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Ichnological analysis in high-resolution sequence stratigraphy: The *Glossifungites* ichnofacies in Triassic successions from the Betic Cordillera (southern Spain)

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Abstract

This study integrates ichnological and sedimentological data in order to refine sequence stratigraphy and interpretations of sea-level dynamics for the Ladinian (Middle Triassic), Muschelkalk succession (Siles Formation) in the Betic Cordillera (southern Spain).

Facies analysis was integrated with a detailed ichnological study, focused on the middle part of the lower member of the Muschelkalk succession (transgressive systems tract), which is characterized by an abundant and conspicuous trace fossil assemblage. Seven lithofacies were recognized, recording sediment accumulation in tidal flat, and inner to outer marine carbonate ramp, depositional environments. Thin-bedded marly limestones with bioclastic shelly beds (Facies E: middle ramp, with storm influence), are characterized by *Diplocraterion* and *Rhizocorallium*. *Diplocraterion* is protrusive, usually eroded on top, and mainly recorded in the marly limestone intervals. *Rhizocorallium* preserves well defined scratch-marks, and is commonly emplaced in bioclastic, shelly beds. The assemblage represents the *Glossifungites* ichnofacies.

Sedimentological and ichnological data are interpreted to record a complex transgressive context, associated with high-frequency sea-level dynamics that allowed formation of transgressive surfaces of erosion (TSE, i.e., ravinement surfaces) of different orders. Major TSE, associated with continuous bioclastic shelly beds, delimit parasequences; the absence of the *Glossifungites* suite reveals that there was little time between erosion and deposition. Intermediate TSE, associated with discontinuous shell beds, are related to comparatively less significant sea-level rises and occur within parasequences. The *Glossifungites* suite reveals colonization of firmgrounds during relatively prolonged times between erosion and deposition related to intermediate TSE. Minor order TSE, recorded between the intermediate TSE, are related to punctuated, highest frequency sea-level changes; phases of colonization by the *Diplocraterion* tracemaker and protrusive, capped structures reveal more or less stillstand phases (TSE/stillstand phases), and minor order erosional phases.
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Keywords: *Glossifungites* ichnofacies; *Diplocraterion*; *Rhizocorallium*; Parasequences; Transgressive surfaces of erosion; Triassic; Betic Cordillera

1. Introduction

Ichnological analysis has become a valuable tool in basin research, being of special interest for recognizing and interpreting genetically related sedimentary packages as well as bounding discontinuities. Biogenic structures can be used in sequence stratigraphy in two principal

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ways: (a) to allow the identification of sequence stratigraphic discontinuities through the recognition of substrate-controlled ichnofacies, and (b) to help in the interpretation of palaeoenvironmental changes through detailed characterization of vertical changes in softground trace fossil successions (Savrda, 1991a; Pemberton and MacEachern, 1995; Pemberton et al., 2001, 2004). In the most favourable situations, integration of data from substrate-controlled ichnofacies with those from the vertical ichnological successions in softgrounds proves particularly informative in sequence stratigraphic analyses, even more so when these data are integrated with other sources of information.

The sequence stratigraphic approach to Triassic basin analysis of the Betic Cordillera (southern Spain) is complicated due to particular features of the Triassic successions, such as outcrop limitations, poor facies expression, scarcity of well-differentiated key boundary surfaces, and the absence of a precise biostratigraphic zonation. Thus, sequence stratigraphic interpretations are scarce and lacking in detail, being mainly at the third order level; correlations with the well-known global sequence stratigraphic charts are difficult to establish.

The aim of this paper is to illustrate the value of ichnology as a tool for improving high-resolution sequence stratigraphy and characterizing sea-level dynamics in a Triassic basin from the Betic Cordillera.

2. Geological setting

Two main tectonic domains may be differentiated in the Betic Cordillera: the External Zones, including sediments deposited on the southern Iberian continental margin, and the Internal Zones, corresponding to the so-called Alboran domain (Fig. 1).

In the External Zones, Triassic sediments have been traditionally differentiated into Buntsandstein, Muschelkalk and Keuper facies. Buntsandstein rocks are rarely exposed and biostratigraphically difficult to characterize, being clearly identified below Muschelkalk carbonates in the northernmost part of the Betic Cordillera, near the Meseta, and in several outcrops in the provinces of Murcia and Jaén (Pérez-Valera et al., 2000; López-Gómez et al., 2002; Pérez-Valera, 2005). Buntsandstein rocks consist of red and grey mudstones with intercalations of gypsum, and sandstones with mudcracks interpreted as deposited in a coastal plain setting (López-Gómez et al., 2002). Muschelkalk rocks consist of carbonate successions showing an upward increase in the proportion of marls. These marine carbonates were deposited on a shallow carbonate ramp and on tidal flats, affected by frequent storm events, mainly in the middle part of the succession. The Keuper rocks include shales, sandstones, gypsum and occasional basic intrusive rocks (Pérez-López, 1991). These deposits accumulated in a variety of environments, from fluvial-coastal (with widespread lakes) to sabkha and lagoon settings, and shallow platforms to tidal flats. Deposition took place in a continental to coastal environment developed on the South Iberian palaeomargin, for which reason they are called the Sudiberic Triassic (Pérez-López, 1991, 1998).

The studied outcrop is located in an area of strong tectonism (Tiscar Fault Zone), belonging to the External Zones of the Betic Cordillera. The Huesa section (RH-1) lies in the eastern sector of the Betic Cordillera, near the town of Huesa (Jaén province) (Fig. 1). It shows a relatively continuous Triassic succession (Fig. 2). At the base, detrital Buntsandstein rocks (Arroyo Molinos Formation) are overlain by the first dolomitic deposits of the marine Muschelkalk ramp. These carbonates of Muschelkalk facies, belonging to the Siles Formation (Pérez-Valera, 2005), are differentiated into two main members separated by a sedimentary discontinuity that is characterized by a hardground surface of bioclastic limestone. Finally, green and red siltstones, sandstones and gypsum (the evaporitic and siliciclastic rocks of the Jaén Keuper Group) occur above the upper carbonates of Muschelkalk facies (Pérez-López, 1991, 1996) (Fig. 2), the transition to the Keuper facies being gradual.

Of the Triassic rocks in the Huesa section, the Muschelkalk sediments (Siles Formation) are best represented, consisting of 27 m of dolomite, marlstone, thin-bedded and fine-grained limestone, with bioclastic and nodular limestone intercalations. Two lithostratigraphic members were differentiated within the Siles Formation at the Huesa section (Fig. 2; Pérez-Valera, 2005).

As a rule, Triassic rocks from the Betic Cordillera are strongly deformed and locally affected by metamorphism. These features, together with a general absence of index fossils, impede biostratigraphic characterization, and therefore correlation and palaeoenvironmental interpretations (Pérez-López and Sanz de Galdeano, 1994; Pérez-López, 1998). In the Huesa section, the scarcity of ammonoids and conodonts precludes a detailed biostratigraphic zonation. The most abundant fossils are bivalves (*Enantiostreon difforme*, *Costatoria goldfussi*, *Bakevellia costata* and *Gervillia jouleaudi*), some of which can be used for a biostratigraphic subdivision at the stage level. Thus, bivalve assemblages in the carbonates of the Muschelkalk facies allow recognition of the Ladinian

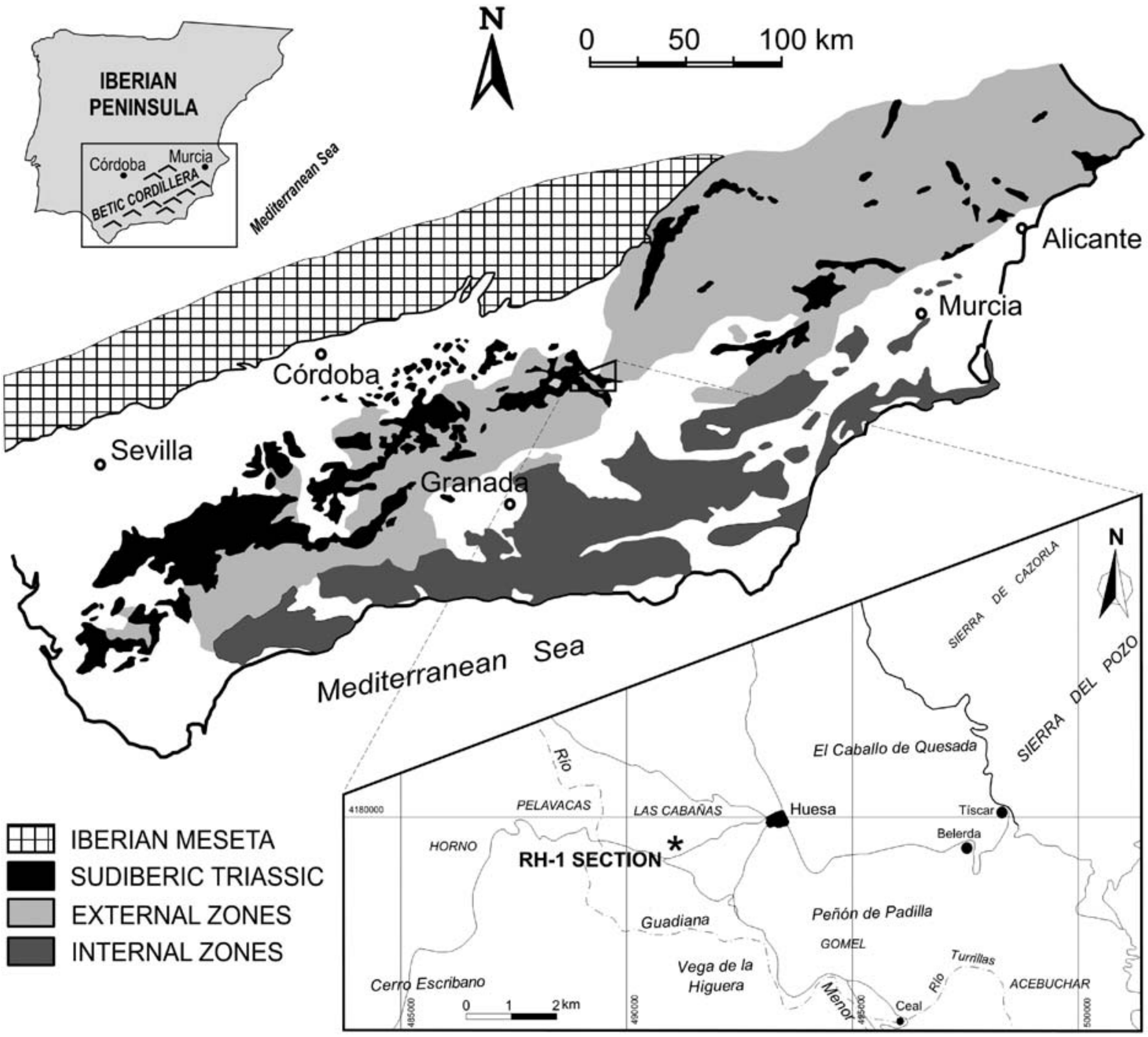

Fig. 1. Geographical location and geological context of the Huesa section (Betic Cordillera, southern Spain).

(Middle Triassic), but no greater precision (Márquez-Aliaga et al., 1986).

3. Facies distribution and depositional environment

Muschelkalk carbonates from the Siles Formation have been previously interpreted as shallow ramp/platform deposits (Pérez-Valera, 2005), but some aspects of this Muschelkalk ramp (i.e., lateral evolution, distal and proximal trends, etc.), remain unknown. Nevertheless, facies analysis and, especially, interpretation of the sedimentary structures, provide some information on the depositional environment, including its stratigraphic evolution.

The lower member of the Siles Formation contains abundant sedimentary structures (wavy lamination, undulating bedding, cross-stratification, etc.), mainly interpreted as due to wave influence. Bioclastic shell concentrations commonly form discontinuous deposits (gutter cast fills), but also continuous horizons. Thus, sedimentological features of the lower member reveal deposition mainly above storm wave-base. The local absence of these sedimentary structures can be indicative of the existence of depositional zones below storm wave-base, or landward restricted areas.

In the upper member, the facies are quite different. The base of this member is marked by a sedimentary discontinuity, followed by marls and marly limestones

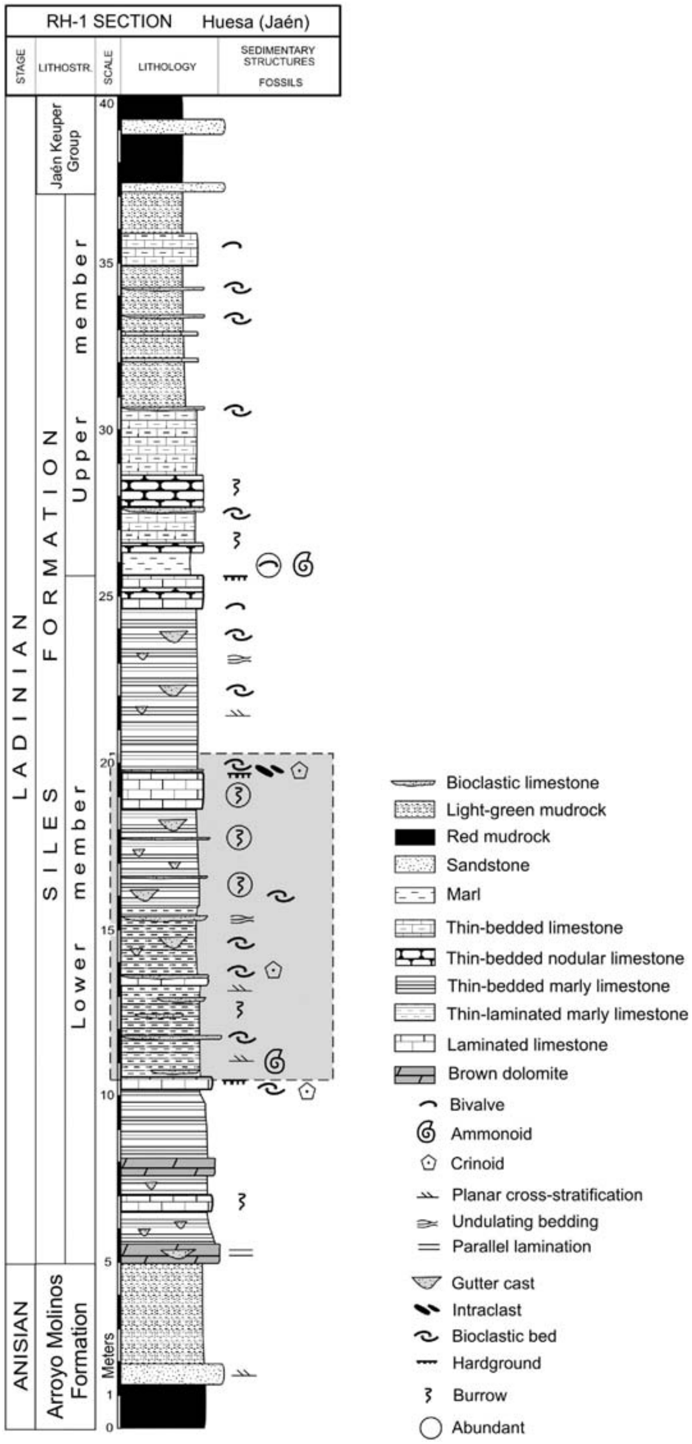

Fig. 2. Lithological column of the Huesa (RH-1) section, including biostratigraphy, lithostratigraphy, sedimentary structures and fossils. Grey selected area denotes the studied succession.

with abundant fauna (bivalves). Upwards, the rest of this member consists principally of nodular and thin-bedded limestones, including bioclastic limestone layers. Towards the top, a general increase in marl and siltstone content is detected, becoming interbedding with red siliciclastic rocks of the Keuper facies. This upper member was deposited under low energy conditions, and probably represents the progradation of coastal systems across the platform.

Compared with the upper member, the lower member is well exposed, thicker, and characterized by different facies and sedimentary structures, as well as displaying a conspicuous and abundant trace fossil assemblage. Detailed facies analysis performed on this lower member, based on lithological features, sedimentary structures, and trace fossil content, permitted the differentiation of seven facies (A to G), particularly well represented in the middle part of this lower member (Figs. 2 and 3 and Table 1).

The facies features (Table 1) are indicative of shallow carbonate environments, probably situated on an inner carbonate ramp influenced by storms and currents

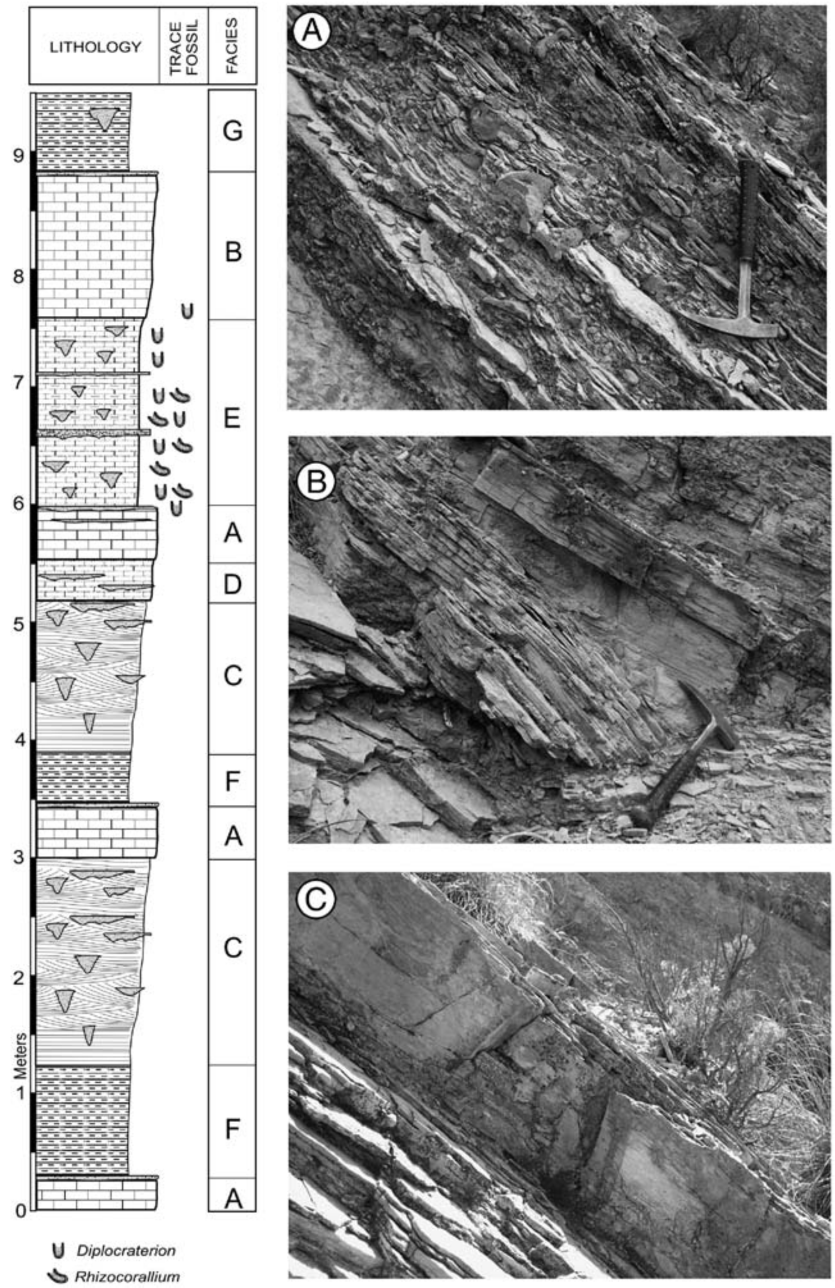

Fig. 3. Facies distribution through the studied interval in the lower member of the Siles Formation. (A–C) Outcrop views (the section is inverted): (A) Facies E, showing gutter cast and bioturbated marly limestone. (B) Facies C with a detail of the cross-stratification. (C) Facies A.

Table 1
Facies differentiated, from shallowest (top) to deepest (bottom), in the lower member of the Siles Formation, based on lithological features, sedimentary structures, fossils and trace fossil content

Facies	Lithology	Bioclastic bed	Sedimentary structures	Body fossils	Bioturbation	Interpretation
A	Laminated micritic limestone	On top	Weak lamination, occasional wave ripples	Bivalves, scarce crinoids	Frequent	Tidal flat
B	Fine-grained limestone	Discontinuous	Scarce cross-lamination near the top	Crinoids, bivalves, gastropods	Frequent	Inner ramp
C	Cross-bedded calcilutite, increase in carbonate upward	Continuous, on top	Gutter casts (larger with less incision towards the top)	Scarce	Scarce	Middle ramp with storm influence
D	Thin-bedded limestone	Discontinuous	Scarce	Scarce	Scarce	Middle transition to inner ramp
E	Thin-bedded marly limestone	Discontinuous and continuous	Abundant small gutter casts, moderately deeply incised	Scarce	Abundant	Middle ramp with storm influence
F	Massive, grey, marl	Absent	Absent	Scarce	Scarce	Outer ramp
G	Rhythmic marl and thin-bedded marly limestone	Absent	Large gutter and pot casts	Scarce	Scarce	Outer ramp

(Pérez-Valera, 2005). Facies A and B are the shallowest facies of the ramp, while Facies C, D and E are situated in an intermediate position; all of them are deposited above storm wave-base and show variations in carbonate content and in the frequency, size and form of gutter casts. Facies F and G are the most distal facies, composed, respectively, of massive and rhythmic marls, deposited below storm wave-base (Duringer and Vecsei, 1998).

4. Sequence stratigraphic framework

The sequence stratigraphic framework of the Triassic basin in the Betic Cordillera is poorly known. The classical sequence stratigraphic approach is limited by a number of factors: (a) the scarcity of subsurface data, (b) relatively narrow outcrops, (c) an absence of well-defined depositional geometries in sedimentary packages, (d) poorly expressed stacking patterns, (e) poorly expressed facies (without evident lithological changes, or fluctuations in abiotic components, etc.), (f) the scarcity of well differentiated key boundary surfaces, (g) relatively scarce fossil assemblages, and (h) the absence of a precise biostratigraphic framework. Even the application of the traditional "procedure inverse" of Vail et al. (1987) for correlation with the well-known global sequence stratigraphic charts is complicated (the near-absence of fossils of the Tethys bioprovince in the Sudiberic Triassic makes it difficult to correlate this with the standard ammonoid zones and subzones).

Recently, sequence stratigraphic interpretations for the Sudiberic Triassic have been presented for the first time (Pérez-López, 1991; Pérez-López and Fernández, 1992; Pérez-López, 1996; Pérez-Valera, 2005). For the Sudiberic Triassic, the carbonates of Muschelkalk facies (Siles Formation) are assigned to a third-order depositional sequence (Pérez-Valera, 2005) that also includes rocks of the Buntsandstein facies (Arroyo Molinos Formation) at the base (Fig. 4). In this third-order depositional sequence, a lowstand – transgressive – highstand systems tract succession is inferred. The lowstand systems tract (LST) is represented by the siliciclastic rocks of the Buntsandstein (Arroyo Molinos Formation: Pérez-Valera, 2005). Atop this formation, a transgressive surface is recognized. The Muschelkalk facies represent deposition during the transgressive systems tract (TST, lower member of the Siles Formation) and during the highstand systems tract (HST, upper member of Siles Formation). The lower member represents coastal facies prograding onto the platform and the ramp. Between the lower and upper members, a sedimentary discontinuity (a hardground surface above bioclastic oolitic limestones) was recognized, interpreted as a maximum flooding surface (Pérez-López et al., 2005). At the top of the Muschelkalk, in the transition with the Keuper facies, a new discontinuity (a fine iron crust at the top of bioclastic limestones) is observed and interpreted as a sequence boundary surface, overlain by the evaporitic and siliciclastic rocks of the Jaén Keuper Group which belong to the LST of the overlying depositional sequence (Pérez-López, 1991, 1996).

Taking into account the new chronostratigraphic scheme for the Anisian–Ladinian boundary (Brack et al., 2005), correlations with regional sequence stratigraphic frameworks for the Tethys domain (Giannola and Jacquin, 1998; Hardenbol et al., 1998), for the German Basin (Aigner and Bachmann, 1992), and the global eustatic chart (Haq et al., 1987, 1988) are presented in Fig. 5. Comparison with other Triassic domains of the Iberian Peninsula (i.e., Catalonian Basin:

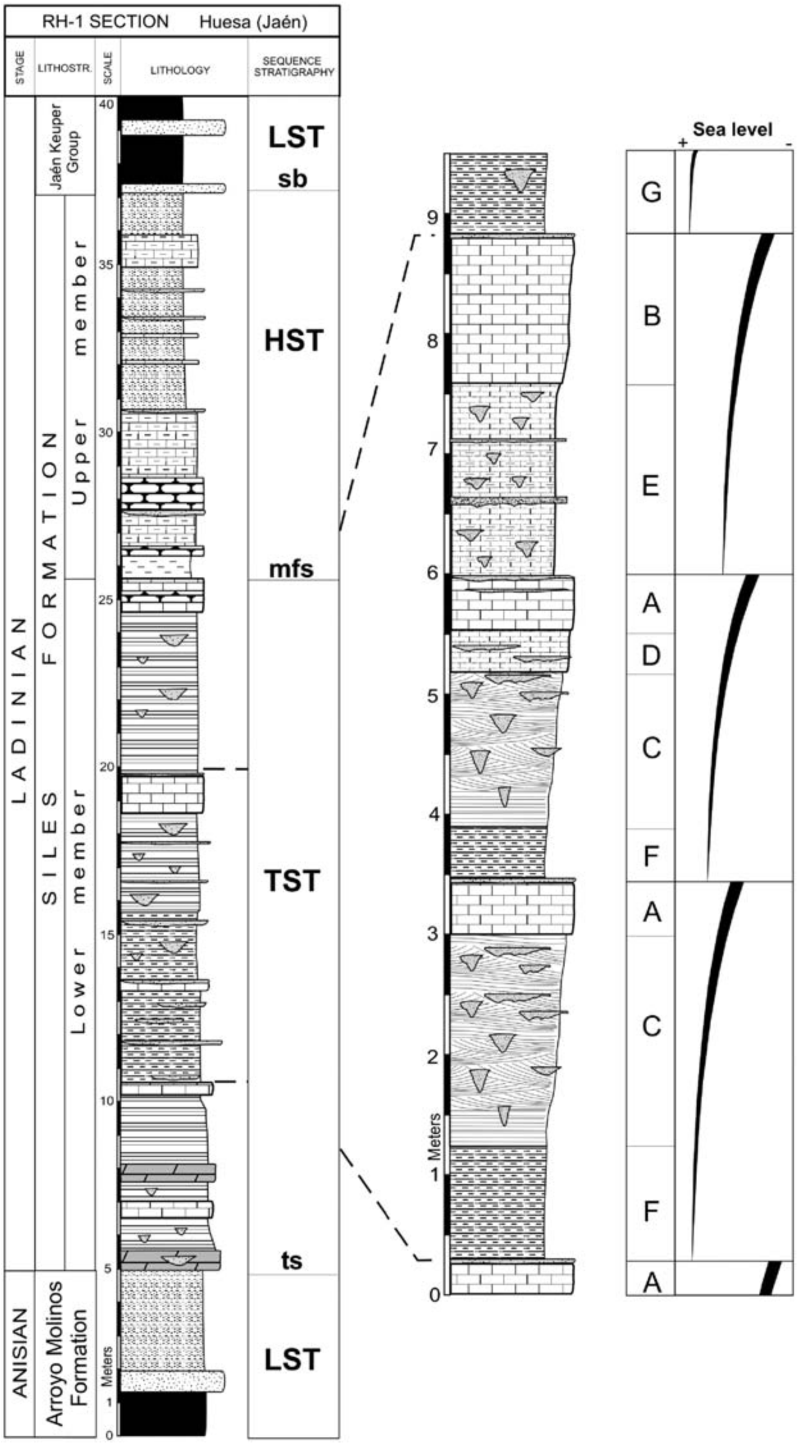

Fig. 4. Proposed third-order sequence stratigraphic framework for the Sudiberic Anisian p.p.–Ladinian (Middle Triassic) (Pérez-Valera, 2005). In this third-order depositional sequence, a lowstand (Buntsandstein p.p.; Arroyo Molinos Formation) – transgressive (lower member of Muschelkalk; Siles Formation) – highstand (upper member of Muschelkalk; Siles Formation) systems tract succession has been interpreted. To the right, regressive tendencies recorded in sedimentary packages from the selected interval are interpreted as parasequences. LST—lowstand systems tracts; TST—transgressive systems tracts; HST—highstand systems tracts; ts—transgressive surface; mfs—maximum flooding surface; sb—sequence boundary.

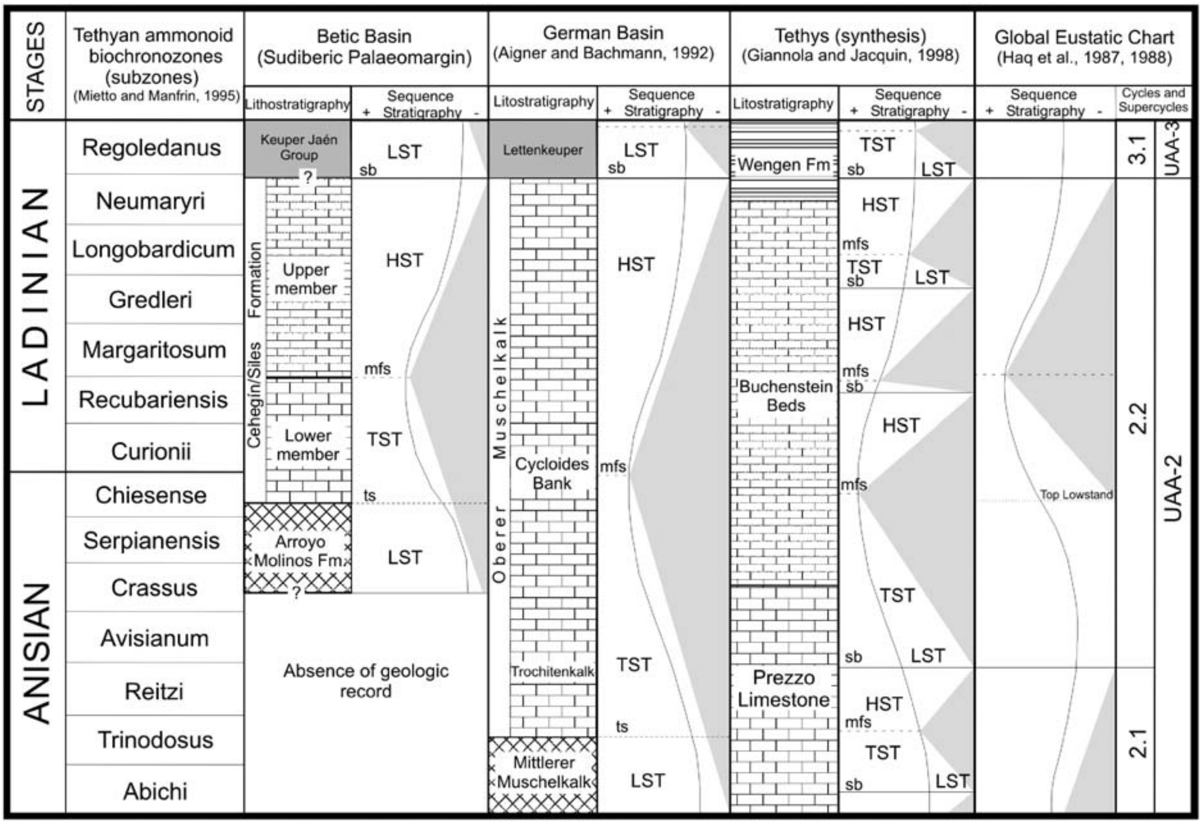

Fig. 5. Correlation of the proposed sequence stratigraphic framework for the Middle Triassic (mainly Ladinian) in the Sudiberic Palaeomargin (Betic Basin), with regional sequence stratigraphic models for the Tethys Domain (Giannola and Jacquin, 1998; Hardenbol et al., 1998), the Germanic Basin (Aigner and Bachmann, 1992), and the global eustatic chart (Haq et al., 1987, 1988).

Calvet et al., 1990; Iberian Ranges: López-Gómez and Arche, 1993), would require a thorough integration of the biostratigraphic data from these areas with the new chronostratigraphic framework (Brack et al., 2005). The sequence stratigraphic interpretation proposed for the Sudiberic Triassic is less detailed than the other interpretations shown in Fig. 5. For the studied stratigraphic interval, in the Tethys domain three depositional sequences have been proposed (Giannola and Jacquin, 1998), while in the Sudiberic Triassic only one has been distinguished (Fig. 5).

Based exclusively on sedimentological features, a more detailed sequence stratigraphic characterization is no easy matter. Only locally, sedimentary packages showing regressive tendencies (Fig. 4) have been differentiated and can be interpreted as parasequences. A detailed ichnological analysis of some of the possible parasequences in the lower member of the Siles Formation was performed in order to test and refine sequence stratigraphic interpretations at a higher level of resolution (4th order and higher).

5. The trace fossil assemblage

A preliminary analysis of the trace fossil assemblage revealed significant differences in composition, abundance and distribution of trace fossils through the succession (Pérez-Valera, 2005). In a context of relatively scarce trace fossil records, the comparatively rich and distinctive trace fossil assemblage in the lower member of the Siles Formation in the Huesa section is especially significant.

5.1. Trace fossil composition

The most common ichnogenera are *Diplocraterion* and *Rhizocorallium*. Unbranched and branched sinuous traces also occur (Fig. 6).

Diplocraterion occurs as mainly vertical U-shaped cylindrical tubes with spreite. Size is extremely variable, but intermediate sizes of around 25–30 mm wide are quite common, with a diameter of the U limbs of about 7–9 mm, and a maximum burrow length between 30

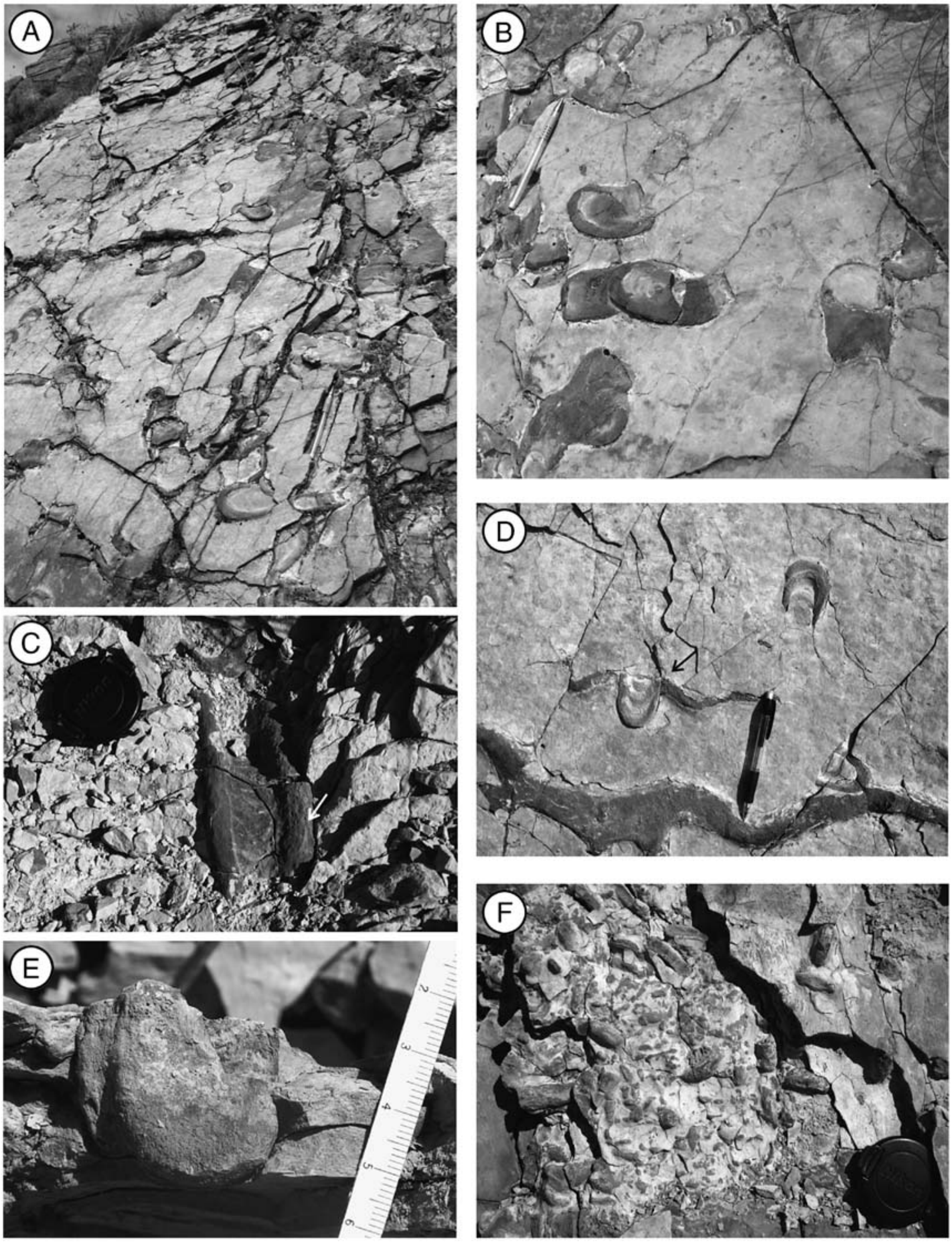

Fig. 6. Outcrop views of trace fossils from the Huesa section. (A) Facies E showing distribution of *Rhizocorallium* at the bottom of beds. (B) Single specimens of U to slightly pear-shaped *Rhizocorallium*. (C) *Rhizocorallium* with scratch-marks (white arrow). (D) *Rhizocorallium* cross-cutting bioclastic beds (black arrow). (E) Protrusive form of *Diplocraterion* capped at the upper part. (F) Concentration of *Diplocraterion* in the marly limestones intervals of Facies E, showing the base of their structures at the bottom of the beds.

and 40 mm (Fig. 6F). However, complete specimens are rare; *Diplocraterion* commonly shows truncation at the top (Fig. 6E; only occasional apertures were observed at the surface). All specimens represent protrusive forms *sensu* Goldring (1962), with parallel tubes (Fig. 6E).

Diplocraterion is a characteristic trace fossil in the softground *Skolithos* and firmground *Glossifungites* ichnofacies, being a common element of the distal end of the *Skolithos* ichnofacies (Pemberton et al., 2001). Previous studies on the relationship between *Diplocraterion*, relative sea-level changes and sequence stratigraphy show this structure to be common, at least in Jurassic rocks, at transgressive surfaces (e.g., Mason and Christie, 1986; Taylor and Gawthorpe, 1993), but it has also been recorded in high-energy and unstable environments during sea-level fall related to sequence boundaries (Olóriz and Rodríguez-Tovar, 2000).

Rhizocorallium consists of straight to slightly sinuous, U-to-pear-shaped spreiten-burrows, with dominant *R. jenense*. A horizontal orientation is most common, though obliquely oriented specimens with a variable angle of burrowing are also recognized. Complete specimens are difficult to discern; only locally were apertures on the bed surface observed. Size varies considerably between specimens. In the straight structures, shorter forms show maximum width ranging from 25 to 30 mm, marginal tunnels 5–7 mm in diameter, and length up to 30 mm, whereas larger structures have a maximum width ranging from 50 to 70 mm, a marginal tunnel diameter of 10–12 mm, and a length of up to 250 mm. Spreiten are typically protrusive and scratch-marks are clearly recognizable (Fig. 6C). The trace is differentiated from *Diplocraterion* by its horizontal to oblique attitude.

Ichnogenus *Rhizocorallium* is a characteristic trace fossil in the softground *Cruziana* and firmground *Glossifungites* ichnofacies (Pemberton, 1992). Most of the interpretations of *Rhizocorallium* in the context of sea-level dynamics are essentially related to the *Glossifungites* ichnofacies (see references below), but occasionally single *Rhizocorallium* records are directly related to omission surfaces and storm-generated beds (i.e., Fürsich et al., 1981; Cotillon et al., 2000; Worsley and Mork, 2001), and to low energy regimes (Fürsich, 1974, 1981). *Glossifungites* ichnofacies is environmentally wide-ranging, restricted to firm but unlithified substrates, such as dewatered muds or highly compacted sands. Firmground traces belonging to the *Glossifungites* ichnofacies are dominated by vertical to subvertical dwelling structures of suspension-feeding organisms, the most common ichnogenera being *Diplocraterion*, *Skolithos*, *Psilonichnus*, *Arenicolites*, and firmground *Gastrochaenolites*; yet there are also dwelling traces of deposit-feeding organisms including firmground *Thalassinoides*, *Spongeliomorpha* and *Rhizocorallium* (Pemberton and MacEachern, 1995; Pemberton et al., 2004).

Good preservation of the trace fossils, together with abundant and well developed scratch-marks on the burrow walls, reveals colonization of firm substrates, and thus the *Glossifungites* ichnofacies, with *Diplocraterion* and *Rhizocorallium* (mainly *R. jenense*) as major components of this ichnofacies. However, slight differences in substrate firmness could be evoked for the colonization of the *Diplocraterion* and *Rhizocorallium* tracemakers, with *Diplocraterion* organisms favouring softer substrates.

5.2. Trace fossil distribution

Trace fossil observations throughout the studied succession reveal a major concentration in the lower member of the Siles Formation, especially in its middle part (Fig. 2). Of the seven facies recognized in the middle part of the lower member, trace fossils are mainly located in Facies E and F, and also at the top of Facies A, while in the rest of the facies bioturbation is scarce or absent. Facies A, characterized by dark, laminated micritic limestone beds (mudstone), locally with wave ripple lamination, contains a few specimens of *Diplocraterion*, most notably at the top of this facies. Facies E, consisting of thin-bedded, marly limestones, is characterized by gutter casts and abundant bioturbation, mainly *Diplocraterion* and *Rhizocorallium* (Fig. 6). Facies F, made up of fine-grained limestone, contains abundant sinuous traces.

Above all in Facies E, a close relationship exists between trace fossils, sedimentary structures and lithology. While *Diplocraterion* occurs mainly in the marly limestone intervals of Facies E (Fig. 6F), *Rhizocorallium* (mainly *R. jenense*) generally cross-cuts the bioclastic shell beds (whether discontinuous or continuous: Fig. 6D).

6. Trace fossils and sequence stratigraphic analysis

From the two potential applications in sequence stratigraphic studies (delineating key surfaces and characterizing palaeoenvironmental changes), the ichnological approach is used here to characterize substrate-controlled ichnofacies and to apply them to the recognition and interpretation of several orders of sequence stratigraphic discontinuities. This concept is reflected by recent papers revealing the usefulness of trace fossils in sequence stratigraphic research based on the characterization of firmground *Glossifungites* ichnofacies (see detailed references below), hardground *Trypanites* ichnofacies (i.e., *Entobia* and *Gnathichnus* ichnofacies in Bromley and Asgaard, 1993; *Trypanites* ichnofacies in Ghibaudo et al., 1996; or bioerosion ichnocoenoses in Domènech et al., 2001), and woodground *Teredolites* ichnofacies (Savrda, 1991b; Savrda et al., 1993; Gingras et al., 2001; Savrda et al., 2005).

6.1. *Glossifungites* ichnofacies and sequence stratigraphy discontinuities

The *Glossifungites* ichnofacies is related to semi-lithified or firm substrates formed either by subaerial exposure or by burial and subsequent exhumation (e.g., Pemberton and Frey, 1985; MacEachern et al., 1992; Pemberton et al., 1992; Pemberton, 1998; Pemberton et al., 2001, 2004; Buatois and Encinas, 2006). Such exhumed surfaces commonly represent stratigraphic discontinuities. Following the most recent review (Pemberton et al., 2004), the erosional discontinuities associated with the *Glossifungites* ichnofacies are: regressive surfaces of erosion (RSE), sequence boundaries (SB), transgressive surfaces of erosion (TSE) and amalgamated sequence boundaries and marine flooding surfaces (FS/SB).

Regressive surfaces of erosion (RSE) and sequence boundaries (SB) are related to eroded, firm or cemented substrates frequently generated during relative sea-level drop. These surfaces would only be colonized by the *Glossifungites* suite when they are subsequently exposed to marine or marginal marine conditions, as occurs in RSE developed beneath forced regressive shorefaces, and in SB underlying lowstand shorefaces, in submarine canyon margins or at the estuarine mouths of incised valleys prior to transgressive infill.

Transgressive surfaces of erosion (TSE) refer to erosional ravinement surfaces that can develop widespread substrate-controlled ichnofacies because the exhumed surfaces originate within a marine or marginal marine environment, favouring colonization by trace-makers before the accumulation of significant thicknesses of overlying sediment.

Amalgamated sequence boundaries and marine flooding surfaces (FS/SB) are usually colonized by substrate-controlled ichnofacies, including the *Glossifungites* ichnofacies. Firmground, hardground and woodground surfaces (corresponding to an RSE or SB) develop after a lowstand erosion event, and can be colonized after the subsequent transgressive event. This generates a TSE and tends to remove most or all the lowstand deposits, after which the re-exhumed original discontinuity is embedded into marine or marginal marine conditions.

Finally, we cannot discard the occasional record of the *Glossifungites* ichnofacies associated with other non-erosional surfaces. Thus, marine flooding surfaces (MFS), without or with minimal erosion, are typically unburrowed, but the development of semi-lithified or lithified substrates could facilitate the appearance of *Glossifungites* ichnofacies. The association of the *Glossifungites* ichnofacies with marine flooding events in deeper water, upper slope deposits, has been demonstrated in recent years (Savrda et al., 2001a,b).

6.2. Ichnological approach and sequence stratigraphic interpretation of the studied succession

As discussed above, previous sequence stratigraphic analyses of the studied succession based mainly on sedimentological data led to the interpretation of a third-order depositional sequence (Fig. 4). However, the absence of distinctive sedimentological features typical of parasequences, or parasequence sets, impedes a more precise sequence stratigraphic characterization, and an interpretation of high-frequency sea-level dynamics. This is the context in which the ichnological approach was applied.

The middle part of the lower member of the Siles Formation corresponds to transgressive deposits belonging to the TST (Fig. 4). Our ichnological analysis indicates that: (a) in a context of relative scarcity of trace fossils, this interval reveals an abundant and conspicuous trace fossil assemblage; (b) *Diplocraterion* and *Rhizocorallium* are the most common ichnogenera, particularly in Facies E, while sinuous traces (simple and bifurcating) are recognized in Facies F; (c) *Diplocraterion* are characterized by their protrusive character and the absence of preserved apertures (usually capped on top); (d) *Rhizocorallium* structures show very well defined scratch-marks, revealing firmground conditions; (e) *Diplocraterion* mainly occur in the marly limestone intervals, while *Rhizocorallium* are associated with the bioclastic, shelly, beds; (f) cross-cutting relationships reveal that *Rhizocorallium* structures cross-cut shell lags and, occasionally, *Diplocraterion*; and (g) *Glossifungites* ichnofacies can be differentiated.

The above ichnological features (i.e., the recognized relationship between *Glossifungites* suite, mainly *Rhizocorallium*, and the more or less continuous bioclastic shell lags), correspond to those of transgressive surfaces of erosion (MacEachern et al., 1992; Pemberton and MacEachern, 1995; Pemberton et al., 2001, 2004). At the base of a parasequence, when the rate of relative sea-level rise is moderate to low, the shoreline transgresses landward through shoreface erosion (Swift, 1975; Arnott, 1995). In such a situation, a transgressive surface of erosion and an associated transgressive lag are created. Such transgressive erosional processes lead to the exhumation of consolidated substrates, which are subsequently colonized by organisms producing the firmground trace fossil suite before the deposition of significant overlying sediments. Thus, a direct relationship between the *Glossifungites* ichnofacies and transgressive surfaces of erosion should exist. However, the numerous bioclastic, shelly beds, and the associated ichnological record, should not merely be interpreted as the product of transgressive surfaces of erosion bounding parasequences. Bioclastic beds (continuous and discontinuous), affected by the *Glossifungites* suite in the transgressive deposits, could be related to a complex transgressive context and high-frequency sea-level dynamics (from fourth to sixth order), representing TSE of different orders (Fig. 7). The observed features could be the consequence of interactions between any number of parameters, such as range of sea-level fluctuations, continuity of sedimentation, sediment supply or exposure time. Hence:

a) Parasequences created during the development of the transgressive systems tract would be bounded in the studied interval by major order TSE, characterized by the most continuous and thicker bioclastic shell beds, deposited during the most important rise in sea-level. The absence of an associated *Glossifungites* suite could be a consequence of rapid sediment supply

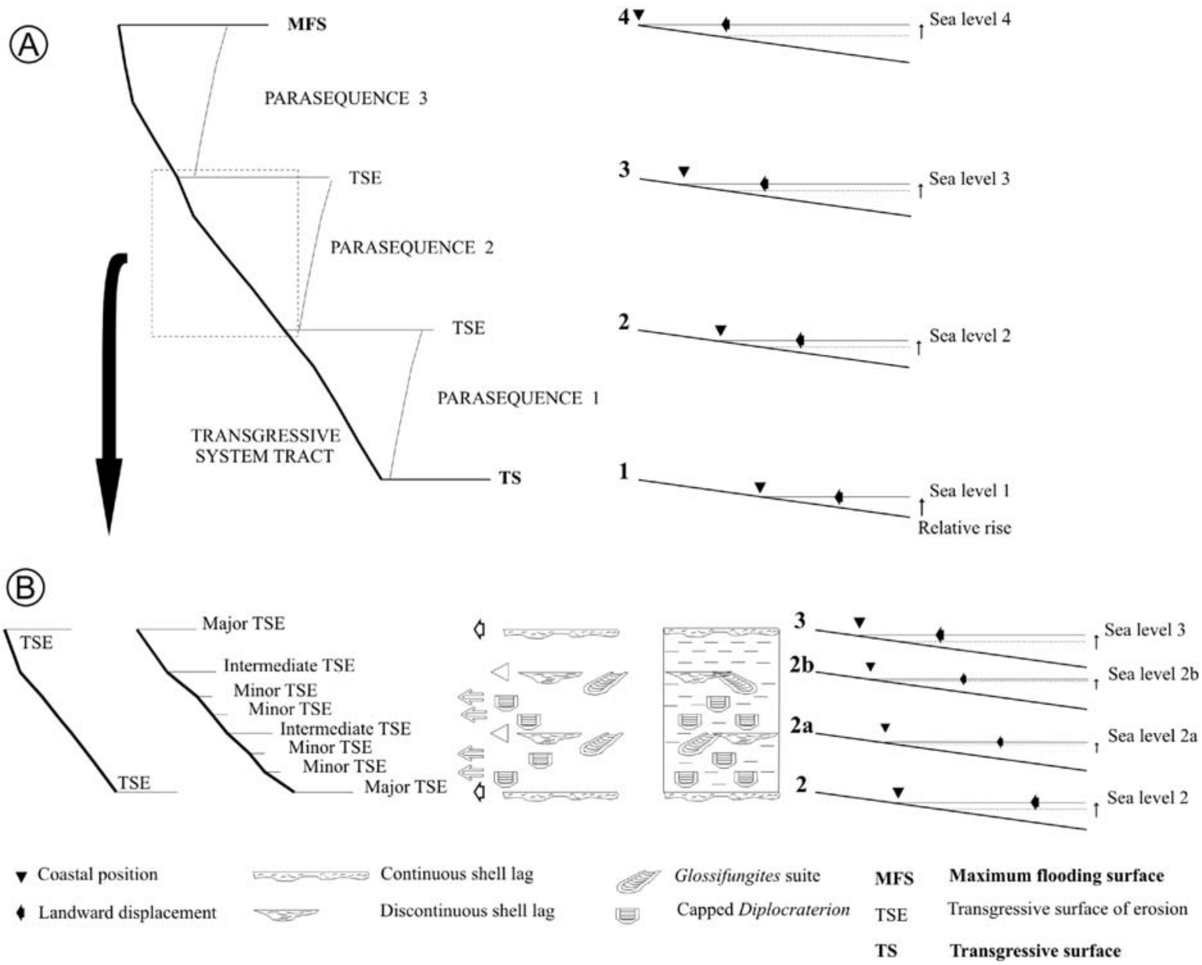

Fig. 7. High-resolution sequence stratigraphic and sea-level dynamic interpretation at high order (fourth to sixth), for the transgressive interval studied in the Huesa section. (A) Theoretical parasequence evolution in the transgressive systems tract and sea-level fluctuation from 1 to 4. (B) Proposed evolution in parasequence 2, bounded by major transgressive surfaces of erosion (ravinement surfaces, TSE) and punctuated by intermediate and minor order TSE, based on sedimentological and ichnological features.

determining the absence of sufficient exposure time for colonization.

b) Through parasequence development (that is, within parasequences), TSE of minor orders will be generated. Intermediate order TSE are represented by more or less continuous bioclastic shell beds (though in places discontinuous), associated with the *Glossifungites* suite (mainly *Rhizocorallium*; Fig. 6D), and generated during less important rises in sea-level. The presence of the *Glossifungites* suite could be a consequence of moderate sediment supply, allowing enough exposure time for colonization of an exhumed firmground.

c) Finally, deposition of the underlying material (marly limestone intervals) registered between TSE would have favoured colonization by tracemakers forming *Diplocraterion* (Fig. 6F), in comparatively less consolidated substrates, and during more or less stillstand phases (the TSE/stillstand phases). Successions of horizons with capped protrusive *Diplocraterion* (Fig. 6E) could be related to downward adjustments forced by erosion during the highest frequency, minor order, transgressive surfaces of erosion.

Similar complex transgressions have been previously recognized in comparable depositional settings. The Lower Cretaceous Viking Formation of central Alberta (Canada) contains numerous TSE, recording a complex history of transgression, in a moderately to highly storm-dominated, upper offshore to distal lower shoreface setting with high-frequency TSE/stillstand phases (MacEachern et al., 1992). Similar features of TSE have been put forth by Bann (1998) and Bann et al. (2004), from the early Permian Pebbley Formation of the Sydney Basin (Australia), in a depositional setting from lower offshore through shoreface to coastal (estuarine) environments. Similarities also exist with the Tarbert and Heather formations of the Middle Jurassic Brent Group of the North Sea in a transgressively backstepped, wave-dominated deltaic setting (MacEachern and Loseth, 2003).

7. Conclusions

The ichnological approach is shown to be a valuable tool for improving high-resolution sequence stratigraphic models and high-frequency sea-level dynamics in Triassic basin analysis, in this case in the Betic Cordillera (southern Spain).

In a context of relatively scarce trace fossil records, transgressive sediments deposited during the evolution of a third order transgressive systems tract are highly bioturbated. *Diplocraterion* show protrusive structures, usually truncated at the top. *Rhizocorallium* exhibits well-defined scratch-marks, revealing firmground conditions. *Diplocraterion* mainly occurs in marly limestone intervals, while *Rhizocorallium* cross-cuts bioclastic shell beds. *Glossifungites* ichnofacies can be differentiated.

Integration of sedimentological and ichnological data leads us to interpret the existence of a complex transgressive context and high-frequency sea-level dynamics (from fourth to sixth order), representing transgressive surfaces of erosion of different orders, between and within parasequences. Bounding parasequences, the shoreline transgressed landward creating major transgressive surfaces of erosion, associated with continuous bioclastic shell beds. The absence of *Glossifungites* suite is related to rapid deposition and a short span of exposure. Within parasequences, comparatively less important sea-level rises determined the formation of discontinuous shell beds and the colonization of firmgrounds by members of the *Glossifungites* suite during relatively prolonged exposure times, and the subsequent generation of intermediate TSE. During deposition of the material between the intermediate TSE, colonization by *Diplocraterion* tracemakers took place during stillstand phases. Punctuated high-frequency sea-level rises could be related to downward displacement of tracemakers into sediment, and to protrusive capped structures associated with minor order TSE.

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