

UNCONFORMITY SURFACES IN PELAGIC CARBONATE ENVIRONMENTS: A CASE FROM THE MIDDLE BATHONIAN OF THE BETIC CORDILLERA, SE SPAIN

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Abstract: Integrative studies of sedimentary and palaeontological topics for unconformity surfaces are useful in basin analysis. A middle Bathonian unconformity surface in the Ammonitico Rosso facies cropping out in the La Mola Unit (Subbetic Domain, Betic External Zone) was studied by integrating ichnological, palaeotectonic, and sedimentological analyses to decipher sea-level, tectonic, and palaeogeographic conditions during its development. The trace-fossil assemblage mainly consists of the *Glossifungites* (*Thalassinoides*, *Arenicolites*, and *Gastrochaenolites*) and *Trypanites* ichnofacies elements. Probable *Ophiomorpha* represents previous softground stages, *Thalassinoides* and *Arenicolites* were formed in firmground, *Gastrochaenolites* reflects an evolved firmground or early hardground, and *Trypanites* can be attributed to an incipient hardground. The degree of firmness, relative sea-level position, and continuity of deposition were related. The softground stage corresponds to a fall in relative sea level and continued deposition. The firmground (semi-consolidated substrate) probably reflects an extremely low sea level characterized by non-deposition, whereas the incipient hardground stage indicates an initial phase of relative sea-level rise, with an increase in marine current energy. The presence of two neptunian dyke systems reflects significant tectonic activity related to the transtensional deformation that affected the South Iberian Palaeomargin. Lateral variations in sedimentological and ichnological features recorded at similar discontinuity surfaces in nearby areas were considered and related to differences in bottom topography, with associated changes in sedimentation, and to the variable duration of the hiatus.

Key words: Unconformity, pelagic swell, softground, firmground, hardground, Middle–Late Jurassic, Betic External Zone.

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INTRODUCTION

A comparison between Jurassic pelagic swells, mainly characterized by the Ammonitico Rosso facies (red, nodular limestones or nodular, marly limestones, both with and without ammonites), and current examples is complicated, mainly owing to changing palaeoceanographic conditions between the Jurassic Tethys and Recent marine pelagic environments (e.g., Jenkyns, 1974; Mullins *et al.*, 1980; Bernoulli and Jenkyns, 2009; among others). A recent comparison between the pelagic swells in the External and Internal Subbetic zones (Betic Cordillera, Southeast Spain) and the Hancock Seamount (Hawaiian Ridge) and the Fieberling Guyot (at 32° N, off the U.S. Pacific coast) reveals that a delicate balance between sediment deposition and winnowing determined the sediment accumulation rate in

these settings (Coimbra *et al.*, 2009). This agrees with the general genetic model proposed for the Ammonitico Rosso facies (Jenkyns, 1974; Seyfried, 1978; Martire, 1992, 1996; Bertok and Martire, 2009, among others), which considers four main factors: (a) bottom currents, (b) early cementation, (c) bioturbation, and (d) gravitational processes.

Ammonitico Rosso facies are common in Mediterranean Alpine chains and typified the Middle and Upper Jurassic of the External Subbetic (Seyfried, 1978; Molina, 1987; Rey, 1993; Nieto, 1997; Coimbra *et al.*, 2009), as in other pelagic Tethyan domains (e.g., Elmi, 1981; Martire, 1992; Santantonio, 1993; Martire and Pavia, 2004; Basilone, 2009; Bertok and Martire, 2009). In the Betic Cordillera, these facies form the Upper Ammonitico Rosso For-

mation (Molina, 1987), dated as Bajocian–Lower Berriasian (Vera, 2001). A typical feature of these facies is their low sedimentation rate (references above). In the Austrian Alps, Jenkyns (1986) estimated sedimentation rates between 0.5 and 1.5 mm/kyr and in the Apennines, sedimentation rates between <1 and 6.5 mm/kyr. In the Subbetic Domain, Vera (1989) calculated sedimentation rates between 1 and 5 mm/kyr, whereas Nieto (1997) deduced values ranging from 1 to 2 mm/kyr for the eastern External Subbetic Domain. In the case of the Oxfordian condensed deposits in the neighbouring Prebetic Domain, Rodríguez-Tovar *et al.* (2010) interpreted a sedimentation rate of 1.5–1.6 mm/kyr. These low sedimentation rates favoured synsedimentary cementation and the development of firmgrounds and hardgrounds (Tucker and Wright, 1990; Coimbra *et al.*, 2009) associated with very long hiatuses, in the order of millions of years, but without marked facies contrasts and/or angular unconformities that might indicate significant tectonically driven environmental changes. Frequently, these hiatuses are associated with a single discontinuity surface that splits laterally into several minor discontinuities, separated by condensed levels.

Ammonitico Rosso facies are usually associated with a record of diverse omission surfaces (Nieto *et al.*, 2012 and references herein). In the External Subbetic Domain, different authors have reported unconformities in the Jurassic record and in the Upper Ammonitico Rosso Formation (Molina, 1987; García-Hernández *et al.*, 1989; Ruiz-Ortiz *et al.*, 1997; O'Dogherty *et al.*, 2000). Recently, Reolid *et al.* (2010) and Nieto *et al.* (2012) have characterized five unconformity surfaces within this formation in several tectonic units (the Quípar, Lúgar-Corque, Cantón, Crevillente, and Reclot units) located in the Lower–Middle Bathonian (Hg1), the Middle–Upper Bathonian (Hg2), the Lower–Middle Callovian (Hg3), the Middle–Upper Callovian (Hg4), and the Callovian–Oxfordian (Hg5). In some outcrops, these authors define a stratigraphic break as Middle Bathonian–Middle Oxfordian, interpreted as the superposition of the Hg1 to Hg5 unconformities.

The aim of this paper is to improve the interpretation of unconformity surfaces developed on carbonate pelagic swells on the basis of the integration of ichnological, palaeotectonic (neptunian dykes), and sedimentological (facies and microfacies) analysis. An unconformity surface in La Mola Unit outcrops (eastern Subbetic Domain) was studied for this purpose. The best outcrop of this unconformity surface is located in the northwest faulted limb of the anticline, made up of Jurassic rocks (Fig. 1). The characterization and evolution of substrate firmness, from softground to firmground and then hardground conditions are of major interest for the interpretation of sedimentary evolution, on the basis of their relationship with sea-level conditions (Christ *et al.*, 2012; Nieto *et al.*, 2012). The conclusions could be applied to other Western Tethys domains where the sedimentation of Ammonitico Rosso facies was important during the Jurassic and unconformity surfaces were abundant (Martire, 1992, 1996; Bertok and Martire, 2009; Basilone, 2009; among others).

SEDIMENTARY CONTEXT

La Mola Unit lies in the easternmost Subbetic Domain (Nieto, 1997) (Province of Alicante, southern Spain; Fig. 1A, B). From a tectonic point of view, it can be defined as a Jurassic tectonic window surrounded by Triassic rocks (Fig. 1B). The Jurassic succession (Fig. 1C) shows stratigraphic features typical of the External Subbetic and of the Intermediate Domain, which indicates that this unit had a palaeogeographic location in the transition between the External Subbetic Domain and the Intermediate Domain (Fig. 2). The External Subbetic Domain has been defined as a row of shallow, pelagic swells characterized by Middle–Upper Jurassic Ammonitico Rosso facies (e.g., Vera *et al.*, 1988; Molina and Ruiz-Ortiz, 1993; Vera, 2001). The Intermediate Domain, north of the External Subbetic Domain, was a pelagic trough where calcareous turbidites were deposited during the Upper Jurassic (Ruiz-Ortiz, 1983). According to the proposed model for the South Iberian Palaeomargin (Vera, 2001), the transition between the two domains is made up of several half-graben structures arranged in a series of steps. These structures were controlled by listric faults. Lateral facies changes between Ammonitico Rosso facies and calcareous turbidites are observed there.

In the La Mola Unit, the lowermost Jurassic stratigraphic formation is the Gavilán (Fig. 1C), dated as Hettangian–Lower Pliensbachian. This formation corresponds to shallow carbonate-platform facies, which crop out in the Intermediate and External Subbetic Domains (Molina, 1987; Nieto, 1997; Ruiz-Ortiz *et al.*, 2004). The overlying Baños Formation (Middle Toarcian–Aalenian) characterizes the Intermediate Domain (Fig. 1C) and encompasses a lower member of marlstones and marly limestones and an upper member of thin-bedded dolostones. These facies represent hemipelagic sediments (Ruiz-Ortiz, 1980). The dolostones developed through secondary dolomitization processes (Nieto, 1997).

The Middle–Upper Jurassic Upper Ammonitico Rosso Formation (UAR Formation) is the most typical formation of the External Subbetic Domain (Figs 1C, 3). This unit comprises two members. The lower member is 10 m thick and devoid of ammonites and macrofossils (Fig. 3). It has been dated as Bajocian–Lower Bathonian on the basis of correlations with the nearest tectonic units (Nieto, 1997). According to the terminology of Martire (1996), this member is made up of red, bioturbated, pseudonodular marly-limestones with intercalated nodular or pseudonodular limestones with local parallel lamination (Fig. 3). All these lithologies are wackestone with “filaments” (F1 facies in Table 1). This member ends with a 40-cm-thick limestone bed with F2 facies (in Table 1).

The upper member is 5 m thick and from base to top consists of thin-bedded limestones, marly limestones, red nodular marly limestones, a thick limestone horizon and pseudonodular limestones. All these lithologies correspond to wackestone to packstone of bioclasts (F3 facies in Figure 3 and Table 1). This member has been dated as Upper

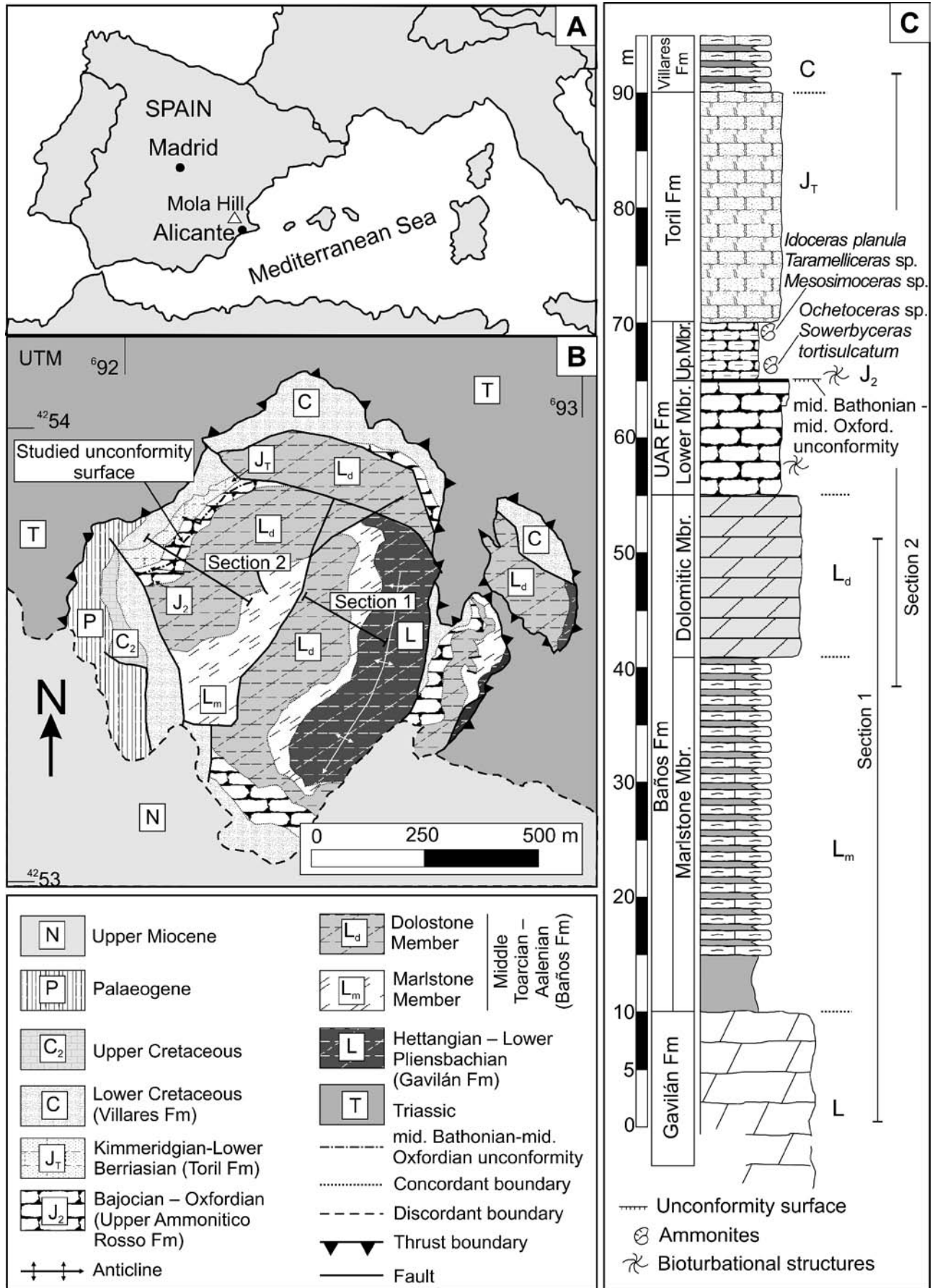


Fig. 1. Geographic and geologic features of study area. A. Location of La Mola Hill. B. Geological sketch map of La Mola Unit. C. Compound stratigraphic section of Jurassic succession of La Mola Unit.

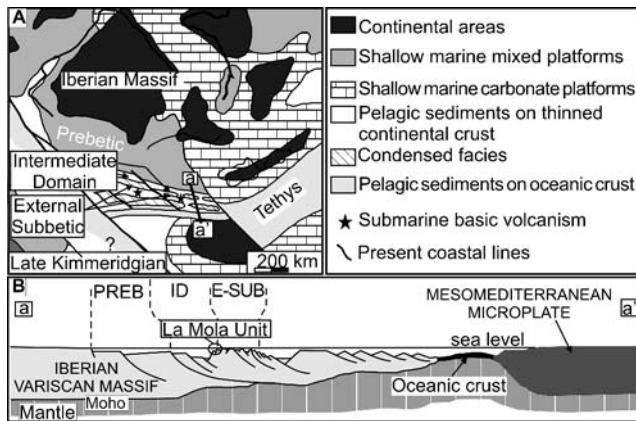


Fig. 2. Palaeogeographic reconstruction of the South Iberian Palaeomargin. **A.** Palaeogeographic map of the South Iberian Palaeomargin for the Late Kimmeridgian (simplified from Vera, 2001). **B.** Palaeogeographic section of the South Iberian Palaeomargin with location of the La Mola Unit (slightly modified from Vera, 2001).

Oxfordian on the basis of ammonites (Nieto, 1997). In the lower and middle parts of the member (Figs 1C, 3), the presence of *Sowerbyceras tortisulcatum* and *Ochetoceras* sp. allows assignment to the Bifurcatus Zone (first biozone of the Upper Oxfordian, after Ogg, 2004, Fig. 4). In the upper part of this member, *Idoceras planula*, *Taramelliceras* sp., and *Mesosimoceras* sp. identify the Planula Zone, which is the last biozone of the Upper Oxfordian biostratigraphy, after Ogg (2004) (Fig. 4). The boundary between the lower and upper members of the UAR Formation is a surface with trace fossils and neptunian dykes that represents the Middle Bathonian–Middle Oxfordian unconformity.

The uppermost Jurassic formation in the La Mola Unit is the Toril Formation (Kimmeridgian–Lower Berriasian, Nieto, 1997), which is made up of calcareous turbidites and pebbly mudstones. This is the most representative formation of the Intermediate Domain (Ruiz-Ortiz, 1980); it corresponds to an apron deposited on the slope of an External Subbetic swell (Nieto, 1997). The Villares Formation (Fig. 1C) is the first stratigraphic unit of the Cretaceous, made up of alternating marls and marly limestones with several sandstone intercalations, especially at the bottom of the formation.

METHODS

Different methods were applied to analyse the facies, neptunian dykes, and trace fossils in order to characterize the Middle Bathonian–Middle Oxfordian unconformity in the La Mola Unit.

The geological map (scale 1:50,000) 871 Elda (IGME, 1978) was reviewed and modified (Fig. 1B). Fieldwork was carried out to log two critical sections of the tectonic unit and 80 rock samples were collected for thin-section study to complete field facies analysis of the Jurassic formations. Twenty samples were taken at the unconformity surface to analyse the (micro)facies and the texture of the materials forming the neptunian dykes. Macrofauna (ammonites) are generally scarce in all the Jurassic formations of the La

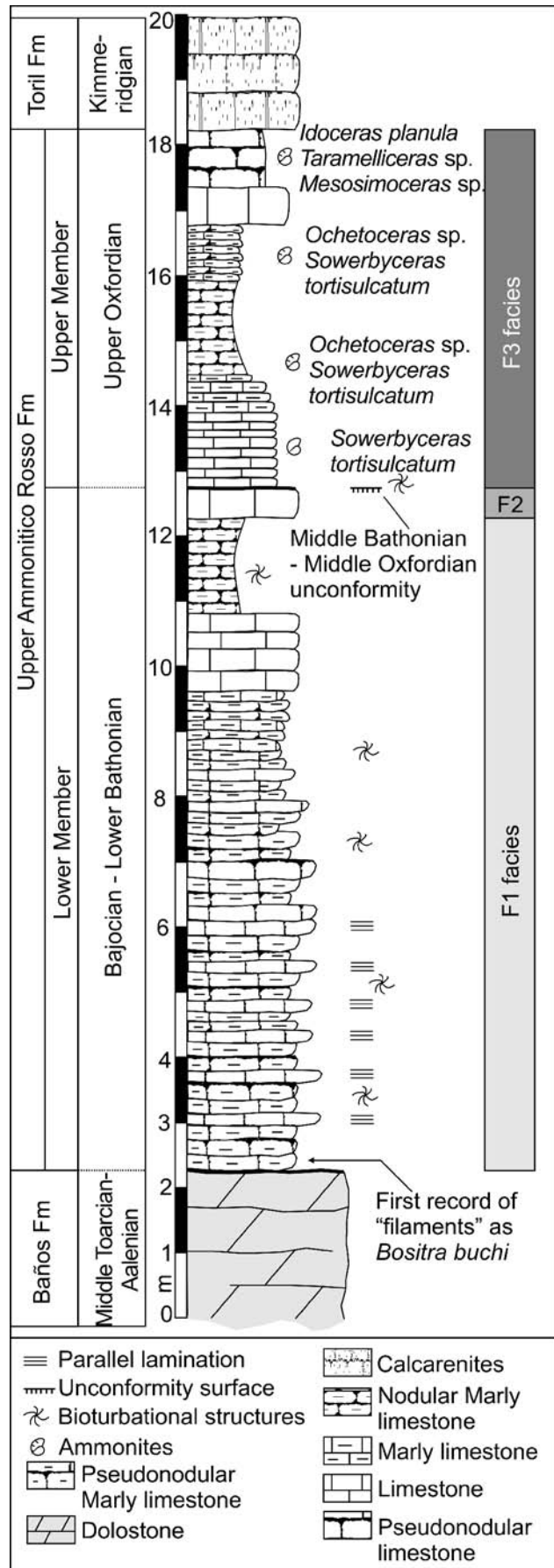


Fig. 3. Detailed stratigraphic section of the Upper Ammonitico Rosso Formation (UAR Fm) in the La Mola Unit.

Table 1

Main features of facies recorded in the lower and upper member of the Upper Ammonitico Rosso Formation in the La Mola Unit

No	Facies	Allochems	Sedimentary structures	Member
F1	Wackestones of "filaments"	"Filaments" (<i>Bositra buchi</i>), peloids, spicules, foraminifera (<i>Globochaete</i> sp., <i>Valvulina</i> sp., <i>Lenticulina</i> sp.)	Burrows infilled by peloids, parallel lamination	Lower
F2	Packstones of "filaments"	"Filaments" (<i>Bositra buchi</i>), aptychi, sponge spicules, gastropods, ammonite embryos, radiolaria, foraminifera (<i>Dimorphina</i> sp., <i>Lenticulina</i> sp.)	Disorganized "filaments"	Lower (40 cm thick limestone bed)
F3	Wackestones to packstones of bioclast	<i>Globuligerina</i> sp., gastropods, ammonite embryos, sponge spicules, aptychi	Burrows infilled by peloids	Upper

Mola Unit. However, around 12 specimens were collected to date the upper member of the UAR Formation. Other stratigraphic units were dated by facies correlation with the nearest tectonic unit (Reclot Unit). The biozonation used is that established by different authors for the Subbetic, correlated with that proposed by Ogg (2004) for the Sub-Mediterranean Domain (Fig. 4).

Only neptunian dykes at right angles to bedding (and therefore originally subvertical) were considered. The original strike of the dykes was recorded at the surface after restoring the unconformity surface to the horizontal (i.e., after correcting for tilting). The rotation of the tectonic unit during the Alpine Orogeny was not considered owing to the absence of palaeomagnetic data from the External Subbetic units in this area.

Ichnological analysis of the unconformity surface involved detailed outcrop observations, including quantitative and qualitative features, such as orientation, shape, length, and diameter of individual burrows, branching angles, burrow walls, as well as density, distribution, and cross-cutting relationships. Ichnofossil samples were taken for petrographic studies, especially in thin section to analyse burrow texture (margins and infill). More data about ichnological analysis were discussed by Rodríguez-Tovar and Nieto (2013).

SEDIMENTOLOGICAL AND ICHNOLOGICAL FEATURES OF THE MIDDLE BATHONIAN–MIDDLE OXFORDIAN UNCONFORMITY SURFACE

The unconformity surface occurs at the top of a 40-cm-thick highly lithified limestone bed, comprising packstone with disorganized "filaments" (*Bositra buchi*) (F2 facies, Table 1; Fig. 5A), located in the uppermost part of the lower member of the UAR Formation. This limestone bed locally displays a pseudonodular texture according to the terminology of Martire (1996). The main feature of this texture is the transitional boundaries between the nodules and the surrounding matrix. The upper member of the UAR Formation overlying the unconformity surface (Figs 1C, 3) has abundant ammonites (Figs 3, 5B). The textures are wackestone to packstone with different bioclasts and some *Globuligerina* tests (F3 facies, Table 1).

The unconformity surface has a flat morphology and does not show evidence of mineralization (crusts or impregnations). The surface is characterized by the absence of macrofossils and by relatively abundant trace fossils. According to the geochronology proposed by Ogg (2004), the hiatus related to the stratigraphic break had a duration of 9.2 Ma (Fig. 6).

Neptunian dykes

Two types of neptunian dykes with straight, sharp rims were recognized. The first type includes thin dykes, with a mean distance of 5 mm between the margins and an infill of red micrite (mudstone). Some dykes have dogtooth white sparite that developed on the margins and grew into the

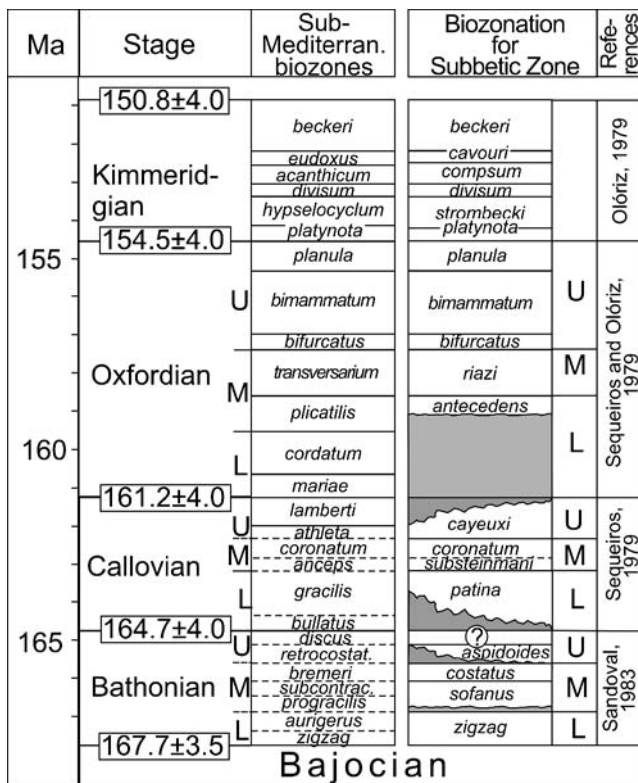


Fig. 4. Correlation between the biozonation proposed for the External Subbetic Zone by different Spanish authors and that proposed by Ogg (2004) for the Sub-Mediterranean domain. Geochronology according to the same author. L – lower, M – middle, U – upper.

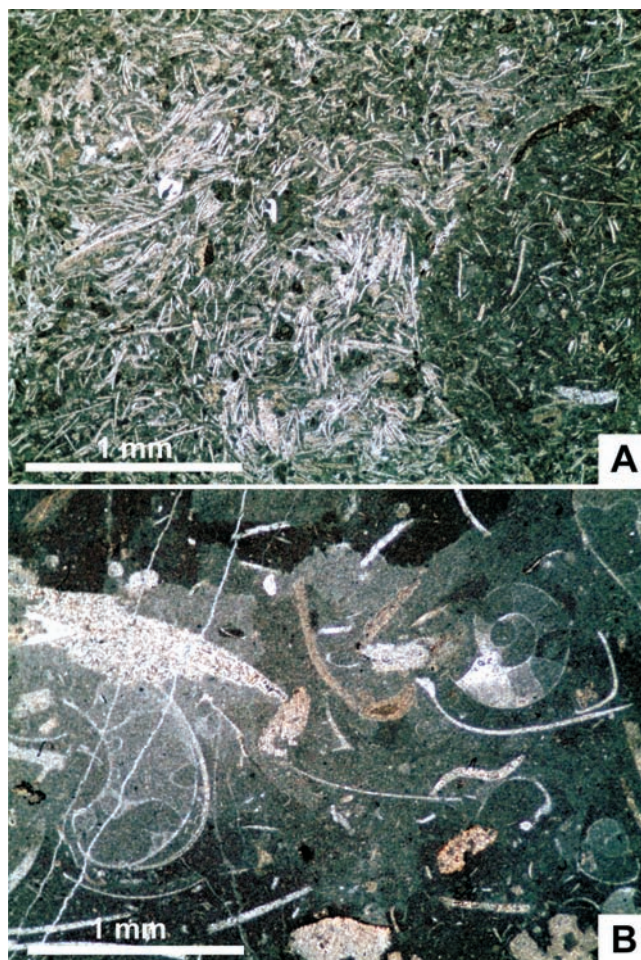


Fig. 5. Some examples of microfacies. **A.** Packstone of “filaments” (F2 facies, Table 1) of the limestone level (uppermost bed of the lower member of the UAR Formation), at the top of which the stratigraphic break studied is located. **B.** Wackestone to packstone of bioclasts (F3 facies, Table 1) in the lower part of the upper member of the UAR Formation.

dyke centre; red micrite fills the rest of the dyke (Fig. 7A, B). The second type of dyke is wider neptunian dykes, with around 10–40 mm between the margins. They are filled by a packstone composed of “filaments” (*Bositra buchi*) with peloids, radiolaria, crinoids, foraminifera (*Globuligerina*), and other bioclasts (Fig. 7C, D), similar to the F2 facies.

After restoring the unconformity surface to the horizontal, two main neptunian dyke strikes were recorded: N–S and N140–150 E (Fig. 7E). The latter cut the N–S dykes and some branched trace fossils. The angle between the two neptunian dyke systems is about 35°.

Trace-fossil composition

Ichnological analysis of the surface by Rodríguez-Tovar and Nieto (2013) was mainly based on the morphological features of the trace fossils. Despite the poor preservation of trace fossils on the surface due to diagenetic effects (which makes ichnotaxonomic determination difficult), several ichnogenera were identified (see Rodríguez-Tovar and Nieto, 2013, for a detailed characterization of the ichnotaxa). These ichnogenera belong to two well-differentiated

morphological groups: branched and circular structures. Table 2 shows the size of each of these morphological groups, according to Rodríguez-Tovar and Nieto (2013).

The branched structures are characterized by poorly preserved T- and Y-shaped, tubular horizontal forms, with only occasional networks. Isolated, simple structures are probably the segments of branched forms. Two ichnogenera have been differentiated in this group (Rodríguez-Tovar and Nieto, 2013): (a) *Ophiomorpha*, with irregular margins, a ferruginous halo between the burrow and the surrounding sediment (Fig. 8A, B), and a sediment infill of similar composition to the host material (Fig. 8C, D); this ichnofossil has pellet-lined walls to reinforce burrows. (b) *Thalassinoides*, with Y- to T-shaped branched structures, sharp margins, and neither a ferruginous halo nor infilling.

The circular structures have been observed as paired or as individual holes (Fig. 8E, F), and assigned to *Arenicolites*, *Gastrochaenolites*, and *Trypanites*. Paired structures characterized by sharp, circular openings and the absence of spreite between the pairs of holes are probably *Arenicolites* (Fig. 8E, F). In individual holes, the absence of vertical cross-sections precludes the observation of clavate or tears drop-like forms, but the local presence of a calcareous lining of the holes, arranged as paired or simple apertures, always with individual holes touching one another, allows their assignment to *Gastrochaenolites* (Fig. 8A). Simple, narrow circular structures with sharp boring margins and no coherent, calcareous lining were assigned to the boring *Trypanites* (Fig. 8E).

Locally, *Thalassinoides* is cross-cut by both neptunian dykes and circular structures (Fig. 7A, B), probably *Gastrochaenolites*. *Arenicolites* is also cross-cut by neptunian dykes.

INTERPRETATION

Evolution of the substrate consistency of the unconformity surface

The integration of sedimentological and ichnological features permits the interpretation of the surface evolution. One of the most important controlling factors of the trace fossils at this surface is substrate consistency, with clear differences associated with each ichnotaxa.

Ophiomorpha is a product of burrowing in sands; the pellet lining reinforces walls and aids in stabilization (Shinn, 1968; Frey *et al.*, 1978). The ichnofossils *Ophiomorpha nodosa* are recorded in softgrounds prior to the development of firmgrounds (e.g., MacEachern *et al.*, 1992). Unlike sandstone environments, in carbonates the lithification process is quick, so the soft-substrate stage is usually brief and firmground conditions are achieved rapidly. Therefore, *Ophiomorpha* probably developed mainly in the final stages of softground conditions (Fig. 9A).

Thalassinoides is found in a wide variety of substrates from soft- to hardgrounds (Fig. 9A, B, C and D), with variations in burrow geometry according to firmness, and is common during the early and middle stages of hardground development (Myrow, 1995). *Thalassinoides* is one of the most common ichnotaxa in the *Glossifungites* ichnofacies,

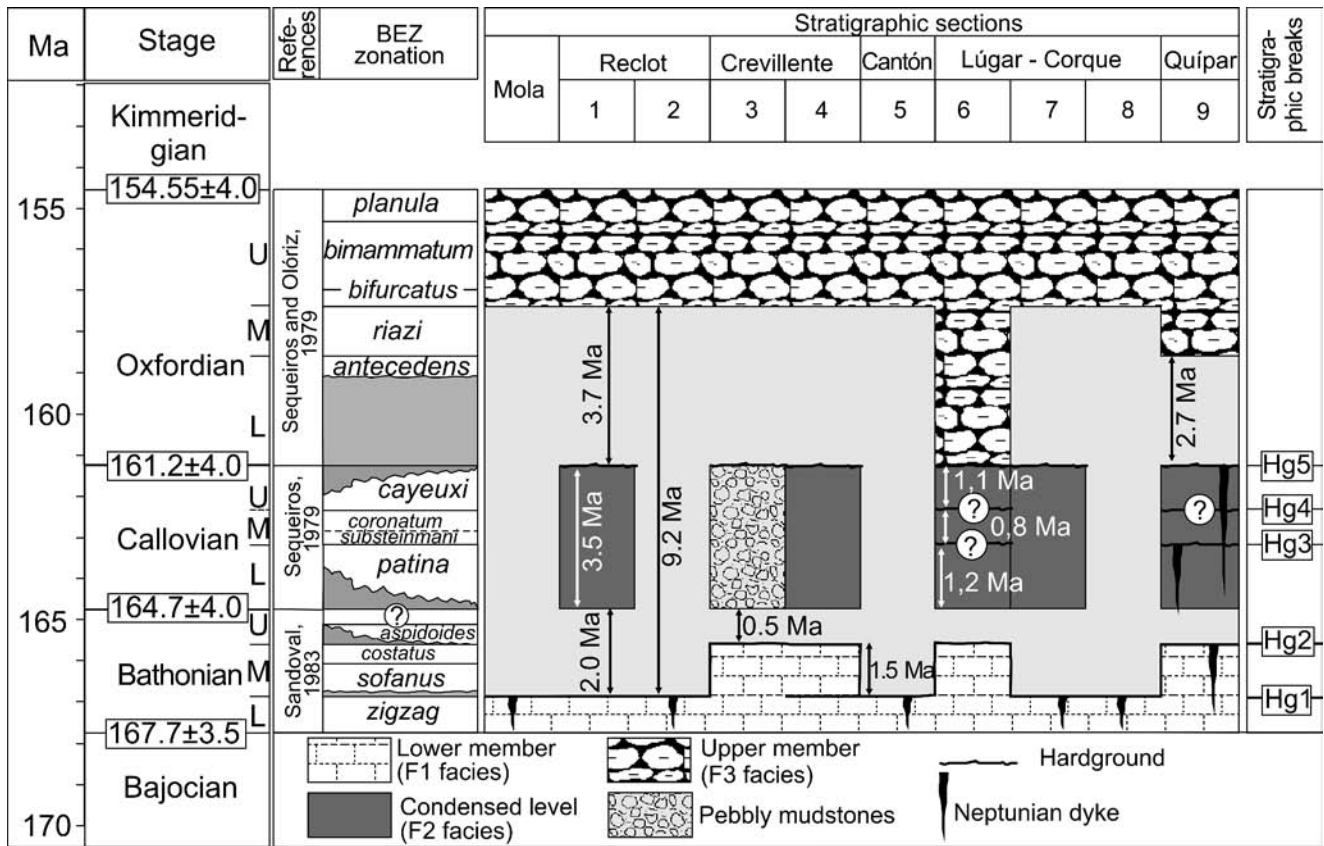


Fig. 6. Chronostratigraphic chart where the Middle–Upper Jurassic succession at the La Mola Unit is correlated with other stratigraphic sections (see numbers) within different tectonic units in the Subbetic Domain (partially modified from Nieto *et al.*, 2012). Geochronology after Ogg (2004). BEZ – Betic External Zones, L – lower, M – middle, U – upper.

which developed in stable, cohesive substrates (firmgrounds), unlithified, especially semi-consolidated carbonate firmgrounds (Fig. 9B, C, D) or stable, cohesive, partially dewatered muddy substrates (Pemberton and Frey, 1985; Lewis and Ekdale, 1992; MacEachern *et al.*, 1992, 2007; Pemberton *et al.*, 1992, 2001, 2004; Pemberton and MacEachern, 2005; Rodríguez-Tovar *et al.*, 2007). In the case studied, the time relations between *Ophiomorpha* and *Thalassinoides* are uncertain. However, these two ichnofossils were probably not contemporary because *Ophiomorpha* indicates unlithified sediment, whereas *Thalassinoides* needed a stable, cohesive substrate (semi-consolidated, Fig. 9), according to the above authors.

Arenicolites was recorded from softgrounds to firmgrounds (Fig. 9A, B), but not in hardgrounds, being a characteristic trace of the *Glossifungites* ichnofacies (Pemberton *et al.*, 2001). Considering that the sedimentation rate is very low in pelagic carbonate environments, partial lithification of the substrate is quick. Therefore, the softground stage is short, which makes it likely that *Arenicolites* were produced in firmgrounds (Fig. 9A, B).

Gastrochaenolites has usually been interpreted as a result of boring in lithic substrates (Kelly and Bromley, 1984), and is therefore related to rockgrounds and hardgrounds. However, this ichnogenus also has been recognized in firm substrates, in some cases together with typical components of the firmground associations, such as *Thalassinoides* isp. (Carmona *et al.*, 2006, 2007). More-

over, firmground *Gastrochaenolites* is considered a common structure in the *Glossifungites* ichnofacies (e.g., Pemberton *et al.*, 2001). Ekdale and Bromley (2001) showed that the tracemaker of *Gastrochaenolites* could work in substrates with different degrees of consistency. In the study case, the presence of carbonate lining in some specimens could corroborate partial substrate lithification. In addition, this ichnofossil cuts *Thalassinoides* (Fig. 9A), proving that *Gastrochaenolites* developed later and probably in an evolved firmground substrate, nearly at hardground conditions (Fig. 9A, C).

The presence of *Trypanites* could evidence a significant change in substrate firmness related to an increase in substrate consistency (Fig. 9A, B, D). *Trypanites* is an ichnotaxon exclusive to lithified substrates such as hardgrounds and rockgrounds, being the eponym trace fossil of the *Trypanites* ichnofacies (Seilacher, 1967) and the *Entobia* ichnofacies (according to Bromley and Asgaard, 1993). The presence of *Trypanites* is associated with trace-fossil assemblages dominated by deep-tier boring (e.g., Lewis and Ekdale, 1992), revealing long-term bioerosion on a surface exposed for an extended period (in this example over 9.2 Ma; Fig. 6). This is the maximum possible time span, but the surface could have formed in a much shorter time after several events not registered in the rock record. Very small borings are evidence of shallow bioerosion, and physical abrasion is discounted, given the absence of examples of deeper-tier activity (Fig. 9A, B).

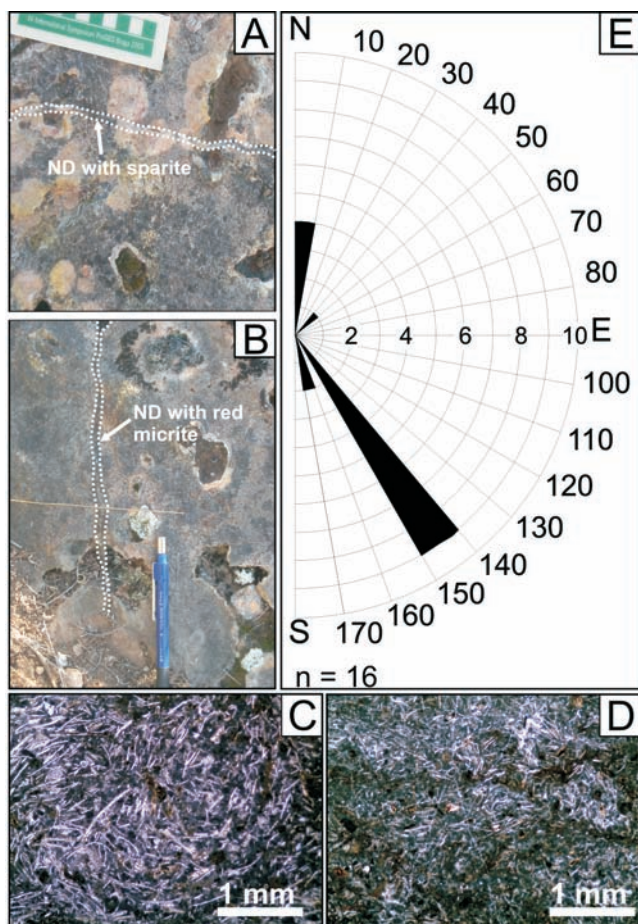


Fig. 7. Examples of trace fossils cut by neptunian dykes (ND). **A.** Neptunian dyke infilled by white sparite. **B.** Neptunian dyke made up of red micrite. **C, D.** Packstone composed of “filaments” (*Bositra buchi*) of neptunian dykes. **E.** Diagram showing the main strikes of neptunian dykes after restoring stratification to the horizontal (n – number of measurements).

Consequently, the trace-fossil assemblage reveals substrate evolution at the top of a pelagic swell (Fig. 9A): *Ophiomorpha* characterizes softgrounds; *Arenicolites*, *Thalassinoides*, and *Gastrochaenolites* are common in the *Glossifungites* ichnofacies firmgrounds (Pemberton and MacEachern, 1995; Pemberton *et al.*, 2004); and only *Trypanites* indicates incipient hardground development. The absence of characteristic features of marine hardgrounds, such as macroencrusts or mineralization (Fürsich, 1979), probably indicates an extremely low sedimentation rate or even a minor erosional phase (suggested by the absence of vertical shafts in *Thalassinoides*).

Glossifungites is the most common ichnofacies, used to delimit semi-lithified substrates that originated either by subaerial exposure or by burial and subsequent exhumation. Colonization of the discontinuity surface by the *Glossifungites* suite occurs under marine conditions during a depositional hiatus. This relationship between the *Glossifungites* ichnofacies and stratigraphic discontinuities has been analysed in numerous papers (e.g., MacEachern *et al.*, 1992, 1999; Pemberton *et al.*, 1992, 2001, 2004; Pemberton and MacEachern, 1995; MacEachern and Burton, 2000; Zonneveld *et al.*, 2001; Gingras *et al.*, 2002; Holz, 2003; Di Celma and Cantalamessa, 2005; Gibert and Robles, 2005; Buatois and Encinas, 2006; Cantalamessa *et al.*, 2006; Rodríguez-Tovar *et al.*, 2007).

Eustatic context

Pelagic swells have been considered sediment-starved environments, with the Ammonitico Rosso regarded as the most characteristic facies (Bosellini, 1989; Martire, 1992). Along these lines, Martire (1992) proposed a sequential stratigraphic model to explain the genesis of this facies that can be applied to the interpretation of the UAR Formation (Fig. 10). This author proposes that Ammonitico Rosso sedimentation in pelagic swells occurred in transgressive and, especially, highstand sea-level conditions. In this context, current activity was lower and the products of pelagic sedimentation may be preserved. The lower member of the UAR Formation, characterized by wackestone with “filaments”, could be related to similar sea-level conditions.

The highly lithified bed at the top of the lower member of the UAR Formation, with a pseudonodular texture, could have formed in shallow seas. In this environment, bottom waters were probably well oxygenated, so infauna should be abundant and bioturbation of the sediment significant, as indicated by the texture of the bed (“filaments” and peloids). The partial lithification of the deposited sediment was the result of the low sedimentation rate (0.20 mm/kyr for the lower member of the UAR Formation; Nieto, 1997; Nieto *et al.*, 2012); therefore, softground conditions and the first stage of firmground conditions developed at the top of the highly lithified bed.

The softground conditions could indicate a relatively low sea level, with a slight increase in marine current energy probably controlling winnowing of fine-grained sediment or concentration during a low sedimentation stage (Fig. 10). These conditions favoured the presence of *Ophiomorpha*, in which wall reinforcement aided in burrow stabilization (Fig. 10). The sediment surface evolved into a semi-consoli-

Table 2

Sizes of different ichnofossils recorded at the unconformity surface studied
(data from Rodríguez-Tovar and Nieto, 2013)

		Diameter (mm)	Length (mm)	Width (mm)	Thickness of the lining (mm)
Branched structures		25–15, usually 20	180–130, maximum 250	–	–
Circular structures	Paired holes	10–20	–	85–35	1–2
	Individual holes	20–30	–	–	2

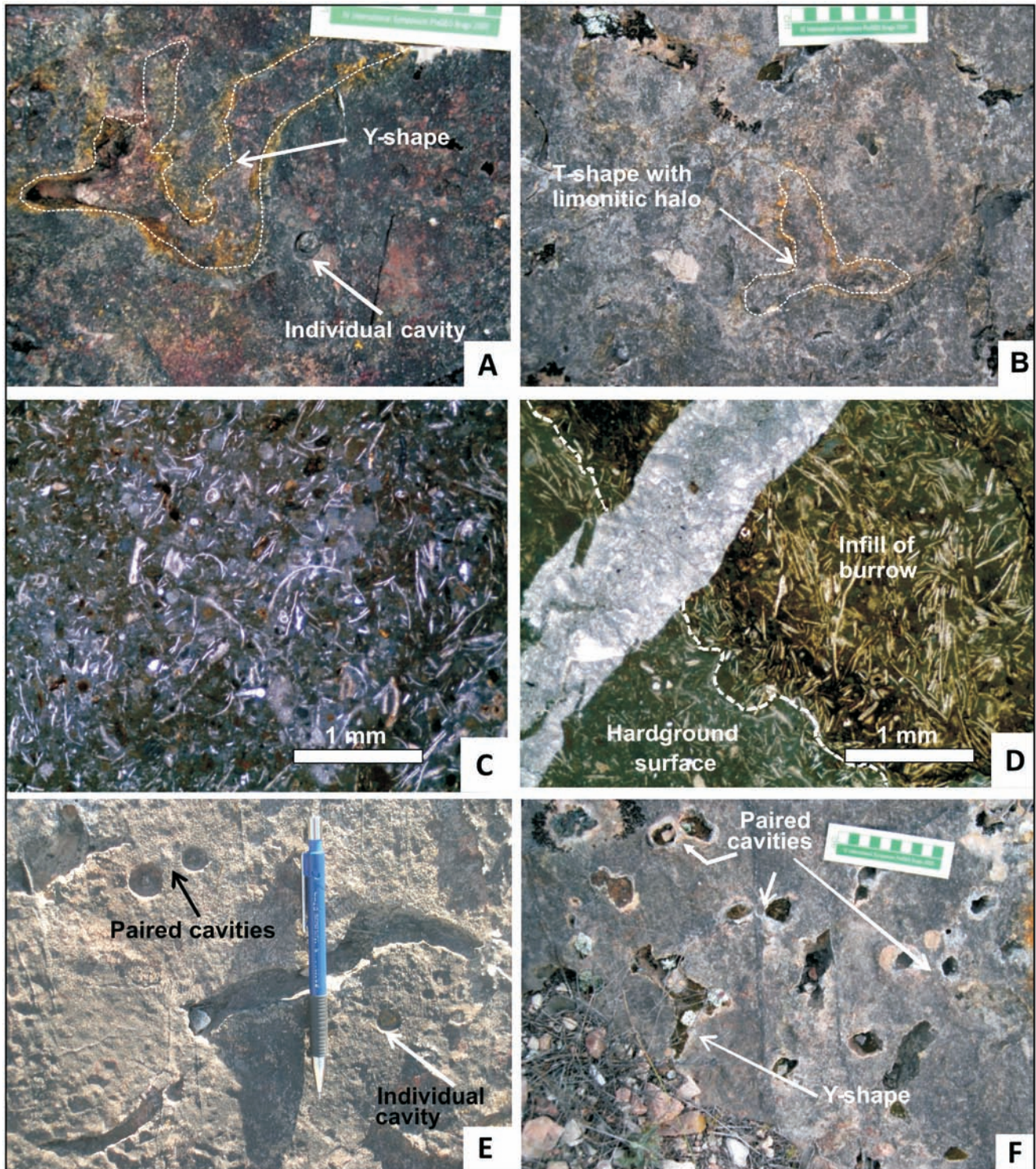


Fig. 8. Some examples of ichnofossils in the studied unconformity surface. **A.** Horizontal trace fossil showing Y-shaped branches (*Ophiomorpha*) with a limonitic halo and boring with a circular section (probably *Trypanites*). **B.** T-shaped trace fossil and limonitic halo. **C.** Microfacies (“filament” wackestone) with bioturbation in the infills. **D.** Thin-section showing the relation between the infill with burrow and the hardground surface. **E.** Poorly preserved branched structure and circular structures assigned to *Gastrochaenolites*. **F.** Circular sections grouped by pairs (*Arenicolites*) and Y-shaped trace fossil (*Thalassinoides*).

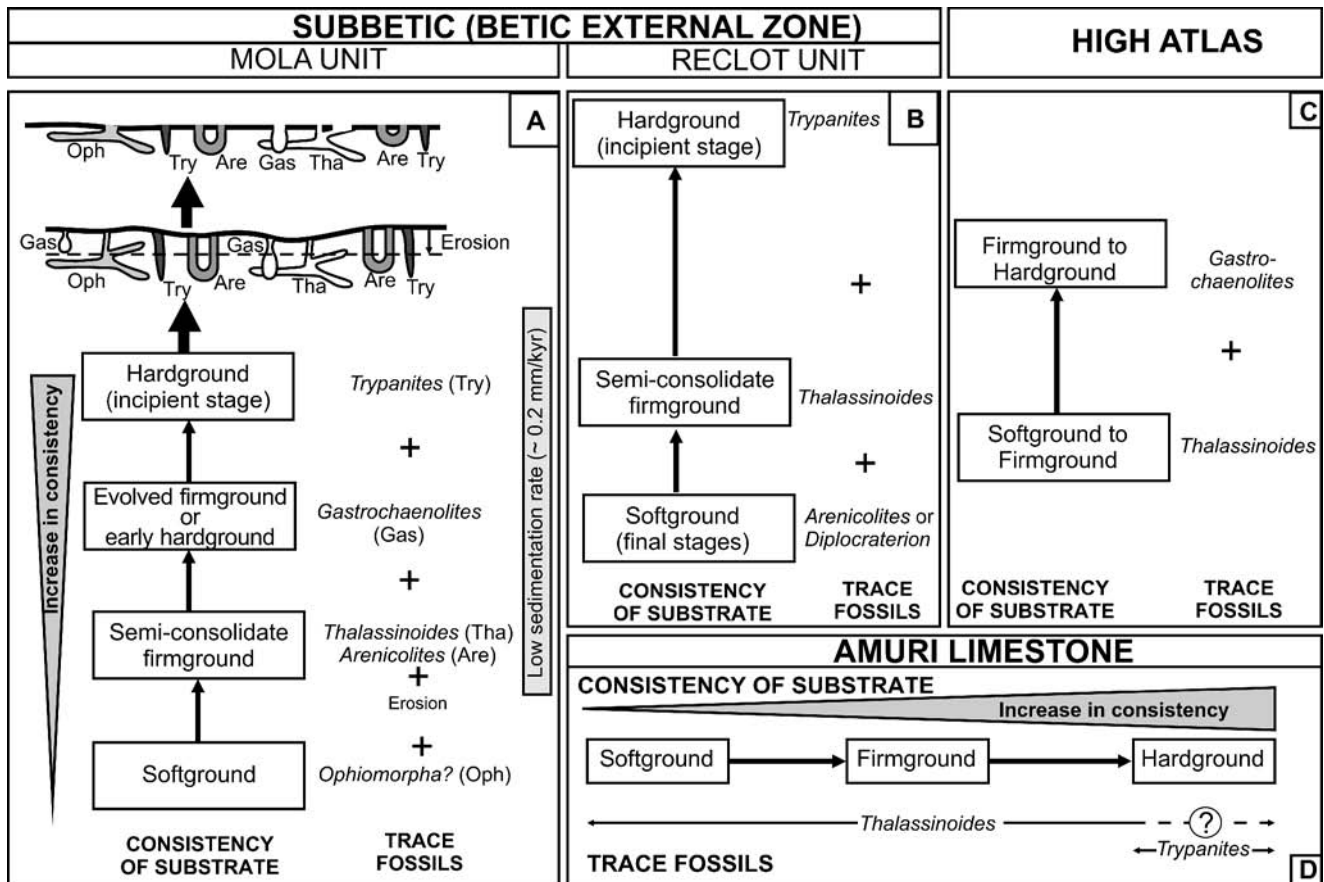


Fig. 9. Model for change of the unconformity surface in the La Mola Unit. Comparison with other models. **A.** Change model of the unconformity surface in the La Mola Unit mainly according to different degrees of firmness. **B.** Change model of the unconformity surface in the Reclot Unit (Eastern External Subbetic; data from Reolid *et al.*, 2010). **C.** Change model of a discontinuity surface in the High Atlas Domain (data from Christ *et al.*, 2012). **D.** Change model of the discontinuity surface at the top of the Amuri Limestone (Middle Oligocene, New Zealand. Modified after Lewis & Ekdale, 1992). Oph – *Ophiomorpha*, Are – *Arenicolites*, Tha – *Thalassinoides*, Gas – *Gastrochaenolites*, Try – *Trypanites*.

dated firmground and early hardground, with *Thalassinoides*, *Arenicolites*, and *Gastrochaenolites* ichnofossils (Fig. 10). Current energy probably increased, causing sediment winnowing and leading to firmer substrates, a halt to sedimentation, and erosion exhuming the concealed firmground. These conditions are typical of very low sea levels, but without karstification structures. Finally, the development of a hardground, with *Trypanites*, was likely associated with enhancement of these prior conditions: a near-absence of sedimentation and a comparative increase in erosion of the seafloor, cutting the vertical galleries of some ichnofossils and favouring the exhumation of firmer substrates. The latter phase reveals a significant increase in marine current energy, possibly associated with the initial stages of a relative sea-level rise (Fig. 10).

The complex unconformities recorded at the Middle–Upper Jurassic transition of the Tethyan domains were related to different transgressive-regressive cycle boundaries. Hardenbol *et al.* (1998) recognized a major sequence boundary (Bat5), dated as Late Bathonian, that bounds two second-order sequences, corresponding to Early–Late Aalenian to Middle–Late Bathonian and Middle–Late Bathonian to Middle Oxfordian. These authors recognize a eustatic sea-level fall prior to the Bat5 sequence boundary

and a subsequent sea-level rise. Also in the Subbetic Domain, Nieto *et al.* (2012) correlate the Hg1 unconformity with a relative sea-level fall, followed by a sea-level rise. The surface studied in the La Mola Unit could be interpreted as the result of low sea-level conditions together with the processes related to the subsequent sea-level rise (increased energy, sediment by-passing and potential erosion). Different authors (Cecca *et al.*, 2005; Ramajo and Aurell, 2008) have shown that a low sedimentation rate is typical of the Middle Jurassic period in the Tethyan domains, because there is a transition from rifting to post-rifting; as a consequence, a global reduction in carbonate productivity is detected during the Late Bathonian–Early Oxfordian.

However, some local conditions related to tilted tectonic blocks cannot be excluded. Areas where the condensed levels were present can be interpreted as being more protected from marine currents, sediment winnowing, and erosion, thereby preserving the scarce sediment. Where the condensed sections are absent, as in the La Mola Unit, the hiatus associated with a stratigraphic break was long. It could be explained as having arisen in shallower areas where the activity of marine currents as well as low production of the carbonate factory did not favour sediment accumulation.

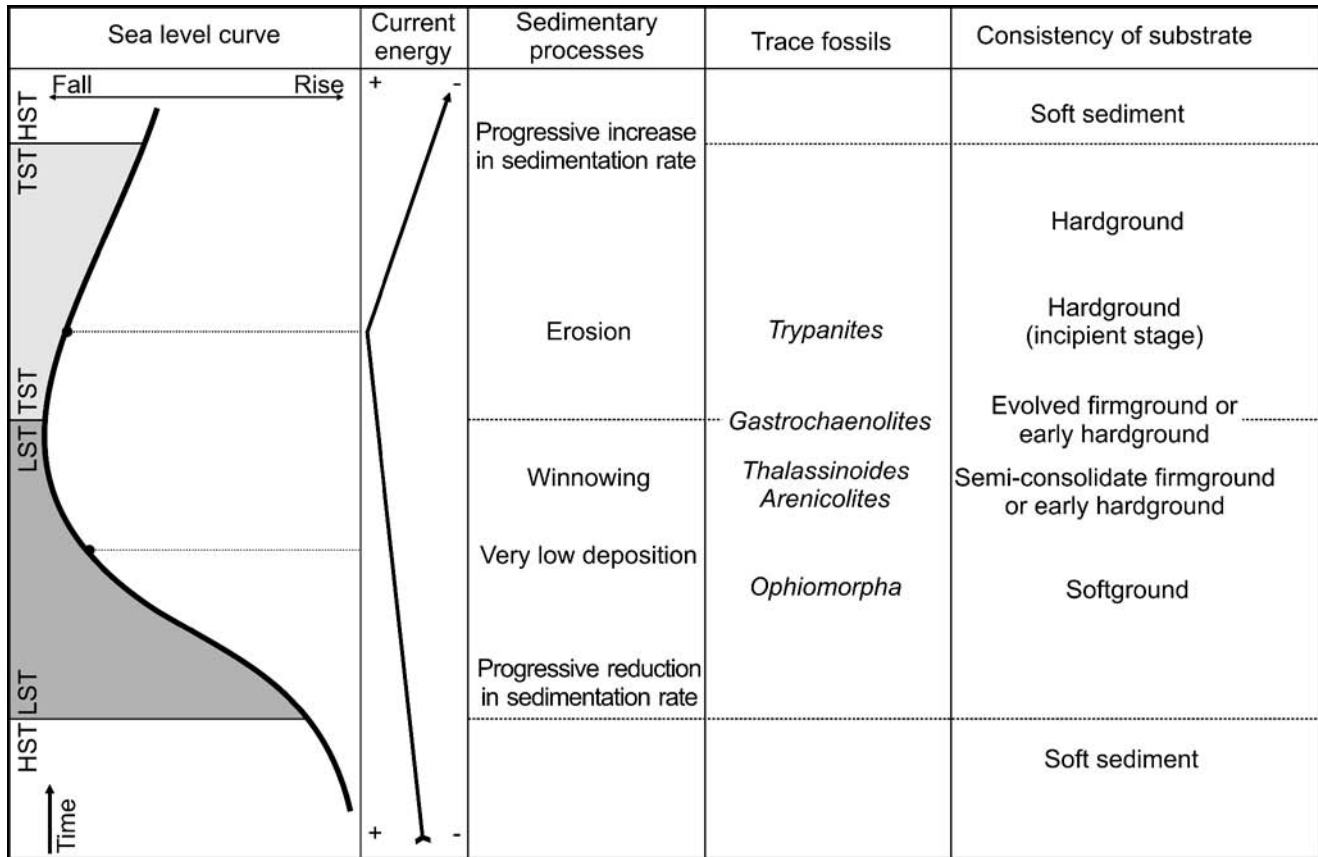


Fig. 10. Changes at the unconformity surface in relation to the sea-level curve.

Tectonic context

At the discontinuity studied, neptunian dykes are indicative of synsedimentary tectonics, probably related to tensional deformation systems (Basilone, 2009; Bertok and Martire, 2009; Nieto *et al.*, 2012). Data from the same interval studied in this research in other Subbetic tectonic units also indicate that synsedimentary tectonics was an important control in sedimentation in the eastern Subbetic (Fig. 6). The successions studied in the La Mola Unit, Reclot Unit (section 1; GPS coordinates: 38°20'52.83" N; 0°55'26.68" W), Cantón Unit (section 5; GPS coordinates: 38°17'49.75" N; 1°00'52.27" W), and Lúgar-Corque Unit (section 8; GPS coordinates: 38°12'15.17" N; 1°11'25.60" W) only record a long hiatus. However, in section 9 of the Quípar Unit (GPS coordinates: 38°04'27.86" N; 1°48'32.79" W) and section 6 of the Lúgar-Corque Unit (GPS coordinates: 38°14'12.77" N; 1°07'49.04" W; Fig. 6), five unconformities (Hg1 to Hg5) bounding condensed sequences have been described (Nieto *et al.*, 2012). These significant stratigraphic differences plain could be the result of half-graben development as a consequence of block rotation by listric faults (Vera, 2001; Nieto *et al.*, 2012).

This interpretation is in accordance with Ziegler (1989), who showed that the Middle–Late Jurassic transition was a tectonically active period with a change from extensional to transtensional conditions in the Western Tethys. In the Eastern External Subbetic (Quípar Unit; Fig. 6), Nieto *et al.* (2012) characterized neptunian dykes related to Hg1 (top of the Lower Bathonian), Hg2 (top of the Middle Bathonian),

and Hg5 (top of the Callovian). In the unconformity surface studied here, correlated to Hg1, the presence of neptunian dykes revealed that the pelagic swell probably was affected by a mixed tensional and shear deformation phase. According to Hancock (1985, 1994), this type of fracture system, forming a dihedral angle ranging between 10° and 50°, are hybrid fractures with mixed tensional and shear deformation, which is in agreement with the hypothesis of Nieto *et al.* (2012). However, it should be noted that the La Mola Unit, like other Subbetic units, was affected by several tectonic stages, only recorded at a single unconformity. On the basis of the relationship between the neptunian dykes and the ichnofossils (especially the branched ichnofossils), the most important deformation stage should be subsequent to the development of these trace fossils. Vera (2001) and Nieto *et al.* (2012) show that around Middle Bathonian to Oxfordian, the South Iberian Palaeomargin was affected by transtensional deformation related to crustal separation between the African, Iberian, and Mesomediterranean plates. In the Subbetic, this situation involved an increase in pelagic swell development and therefore a significant reduction in sedimentation rates and a relative sea-level fall.

DISCUSSION: COMPARISON WITH OTHER GEOLOGICAL DOMAINS

Detailed analyses of Middle–Upper Jurassic hardground surfaces recorded in the Eastern External Subbetic

(developing in pelagic swells in the South Iberian Palaeo-margin; Western Tethys; Fig. 6) reveal significant lateral facies changes, mainly related to specific locations and differences in palaeobathymetry (Reolid *et al.*, 2010; Nieto *et al.*, 2012). Lateral variations can also be observed in the trace-fossil assemblages (Fig. 9).

In previously studied surfaces, especially those in the Reclot Unit sections (Fig. 9B), the most abundant trace fossil is *Thalassinoides*, co-existing with other trace fossils recorded as paired vertical tubes, assigned to *Arenicolites* or *Diplocraterion*, and isolated tubes, interpreted as borings of the *Trypanites* ichnofacies (Reolid *et al.*, 2010; Nieto *et al.*, 2012). On the basis of the different kinds of ichnofossils recorded (*Trypanites* with either *Arenicolites* or *Thalassinoides*), the progressive substrate lithification went from a softground to a firmground or hardground (Reolid *et al.*, 2010; Nieto *et al.*, 2012). Several significant differences can be recognized with respect to the surface studied in the La Mola Unit, particularly the record of *Ophiomorpha* and *Gastrochaenolites* and the less abundant *Trypanites* (Fig. 9A, B). The significance of substrate consistency related to trace-fossil assemblage and its evolution probably reflect a change from comparatively softer, more unstable substrates associated with the surface in the La Mola Unit to incipient hardground conditions. These ichnological features, and their corresponding interpretations, are in agreement with other sedimentological data recorded in the Reclot Unit (Reolid *et al.*, 2010; Nieto *et al.*, 2012), but absent in the section at the La Mola Unit. For instance, in the discontinuity surface at the La Mola Unit, there is an absence of features, such as Fe-Mn oncoids and crusts related to well-developed stratigraphic breaks, and of taphonomic features of the macroinvertebrate assemblages, evidencing long exposure of the remains on the seafloor (such as corrosion, faceting, and encrustation).

In comparison with other carbonate environments, the diversity of trace fossils associated to different steps in seafloor evolution is higher. For instance, in the Jurassic of the Central High Atlas (Western Tethys, Morocco), Christ *et al.* (2012) show that *Thalassinoides* is the trace fossil that characterizes soft- and firmground stages in seafloor evolution, and *Gastrochaenolites* is related to hardground conditions (Fig. 9C). Lewis and Ekdale (1992) analysed the Amuri Limestone (Middle Oligocene, New Zealand; Fig. 9D), deposited in a pelagic environment. These authors show that *Thalassinoides* is the trace fossil associated with softgrounds to hardgrounds (see Lewis and Ekdale, 1992, fig. 14); this last ground also is accompanied by *Trypanites*.

CONCLUSIONS

An integrative analysis of sedimentologic, stratigraphic, palaeotectonic, and especially ichnological data obtained from unconformity surfaces in the External Subbetic Zone (La Mola Unit, Betic Cordillera) developed in pelagic carbonate-swell environments reveals the importance of sea-level conditions, tectonic context, and palaeogeographic location in their genesis. The use of trace fossils for characterizing the evolution of seafloor features is clearly

exemplified in the middle Bathonian–middle Oxfordian unconformity surface studied, and has wide applicability to the Jurassic Ammonitico Rosso facies, where unconformities are frequently recorded.

The presence of *Ophiomorpha* characterizes softground conditions and unstable substrates. The association of *Thalassinoides*, *Arenicolites*, and *Gastrochaenolites* reveals an increase in firmness, with firmground development. Finally, *Trypanites* denotes an incipient hardground stage. The evolution in substrate consistency is related to different sea-level phases and, therefore, to characteristic marine-current energies and variable continuity of deposition. Softground to early firmground stages could indicate relatively low sea levels, with low-energy currents and comparatively continuous deposition. Subsequent firmgrounds or early hardgrounds developed at extremely low sea levels (relatively) with higher-energy currents, which could be responsible for sediment winnowing and therefore for non-deposition. The initial phases of sea-level rise were marked by hardground conditions, with higher-energy currents that resulted in seafloor erosion. Differences in sedimentological and ichnological features with regard to previously studied discontinuity surfaces from nearby areas (e.g., the Reclot Unit), are related to variations in the palaeogeographic location and bottom topography, determining changes in deposition and in the probable duration of the associated hiatus. Ichnofossil abundance is very high in the Subbetic compared with other carbonate environments, which aids the improved establishment of sequences in seafloor evolution.

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