undulatus* exhibits a wavy, folded peripheral furrow or a subrhomboid shape when the furrow is absent (Pl. 1, fig. i, Pl. 2, fig. a). Both of these structures possess inner concentric furrows, however there are circular or suboval for *A. undulatus* (Pl. 2, figs e-f), and crenulate for *C. concentricus*, which are the repetition of its crenulated margin. On the other hand, one of the most important distinctions between *C. concentricus* (Fig. 2 g) and *A. undulatus* is the lack of a deep central depression in the latter.

In those cases where the attachment was loose, the scars can be confused with those left by the gastropod *Hippoxis conicus* (Schumacher). Such scars clearly reflect the shape of the gastropod, with a central depression that is deeper than the remainder of the older apical portion of the shell. Unlike *C. concentricus*, the depres-

sion lies between the edge and the centre. Also, the scars are much more elliptical and asymmetric, and the crenulate edge, when present, spans only a portion of the boundary, which in turn reflects the presence of very soft radial ribs on the substrate (Radwanski 1977). These radial ribs as such have never been encountered in *A. undulatus*.

## Discussion

The above described trace fossils can be considered to be bioerosive structures produced by the attachment of balanomorphous cirripeds. This assignation is easily arrived at as the structures are normally closely related to the tracemakers, which occur in their natural living position, and to the preservation state of the scars (Miller & Brown 1979). As regards the ichnotaxa studied in this work, the tracemaker for *Anellusichnus undulatus* is a species related to *Balanus (B.) crenatus* Bruguière (Pl. 1, Fig. g). On the other hand, the tracemakers for *A. circularis* include at least *Balanus (B.) spongicola* and *Balanus (B.) amphitrite*. The lines within the smaller structures, which are simpler, reflect the successive growth stages of the basal plate of the balanomorph. This grows from a wedge of mantle tissue, located between the base joint and the wall plates, and successively incorporates new material to the periphery of the bottom and the lower edges of the older plates.

The outer furrow originates from the interaction between new cuticle secreted by the organism as it grows and the surface of the substrate on which it rests (Pl. 2, fig. d). This form of attachment distinguishes these signals from those of verrucids, which are quite similar. These organisms lack a stable calcareous basal plate bound to the substrate. In fact, they attach to it by a chitin membrane (Radwanski 1977). The typical central depression of *Centrichnus*, which is relatively deep compared to the adjacent ridge, suggests that the organism attaches to the substrate not only by the membrane, but also throughout the growth zone of the verrucid tracemaker. This growth mechanism is not observed in balanids, which, as noted earlier, provide a rather different record.

Finally, the different morphologies observed for *A. undulatus* are directly related to the successive growth stages of the organism. The studied specimens allow a comprehensive ontogenetic series spanning from the early juvenile stages to adult to be established (Figs 2 c-e, Pl. 1, figs i-j, Pl. 2, figs a-c).

This new bioerosive structure possesses a high paleoecological significance. In fact, it can be used to precisely quantify balanid populations when these are absent as a result of detachment from the supporting substrate. Also, as noted by Boekschoten (1967), they

can be used to reconstruct their relationship to their substrates, particularly if they were organic, for example molluscs. Thus, in the case of bivalves, the location of the scars in the shells can be used to ascertain whether the host substrate was colonized while living, and hence to reconstruct its position in the bottom, or at a post-mortem stage, which can provide highly precise information about the taphonomic history of the bivalve (Mayoral 1986).

## Conclusions

The study of surface structures on shells from epifaunal and infaunal bivalves, and gastropods, obtained from subtidal marine sediments from the Upper Miocene and Lower Pliocene in the SW of the Iberian Peninsula, revealed the presence of attachment scars produced by balanid cirripeds. The signals are described as a new ichnotaxon called *Anellusichnus* after the ring-shaped marks observed. Two new species were identified, namely *A. circularis* and *A. undulatus*. The former consists of a circular or subcircular boundary that bounds a discolored area with a soft relief in relation

to the neighbouring zones. It is occasionally bounded by a very shallow, curved furrow. The latter exhibits a variable morphology that is essentially subpolygonal and consists of a rectilinear or markedly wavy furrow that is the most typical shape for this ichnospecies and corresponds to the latest ontogenetic stage. Both ichnospecies can exhibit a series of circular, oval or subpolygonal inner lines.

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