

Integrated taphonomy in an open-marine platform: The Lower Cretaceous of Sierra Helada (Betic Cordillera, SE Spain)



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ABSTRACT

A detailed taphonomic analysis was carried out on the lower Albian deposits of the Sierra Helada section (Alicante, Betic Cordillera, southeastern Spain). Ten taphonomic characters were studied and ten skeletal concentrations were defined on the basis of taphonomic features and the dominant taxa. Cluster analysis was performed on the dataset represented by the abundance of the taphonomic characters in each skeletal concentration. This enabled the definition of four different taphonomic categories: 1) skeletal concentrations characterized by the presence of fossils preserved in life position, 2) skeletal concentrations showing very little physical reworking, 3) skeletal concentrations related to high-energy background conditions, and 4) skeletal concentrations produced by medium- to high-energy events.

Four taphofacies were defined on the basis of the main sedimentological features and the most representative skeletal concentrations. Taphofacies A represents the low energy outer platform, rich in skeletal concentrations with echinoids in life position and only slightly reworked. The second taphofacies (taphofacies B) is very rich in reworked echinoid tests and calcarenitic beds and records the transition to shallower areas, while taphofacies C shows abundant thick-bedded calcarenites and skeletal concentrations produced by sediment transport and rapid deposition. Finally, cross-bedded grainstone beds, which are rich in fine-grained fragmented, locally reoriented bioclasts (taphofacies D), record the existence of shifting sandy dunes in the shallow inner part of the platform.

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1. Introduction

Sierra Helada is a long mountain chain located on the Spanish coast between Benidorm and Altea, near Alicante (southeastern Spain). Most of the materials observed in this area belong to the Upper Jurassic–Lower Cretaceous and were first studied by Verneuil and Collomb (1852) and described in their book about the geology of southeastern Spain. At the end of the 19th/beginning of the 20th century, a more detailed series of studies was carried out in the province of Alicante that focused in part on the Cretaceous deposits (Nicklès, 1890, 1892, 1904). The geological descriptions in these studies were used with few changes until the 1980s, when the area was selected for a new series of research projects especially aimed at a detailed litho- and biostratigraphic characterization of its Jurassic and Cretaceous deposits (Vilas et al., 1982; Granier, 1987; Castro and Ruiz Ortiz, 1994; Castro, 1996, 1998; Yébenes, 1996). As regards the Cretaceous materials, and with the exception of

some geomorphological/tectonic studies (Yébenes et al., 2002 and references therein), almost all the research in the area had been addressed to stratigraphic/biostratigraphic characterization of the deposits (Castro et al., 2001; Vilas et al., 2001 and references therein), while less attention had been paid to detailed paleo-environmental reconstructions. The first ichnological analysis carried out in the area (Monaco et al., 2005) contributed to highlighting the richness and uniqueness of the Sierra Helada Cretaceous fossil record. A detailed taphonomic analysis was carried out on the various shell beds present in the Albian deposits of Sierra Helada, and the main results are presented in this article. It is well-known that taphonomic features capture paleoenvironmental signals, and provide detailed information about both sedimentary events and background processes (Brett and Baird, 1986; Kidwell et al., 1986; Wilson, 1988; Brandt, 1989; Davies et al., 1989; Fürsich, 1990; Kidwell, 1991; Kidwell and Bosence, 1991; Brett, 1995; Olóriz et al., 2002; Zuschin et al., 2002; Chen et al., 2010). The aim of this paper is to approach the Lower Cretaceous deposits, and analyse their taphonomic characters and taphofacies for a more accurate reconstruction of the paleoenvironmental scenario.

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2. Geographical and geological setting

The studied materials are part of a very well-exposed section cropping out in Sierra Helada, a long narrow mountain chain in the north-east of the Alicante province, between the Benidorm and Altea bays (southern Spain, Fig. 1). The area belongs to the Jijona-Aspe-Alicante Prebetic Domain (Arias et al., 2004), previously defined by several authors as the Internal Prebetic Domain (Azéma et al., 1979; García-Hernández et al., 1980; Castro, 1998; Yébenes et al., 2002), and it corresponds to the (par-) autochthonous sector of the External Zone of the Betic Cordillera (De Ruig, 1992; Yébenes et al., 2002). In the Sierra Helada, Upper Jurassic-Lower Cretaceous sedimentary rocks are well-exposed for a total thickness of about 800 m. The whole succession is subdivided into seven lithostratigraphic units (Yébenes, 1996, 2004; Yébenes et al., 2002), the last two of which belong to the Sácaras Formation (defined by Vilas et al., 1982) and include the studied section. According to biostratigraphical analysis, these units were assigned to the lower-middle Albian (Granier, 1987; Castro, 1998) in the study area. As for the paleoenvironmental setting, the Sácaras Formation ranges from littoral-sublittoral deposits in Valencia to open platform with a continental area developed at the back, north of Alicante. The Sácaras Formation is generally characterized by the presence of marls, calcarenites and roughly-bedded limestones, with a total thickness of about 300 m (units C5 and C6 of Yébenes, 2004; Fig. 2). The formation is part of a first order asymmetric megasequence, with a first large transgressive system tract followed by a short regressive one (Castro, 1998; Castro et al., 2008). Second and third order sequences were defined too, and their origin is most probably related to the sum of the effects of eustasy and the complex tectonic activity of the Iberian margin (Castro et al., 2008).

3. Stratigraphy of the studied section

The studied section has a total thickness of about 180 m and includes the upper part of unit C5 and the lower part of unit C6 (Fig. 2).

Unit C5 (lower Albian), about 100 m thick, lies disconformably on the Seguilí Formation (Castro, 1998; Yébenes et al., 2002; Yébenes, 2004). This unit is characterized by the presence of marl/limestone alternations (LA), nodular, burrowed marly wackestones (LB) and cross-bedded, bioclastic grainstones (LC), which are organized in coarsening, thickening and shallowing-upward small-scale sequences. Unit C6 is referred to the lower-middle Albian and is about 200 m thick; it is poor in calcarenites and very rich in bioclasts, and is mainly represented by echinoid tests, bivalves, gastropods and brachiopod shells. In both units,

burrowing is very well-developed, and large *Thalassinoides* mazes and many preservational types of *Scolicia* are abundant (Monaco et al., 2005). A peculiar type of tubular burrow (*Ereipichnus geladensis*), so far only known from the Sierra Helada area (Monaco et al., 2005), is also very common.

Lithofacies LA: marls with interbedded limestones (Fig. 2b). This lithofacies is characterized by regular, tabular grey limestones, 10–15 cm thick, with interbedded marly beds, 10–30 cm thick. The average thickness of this lithofacies is about 2–2.5 m. Limestones are mainly represented by very fine-grained wackestone/packstone rich in small, rounded quartz grains and fine-grained bioclasts (echinoids, bivalves, gastropods, planktonic and benthic foraminifers, and rare serpulids). Marly beds are poor in bioclasts and contain only echinoid fragments and planktonic and rare benthic foraminifers.

Lithofacies LB: bioclastic packstone. This lithofacies is characterized by 40–60 cm thick, grey bioclastic packstone beds. The average thickness of this lithofacies is about 1.5–2 m. The finely to coarsely fragmented bioclasts are represented by pectinids, ostreids, thick-shelled bivalves, gastropods, brachiopods, crinoid ossicles and corals, echinoids, red algae, bryozoan, serpulids and very rare belemnites and ammonites. Orbitolinids and benthic microforaminifers are also present.

Lithofacies LC: cross-bedded bioclastic rudstone/grainstone. The most distinctive feature of this lithofacies is its yellowish colour and large-scale cross bedding, which commonly also shows internal cross-lamination. Beds are from 10 to 50 cm thick and the total thickness of the lithofacies is variable, from 10 to 20 cm in unit C6 to 10 m in unit C5. Bioclasts are represented by bivalves, brachiopods, bryozoans, echinoids, red and green algae, gastropods, crinoid ossicles and micro- and macro- benthic foraminifers.

4. Material and methods

The Sierra Helada section was studied bed-by-bed, both sedimentologically and taphonomically. Sedimentological field observations were supplemented with the study of 30 thin-sections and 10 washed samples.

As for the taphonomic analysis, ten taphonomic characters (Table 1) were considered and evaluated using a semi-quantitative scale ranging from 0 (absent) to 5 (extremely abundant). Character abundance was analysed *in situ* for each bed using a 20 × 20 cm grid. The vertical section of the beds was studied in most of the cases, and where possible, observations were complemented with analysis of the lower and upper planar surfaces. Skeletal concentrations were defined according to the abundance of the taphonomic characters present and grouped into different taphonomic categories through cluster analysis. This was carried out on a dataset representing the abundance of the 10 characters in each skeletal concentration with the free software PAST (Hammer et al., 2001). Finally, taphofacies were defined considering the presence or abundance of diagnostic skeletal concentrations.

The following taphonomic characters were considered (Table 1):

A. Characters produced without significant transport, mainly derived from biological and chemical processes

- A1) Encrusting/colonization. Percentage and position (i.e. inner/outer surface of the shells, lower/upper part of the massive corals, etc.) of the bioclast covered by encrusting organisms were considered. Where possible, information about the type of encrusters was also considered.
- A2) Deformation by collapse. This is a character related to compaction and depends on the morphology and microstructure of the bioclast as well as on the absence of filling. Both its

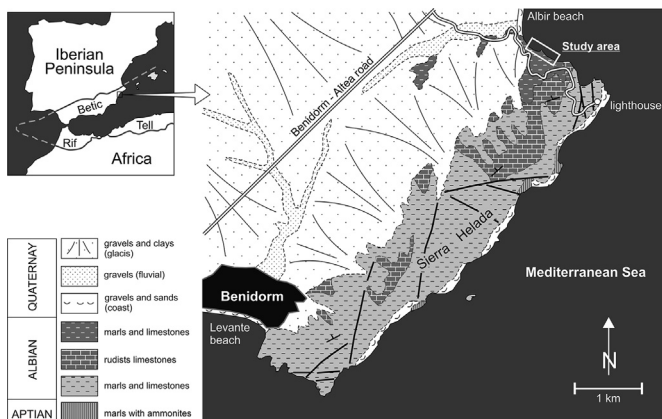


Fig. 1. Study area and schematic geological map.

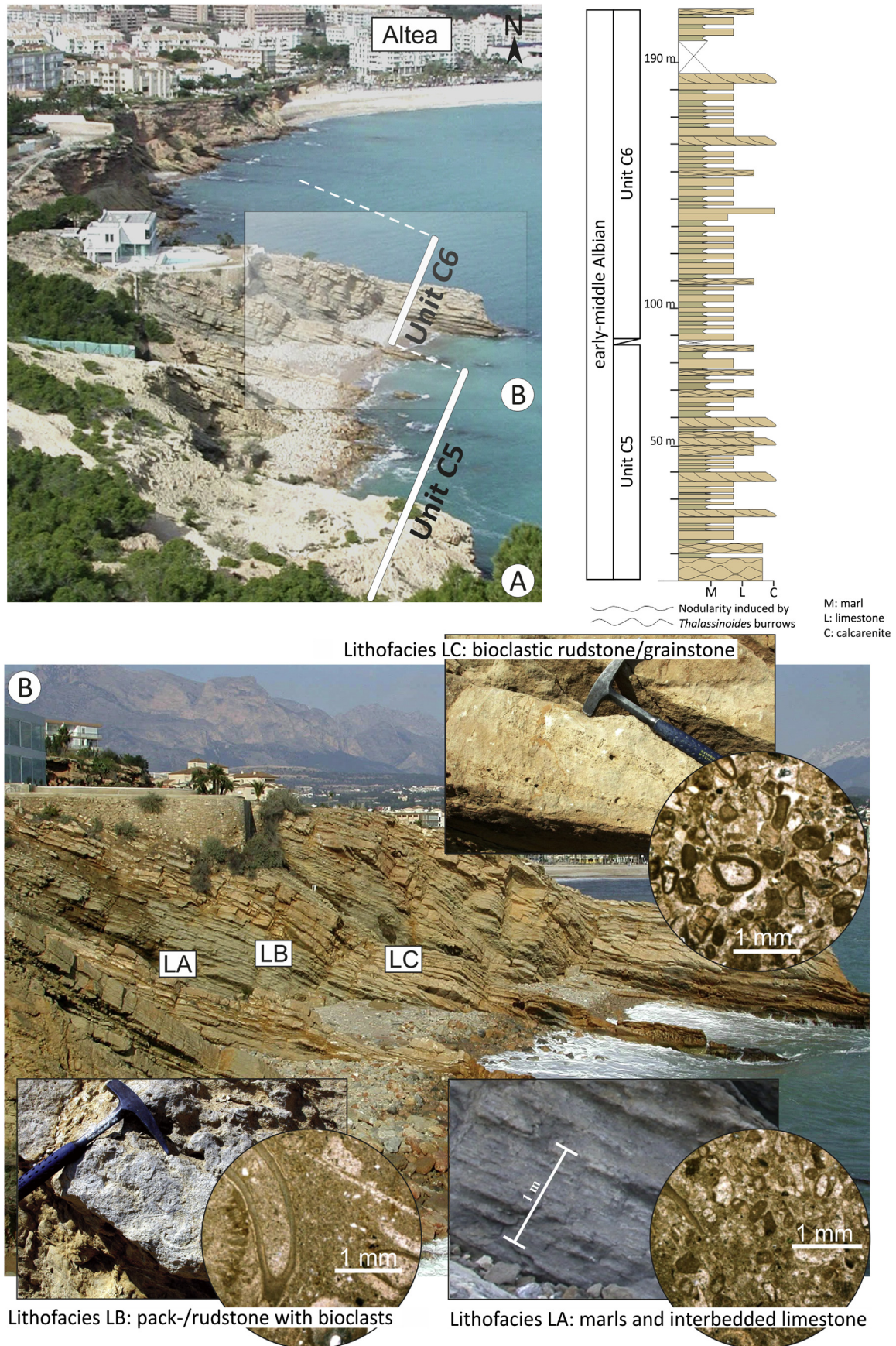


Fig. 2. A. Field view of the studied section and stratigraphical log. The two uppermost units of the Sácaras Formation are marked. B. Field view and microfacies photograph of the three lithologies observed in the section.

Table 1

Abundance of the 10 taphonomic characters in the 10 skeletal concentrations defined in the studied section. An abundance index from 0 (absent) to 5 (dominant) has been used. An asterisk (*) is used where the character could not be evaluated. See text for protocol.

Taphonomic characters	SkC 1	SkC 2	SkC 3	SkC 4	SkC 5	SkC 6	SkC 7	SkC 8	SkC 9	SkC 10
A1 Encrustation	0	0	0	0	0	3	3	0	*	*
A2 Fracture by collapse	2	0	3	0	0	0	0	0	*	*
A3 Corrasion	0	0	0	3	1	3	4	2	*	*
A4 Ferruginization	0	0	0	2	0	2	0	0	*	*
B1 Biogenic reworking	1	0	2	4	4	4	4	2	2	1
C1 Disarticulation and fragmentation	0	0	3	4	3	4	3	5	5	5
C2 Reorientation	0	1	3	5	5	5	5	4	4	5
C3 Packing	0	0	2	3	3	3	3	1	5	5
C4 Convex-up orientation	0	1	0	0	0	0	0	1	0	3
C5 Mud/sand filling	2	2	4	0	0	0	0	0	0	0
Allochthonous	0	0	0	5	4	5	3	3	3	3

intensity and abundance (i.e. the percentage of bioclasts affected) were evaluated. It was studied particularly in skeletal concentrations rich in echinoid tests.

- A3) Corrasion. Corrasion *sensu* Brett and Baird (1986) was evaluated by identification of (a) the preservation pattern of macroinvertebrates, such as ribs and growth lines in brachiopod (Kolbe et al., 2011) and bivalve shells; (b) exposure of internal parts of the shells in the case of thick-shelled bivalves; and (c) preservation of the external features of echinoids.
- A4) Ferruginization. This character has been considered only to single bioclasts and not to the whole bed, in order to avoid overestimation due to late diagenetic processes not formed in the original environment.

B. Characters related to significant biogenic reworking

- B1) Reworking by biogenic activity. Burrowing activity is well-represented in the studied section by a wide variety of trace fossils; it was considered in order to distinguish the biogenic from the physical reworking. The evaluation of this parameter was made regardless of the type of trace fossil present.

C. Characters related to significant physical reworking

- C1) Disarticulation and fragmentation. Disarticulation was evaluated considering the percentage of disarticulated parts of the total skeletal elements. Intensity of fragmentation was considered in both the percentage of broken parts and the average size of clasts. As both disarticulation and fragmentation might also be taxon-controlled (Brett, 1990), they were evaluated separately for each taxon.
- C2) Bedding-plane reorientation. The degree and type of reorientation were quantified (e.g. unidirectional or bidirectional orientation, absence of preferred orientation). Relationships between reorientation and sedimentary structures were also analysed.
- C3) Packing. Intensity was evaluated considering the amount of closely packed clasts and the abundance of matrix. Taxon diversity within the grouped clasts and mixing of allochthonous and autochthonous fauna were also considered.
- C4) Side-view orientation. In the case of bivalve and brachiopod shell beds, this parameter was differentiated from reorientation as it is related to peculiar hydrodynamic conditions (Allen, 1990). It was evaluated considering the percentage of convex-up oriented valves.
- C5) Mud/sand filling. This parameter was considered exclusively for echinoid tests and articulated brachiopod and bivalve shells.

Finally, in each skeletal concentration, the abundance of allochthonous fauna was recorded and quantified. Allochthonous

fauna were identified based on both ecological (e.g. taxa typical of very shallow water or continental areas) and taphonomic features.

5. Skeletal concentrations: definition and taphonomic characterization

Taphonomic analysis was carried out analysing 10 taphonomic characters (Table 1), which led to the differentiation of ten skeletal concentrations (*sensu* Kidwell et al., 1986; Fürsich, 1995) (Fig. 3) whose characteristics are given below. Fabric description follows the nomenclature proposed by Kidwell et al. (1986), Kidwell (1991) and Kidwell and Holland (1991). In the definition of skeletal concentrations, dominance of particular taxa was considered (Table 2) together with differences in preservation, as this can give information about intensity of transport and the allochthony of the material. A total of 59 shell concentrations were analysed.

5.1. Skeletal concentration SkC1: complete echinoid tests

The only fossils recovered in this skeletal concentration were infaunal, irregular echinoids of the genera *Discoidea*, *Epiaster*, *Holaster* and *Toxaster* (Monaco et al., 2005). They were dispersed in the matrix and usually preserved in life position (Table 2). Most of the echinoids were completely filled with sediment and tests were complete; only a few empty tests were slightly flattened due to compaction (Fig. 3, Table 1). Spines were very abundant in the bed, but they were never found articulated to the test. Reoriented echinoids were very rare and were usually positioned very close to *Thalassinoides* isp. and *Scolicia* burrows. Therefore, reorientation was most probably related to biogenic rather than to physical reworking, as was also confirmed by the perfect preservation of the very fragile tests. Encrustation and borings were completely absent. SkC1 was found exclusively in the marls of lithofacies LA and was observed in thirteen shell beds.

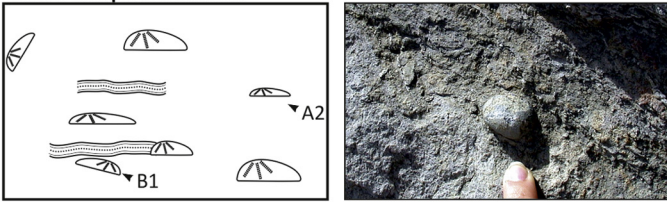
5.2. Skeletal concentration SkC2: articulated ostreids

In this skeletal concentration only ostreids were observed. They were preserved in life position (Table 2, Fig. 3) and distributed in different superimposed layers. Shells were rarely disarticulated and always complete, without any sign of encrusting or boring (Table 1). They were filled with the coarse-grained material of the overlying beds. SkC2 was found at the top of some beds in lithofacies LB, and was observed in two shell beds.

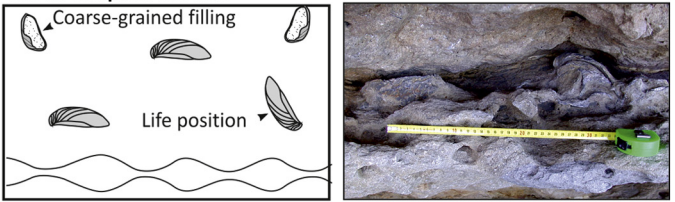
5.3. Skeletal concentration SkC3: packed, mostly complete echinoids

This skeletal concentration differed from SkC1 due to the bio-fabric of the echinoids, which were usually packed in groups of 3 to

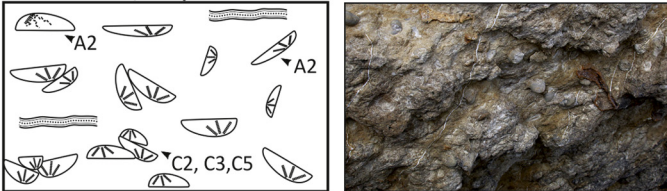
SKC 1: Complete echinoids



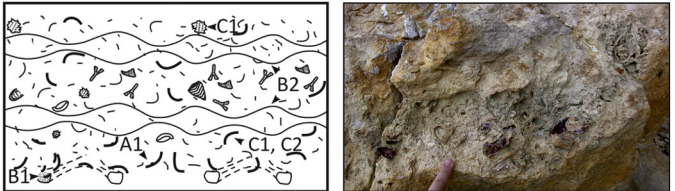
SKC 2: Complete ostreids



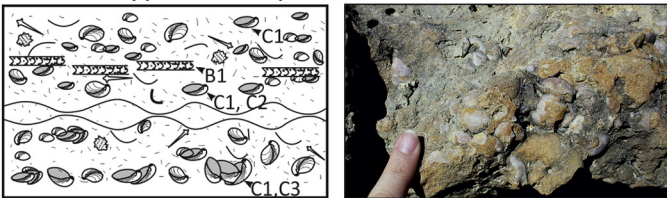
SKC 3: Packed, complete echinoids



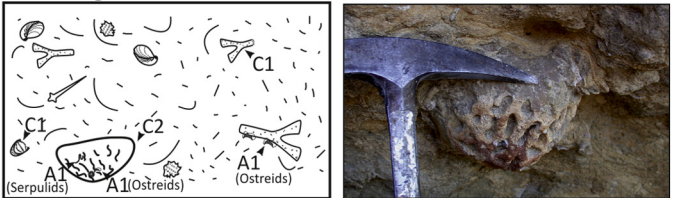
SKC 4: Coarsely fragmented bioclasts



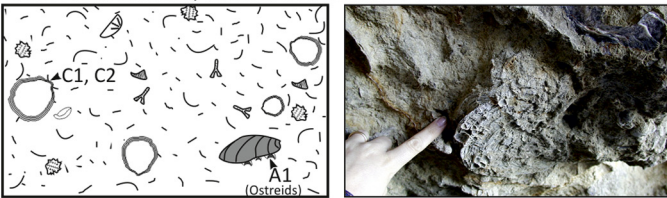
SKC 5: Densely packed brachiopods



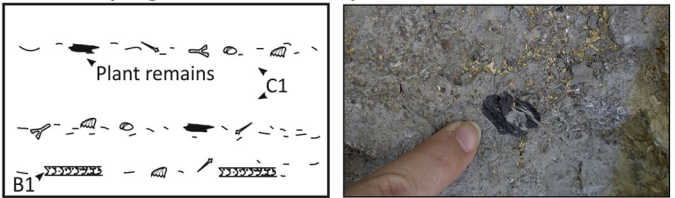
SKC 6: Fragmented and encrusted corals



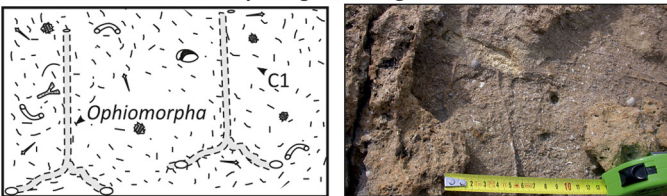
SKC 7: Disarticulated, abraded and encrusted ostreids



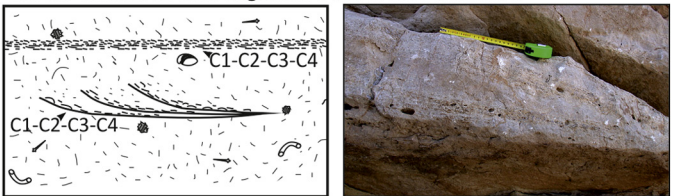
SKC 8: Finely fragmented bioclasts and plant remains



SKC 9: Grainstone with very fine-grained fragmented bioclasts



SKC 10: Grainstone with fragmented and oriented bioclasts



Key

A1: encrustation/colonization

A2: collapsed shells

B1: reworking by biogenic activity

C1: disarticulation/fragmentation

C2: reorientation

C3: packing

C4: convex-up oriented shells

C5: mud/sand filling



Irregular echinoids



Plant remains



Ramose corals



Massive corals



Articulated and disarticulated oysters



Brachiopods



Thalassinoides- induced nodularity



Ereipichnus geladensis

Fig. 3. Sketches and representative photographs of the 10 skeletal concentrations described in the section.

Table 2

List of the main fossil groups observed in the section, mode of life of the organisms and their abundance in the 10 skeletal concentrations. Keys: Ep = epifaunal organism, In = infaunal organism, – = absent; x = rare; xx = common; xxx = abundant.

	Mode of life	Life position	SkC 1	SkC 2	SkC 3	SkC 4	SkC 5	SkC 6	SkC 7	SkC 8	SkC 9	SkC 10
Irregular echinoids	In	SkC1	xxx	x	xxx	xx	x	x	x	xx	–	–
Thin-shelled bivalves	Ep/In	–	–	xx	–	xxx	x	xxx	xxx	xx	xxx	xxx
Thick-shelled bivalves	Ep	SkC2	–	xxx	–	xxx	x	x	xxx	–	–	–
Terebratulids	Ep	–	–	–	–	–	xxx	x	–	–	x	x
Rhynchonellids	Ep	–	–	–	–	–	xxx	x	–	–	–	–
Massive/ramose corals	Ep	–	–	–	–	x	–	xx	x	xx	x	x
Plant remains	–	–	–	–	–	–	–	–	–	x	–	–

a maximum of 7 tests. Moreover, tests were commonly upside-down oriented, and no close relationship between reorientation and burrows was detected. Although reorientation and packing was abundant, tests were mostly complete. SkC3 was found in marl or at the bottom of packstone beds of lithofacies LA and was observed in seven shell beds. As in SkC1, the echinoids mainly belonged to the genera *Discoides*, *Epiaster*, *Holaster* and *Toxaster* (Monaco et al., 2005).

5.4. Skeletal concentration SkC4: coarsely fragmented bioclasts

SkC4 occurred in laterally continuous, tabular beds that commonly exhibited nodular texture, due to large *Thalassinoides suevicus* systems (as described in Monaco et al., 2005). Thick-shelled and thin-shelled bivalves were the most abundant bioclasts (Table 2) and were usually associated with echinoids, brachiopods, gastropods, branched and massive corals, as well as belemnites. With the exception of belemnites and massive corals, all bioclasts were fragmented. In addition, thick-shelled bivalves very commonly showed oxidation, abrasion and colonization of both the internal and external surfaces of shells. Preferred orientation was absent. In some cases, the fragmented bioclasts represent the passive infilling of *Thalassinoides* burrows, most probably by storms. SkC4 was found in limestones of lithofacies LA and in lithofacies LB and was observed in nine shell beds.

5.5. Skeletal concentration SkC5: densely packed brachiopods

The great abundance of the terebratulid *Sellithyris* and the rhynchonellid *Cyclothyris* (D. García-Ramos, pers. comm.) was one of the most distinctive features of this skeletal concentration (Table 2). Disarticulation was present, although not common, while intense fragmentation was absent. Bivalves present in the same assemblage were usually both disarticulated (as a result of weaker articulation) and coarsely fragmented. Crinoids were completely disarticulated and echinoids were fragmented. Preferred orientation was completely absent in both planar and cross-sectional view. SkC5 formed 10–30 cm thick laterally discontinuous rudstone beds in lithofacies LB, and these were observed in six shell beds.

5.6. Skeletal concentration SkC6: fragmented and encrusted corals

Massive and fragmented ramose corals were very common in this skeletal concentration. Encrustation by serpulids and small attached ostreids was observed on the coral surface. Massive corals were commonly upside-down and ramose corals did not show any preferred orientation and were clearly not preserved in life position. The other bioclasts (bivalves, gastropods, echinoids, and very rare brachiopods) were fragmented and abraded. SkC6 formed thin strings in lithofacies LA and an entire bed in lithofacies LB. It was observed in two shell beds.

5.7. Skeletal concentration SkC7: disarticulated, abraded and encrusted ostreids

The presence of disarticulated ostreids distinguished this skeletal concentration from SkC2, where ostreids were in life position, articulated and complete. In SkC7, ostreids showed clear signs of abrasion and colonization by very small, encrusting bivalves both on the external and internal surfaces of the valves. Associated bioclasts were thin-shelled fragmented bivalves, gastropods and echinoids. SkC7 was found in three beds of lithofacies LB.

5.8. Skeletal concentration SkC8: scarcely packed, finely fragmented bioclasts and plant remains

This skeletal concentration exhibited low packing density of the bioclasts and high abundance of fine-grained, marly sediment. Thin shelled, fragmented bivalves, as well as coarsely fragmented echinoids, echinoid spines, belemnites, fragmented ramose corals, and plant remains were observed. SkC8 formed thin strings in lithofacies LA and LB. It was observed in three shell beds.

5.9. Skeletal concentration SkC9: grainstone with fragmented bioclasts

In this skeletal concentration fragmented bioclasts were minute (3–5 mm large). Thin-shelled bivalves, echinoid spines, gastropods, fragmented red and green algae, as well as serpulids were seen in thin-section. Bioclasts did not show any kind of preferred orientation. Abrasion, encrusting and colonization could not be evaluated due to the very small size of bioclasts. This skeletal concentration formed the cross-stratified beds of lithofacies LC and was observed in seven shell beds.

5.10. Skeletal concentration SkC10: grainstone with fragmented and oriented bioclasts

As for the texture, this skeletal concentration was very similar to the previous one, and was characterized by the absence of a matrix and the very high packing of the small fragmented bioclasts. The most important difference was the presence of flat and long bioclasts (as fragments of bivalve shells and crinoid ossicles) oriented parallel to the foresets. In thin-section, the same bioclasts observed in the previous skeletal concentration were visible (thin-shelled bivalves, gastropods, echinoids, serpulids and red and green algae). SkC10 was found in seven beds of lithofacies LC.

6. Skeletal concentrations: taphonomic categories and their interpretation

Interpretation of skeletal concentrations was based on the type of bioclasts observed and their taphonomic features, taking into account that some differences in preservation (i.e. fragmentation

and disarticulation) could also be related to differences in the shell structures of the different taxa, and not only to background processes and sedimentary events. It was also considered that taphonomic distortions might have been inherited in those skeletal concentrations with widespread bioclast transport. Interpretation and definition of genetic categories for 10 skeletal concentrations was improved by applying cluster analysis to the dataset represented in Table 1, using the software PAST. This enabled the grouping of skeletal concentrations into clusters depending on the grade of similarity of bioclast preservation patterns (Fig. 4).

Cluster A. The first cluster is represented by skeletal concentrations 1 and 2. Both show abundant and complete bioclasts (echinoids and ostreids, respectively), preserved in life position. However, the preservation in life position was related to completely different processes in the two skeletal concentrations. In the case of endobenthic echinoids of SkC1, the preservation in life position was simply related to low energy of bottom currents. Even if an infaunal habit *per se* does not necessarily prevent *post mortem* sea-floor exposure (Greenstein, 1993), the absence of test colonization speaks against sea-floor exposure (Zamora et al., 2008). On the contrary, preservation of ostreids was enabled by very rapid burial that prevented shells from being reworked by physical and biological processes acting on, or immediately below, the sea floor. The association of large oyster shells in life position and small disarticulated but complete shells points to brief and not very strong storm events (Jiménez et al., 1991; Ragaini and di Celma, 2009) that deposited a thick layer of sediment on the sea-floor, which also filled ostreid valves.

Cluster B. A second cluster is represented by skeletal concentration 3, which shows peculiar taphonomic features, with echinoid tests that are packed but complete. As shown in Fig. 4, this skeletal concentration shows some similarity in its bioclast preservation pattern to SkC1 and 2 (due to the absence of fragmentation) but differs strongly from SkC4 to 10, characterized by intense fragmentation. The abundance in SkC3 of slightly reworked, complete tests implies the presence of winnowing by currents on the substrate producing packing and reworking of echinoid tests (Kier, 1972; Mancosu, 2012). The good preservation of the tests and the correspondence of echinoid taxa with those present in SkC1 points to very limited transport.

Cluster C. The third cluster is represented by skeletal concentrations in cross-stratified beds with finely fragmented bioclasts locally oriented on foresets. These skeletal concentrations record high hydrodynamics in the background conditions, as shown by intense winnowing, the very small size of the fragmented bioclasts, and a very high degree of sorting (Kidwell and Bosence, 1991).

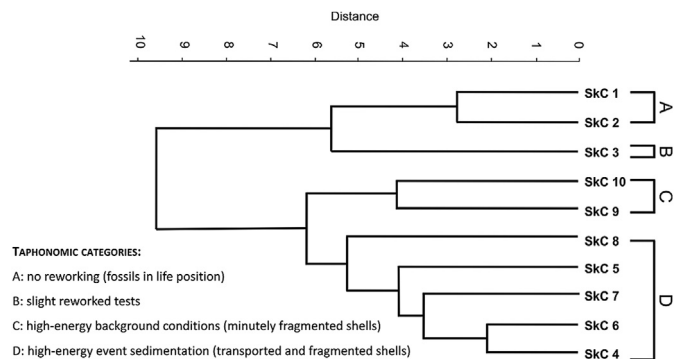


Fig. 4. Cluster analysis of shell concentrations based on the abundance of each taphocharacter. Four clusters (taphonomic categories) can easily be recognized that consist of skeletal concentrations having similar preservation patterns.

Cluster D. The fourth cluster groups SkC4 to SkC8. Despite secondary differences in preservation, mostly related to the taxa involved (“taxonomy-controlled preservation pattern”), all these skeletal concentrations are characterized by coarse-grained fragmented, abraded and reworked bioclasts, which are allochthonous in some cases (i.e. brachiopods in SkC5, corals in SkC6, and plant remains in SkC8). Preferred orientation is mostly absent and skeletal concentrations form thick, internally complex beds. On the basis of these common features, skeletal concentrations of this fourth cluster were interpreted as transported material, rapidly deposited during storm events (Fürsich and Oschmann, 1993; Bressan and Palma, 2010; Tsujita, 1995). Fragmentation and disarticulation were partly related to the energy of the sedimentary events, but in part also inherited from the shallower source area of the bioclasts. In this fourth cluster, SkC8 is slightly separated from the other skeletal concentrations (Fig. 4). Although SkC8 shares the same general taphonomic pattern with SkC4–7, some significant differences can be pointed out. SkC8 is characterized by tiny fragmented bioclasts that are partially oriented parallel to laminae and form very thin levels within marly beds (lithology LA). These features point to more intense sorting by transport and deposition under lower-energy, tractive currents (Bressan and Palma, 2010).

7. Taphofacies: definition and interpretation

Analysis of taphonomic characters and skeletal concentrations allowed for the differentiation of four taphofacies (*sensu* Speyer and Brett, 1986; Fig. 5). In order to provide a more accurate interpretation, taphonomic and sedimentologic data were integrated with those derived from microfacies analysis.

7.1. Taphofacies characterization, interpretation and paleoenvironmental significance

7.1.1. Taphofacies TjA: wackestone with abundant echinoids and scarce fine-grained bioclasts

This taphofacies is characterized by the abundance of complete irregular echinoids, sparsely distributed and preserved in life position (SkC1), fragmented thin-shelled bivalves and rare orbitolinids, mostly forming thin shell layers. Echinoids did not show any evidence of sea-floor exposure; some of them were flattened by compaction. With the exclusion of biogenic sorting and packing of fragmented shells related to the activity of the *Ereipichnus geladensis* trace maker, grouped bioclasts were very rare. They were organized in laminae and slightly reoriented (SkC8).

This taphofacies occurs in the regular, tabular grey marly beds of LA lithofacies, where sedimentary structures are very scarce, while trace fossils are very abundant. Most of them belong to the ichnogenera *Scolicia* and *Cardioichnus* and were produced by irregular echinoids. The tubular trace fossil *Ereipichnus geladensis* is also present, even though quite rare (Giannetti et al., 2005; Monaco et al., 2005).

The main background taphonomic processes were related to the activity of echinoids, which reworked the substrate and produced well-preserved burrows. The paleoenvironment in which this taphofacies formed was characterized by very quiet hydrodynamic conditions, which was demonstrated by the perfect preservation of the tests and the absence of any sign of sea-floor exposure and physical reworking (SkC1). This enabled continuous and regular sedimentation of fine-grained material and the consequent preservation of dead echinoids in life position. Even though bioclasts other than echinoids were not abundant in the bed, it has to be noted that the wall of *Ereipichnus geladensis* was composed by fragments of shells and orbitolinids that were selected from the substrate by the trace maker. The surrounding substrate was

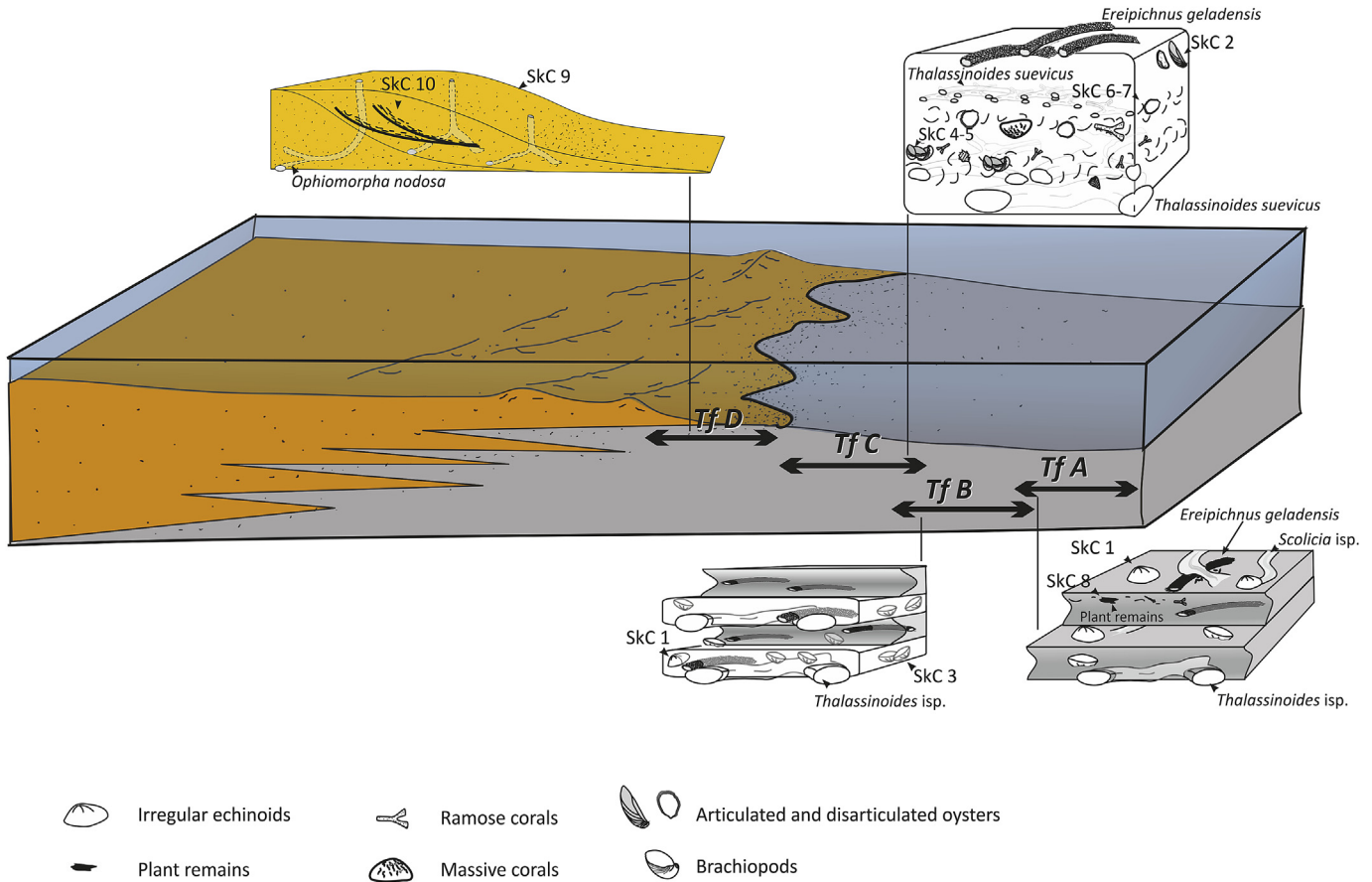


Fig. 5. Schematic paleoenvironmental reconstruction with the distribution of the four taphofacies recognized in the study area.

therefore greatly impoverished in bioclasts. In the marly beds, sedimentary events were rarely recorded. They showed the interference on the sea floor of two types of processes: the slight reworking of autochthonous elements (echinoid tests, SkC3) and the sedimentation of transported and fragmented bioclasts from more proximal areas, as shown by the presence of orbitolinids and plant remains (SkC8). Locally, bioturbation had affected SkC8 shell concentrations, interrupting the lateral continuity of the deposits and redistributing skeletal remains.

All elements characterizing this taphofacies therefore pointed to a relatively deep and quiet environment, in which high-energy events were completely absent.

7.1.2. Taphofacies TfB: reworked echinoids

Fossil content consists mainly of irregular echinoids *Discoidea*, *Epiaster*, *Holaster* and *Toxaster* associated with fragmented thin-shelled bivalves and rare orbitolinids. Fine-grained calcarenites interbedded to marly beds (LA lithofacies) were more abundant and thicker than in taphofacies TfA. Both calcarenites and marls were laterally continuous and tabular. In this taphofacies, echinoids preserved in life position (SkC1) were extremely rare, while slight reworking of autochthonous material was common and represented by reoriented, packed but scarcely fragmented echinoid tests (SkC3).

As in taphofacies A, regular background sedimentation of fine-grained material led to development of softgrounds, favouring intense bioturbation by echinoids. Locally deep bioturbation by large *Thalassinoides* caused reorientation of echinoid tests. While physical sorting was scarce, biogenic sorting was abundant and

related to the activity of the *Ereipichnus geladensis* trace maker, whose burrows are very common in this taphofacies. Reworking of echinoid tests were the most important sedimentary events, which were also represented by thin laminae of SkC8, rich in allochthonous bioclasts. From the abundance of reworked tests and the presence of interbedded calcarenites resulting from rapid sedimentary events, a clear energy increase in the sedimentary environment could be inferred.

7.1.3. Taphofacies TfC: intense background bioturbation and transported bioclasts

This taphofacies shows a greater complexity compared with the previous ones. The fossil content was more diverse and included fine-grained fragmented echinoids, gastropods, and thin- or thick-shelled bivalves that were commonly ferruginized (SkC4). Locally, densely packed brachiopods (SkC5), corals (SkC6), and disarticulated, abraded and colonized ostreid shells (SkC7) were also present. The lithology was mainly represented by strongly bioturbated, thick-bedded bioclastic packstone beds, which locally could be nodular due to abundant large *Thalassinoides* (Monaco et al., 2005). On the top of some beds, *in situ* preserved ostreids (SkC2) were present. They were commonly articulated and filled with the same material as the overlying bed. All skeletal concentrations from SkC4 to SkC8 represented sedimentary events with transport and rapid deposition, which were responsible for the bed thickness and bioclast abundance typical of this taphofacies. In these skeletal concentrations a clear taxonomic control on preservation could be observed. In fact, fragile bioclasts such as echinoid tests and thin-branched corals were always minutely fragmented

and often recognizable only in thin-section. More robust bioclasts such as thick-shelled bivalves, ostreids and pectinids were disarticulated but complete, while brachiopods were usually complete and in most of the cases articulated. The presence of serpulids and small ostreids on corals and on the internal and external surface of valves of thick-shelled bivalves showed long-term exposure on the sea floor prior to transport and sedimentation.

The sedimentation rate in this taphofacies was higher than in taphofacies A and B, surely due to the strong and abundant sedimentary events. Sedimentary conditions stimulated bioturbation, which in this taphofacies was very intense and represented the most important background process. Background bioturbation and sedimentary events produce conflicting superimposed signatures (Speyer and Brett, 1991). In fact, intense burrowing altered the continuity and preservation of bioclastic levels related to episodic sedimentation, in particular of the thinnest ones, which are easily destroyed by burrowing. Contemporary thick shell beds limited deep bioturbation, making the penetration of substrate difficult.

7.1.4. Taphofacies TfD: minutely fragmented bioclasts redistributed by currents

This taphofacies is characterized by cross-bedded bioclastic grainstone beds (LC) associated with SkC9 and SkC10. Beds were 20–100 cm thick. Bivalves, brachiopods, echinoids, and serpulid tubes were the most abundant bioclasts, associated with rare fragmented corals and ostreids. Shells were so minutely fragmented that they were often recognizable only in thin-section. Intense fragmentation of bioclasts pointed to persistent high-energy currents, continuously acting on the substrate, as was also shown by cross-stratification. These sedimentary bodies could be interpreted as bioclastic, bottom current flow-induced sand dunes migrating towards the northeast due to their geometry, as well as their sedimentary and taphonomic features. Apart from continuous reworking by currents, bioturbation by crustaceans was a very important background process, as shown by the extremely abundant shafts and horizontal mazes of *Ophiomorpha*.

7.2. Taphofacies and shallowing-upward trend

Taphofacies TfA–TfD clearly recorded a shallowing-upward trend, reflecting different subenvironments within the Cretaceous Sierra Helada carbonate platform (Fig. 5). The differences between each taphofacies could be explained in terms of increase in water energy during background processes and sedimentary events related to repeated shallowing-upward trends (Brett, 1995). Taphofacies A represented the more distal and deep facies, characterized by muddy substrate and very low water energy. The abundance of burrowing of irregular echinoids and their preservation pattern was consistent with the presence of a soft, muddy sea-floor. In this environment, rare high-energy storm events (represented by thin-bedded calcarenites) introduced bioclastic and sandy material from the inner shallower part of the platform. This environment was very well-recorded in the lowermost part of the shallowing-upward sequence. The gradual substitution of marl by increasingly thicker calcarenites beds (taphofacies B and C) pointed to shallower conditions and an increase of the sediment input. This was confirmed from the taphonomic standpoint by the replacement of SkC1 (echinoids preserved *in situ*) by skeletal concentrations produced by transport and deposition by high-energy sedimentary events (SkC4 to SkC7). The middle part of the shallowing-upward sequence recorded this transition from the low energy to high-energy environment of the uppermost (and shallowest) part of the sequence, where taphofacies D was present. The latter represents the acme of shallowing-water trend with shifting of sand dunes transported by bottom currents and producing a

strong fragmentation of bioclasts. The shifting dunes have so far been related to NE–SW directed geostrophic currents, in the opposite direction from the progradation of the platform (Giannetti et al., 2005).

The distribution of taphofacies throughout the section showed a clear decrease in energy from the bottom at least up to 120 m. This was clearly expressed by the gradual disappearance of taphofacies TfD, which from being up to 4 m thick in the lowermost part of the section was only sporadically present between 60 and 120 m. Also the abundance and thickness of taphofacies TfA, TfB (*in situ* and slightly reworked echinoids, respectively) pointed to the predominance of low energy, muddy bottoms. A clear correlation existed between the deepening-upward trend revealed by taphofacies and the transgressive tract that represents the first part of megasequence III, according to Castro (1998), which in the Sierra Helada area included the whole Sácaras Formation. A subsequent increase in detrital input was recorded in the upper part of the section. In fact, from 120 m taphofacies TfC increased in thickness and, most importantly, taphofacies TfD reappears, with its thickness increasing from 60 cm to 1 m at the top of the section. As this part would be completely included in the transgressive phase (Castro et al., 2008), the greater amount of detrital input was most probably related to minor variations in sedimentation rate and subsidence related to local tectonic activity, as also observed in deposits from the Sácaras Formation studied in adjacent areas (Castro et al., 2008).

8. Conclusions

A detailed bed-by-bed analysis performed on the 180 m thick, lower Albian Sierra Helada section led to an accurate taphonomic characterization of the deposits. The most common fossils were irregular echinoids, thin- and thick-shelled bivalves, brachiopods and orbitolinids.

Ten taphonomic characters were determined and their abundance evaluated in each shell bed, which enabled the differentiation of ten skeletal concentrations. Fragmentation, disarticulation, and reworking by currents were the most variable taphonomic characters. Moreover, clear taxonomic control over fragmentation and disarticulation was observed, with echinoids and thin-shelled bivalves being the fossils most prone to fragmentation, and brachiopods the least susceptible to disarticulation and fragmentation. A cluster analysis produced four taphonomic categories, each represented by one or more skeletal concentrations with a typical preservation pattern of bioclasts.

The first taphonomic category (A) contains autochthonous assemblages (SkC1 with echinoids and SkC2 with ostreids), the second taphonomic category (B) is represented by a single skeletal concentration (SkC3), characterized by slightly reworked echinoid tests. The remaining categories (C, D) are characterized by high-energy background conditions (SkC9 and SkC10) and by medium to high-energy sedimentary events and low to medium energy background conditions (SkC4 to SkC8). Categories B–D are genetic categories, as they group skeletal concentrations produced by similar processes. In contrast, category A simply represents a particular preservation pattern, since its skeletal concentrations have a completely different origin (absence of physical reworking for SkC1 and rapid burial for SkC2).

The presence and abundance of diagnostic skeletal concentrations were combined with a sedimentological analysis to define four taphofacies, representative of four different subenvironments within an open, shallow-water mixed carbonate-siliciclastic platform. The first taphofacies (TfA) was recorded in marly beds (lithofacies LA) and was characterized by the abundance of SkC1 (echinoids in life position) and the occasional presence of SkC3

(reworked echinoids). It records low energy environments with muddy substrates representing the optimal habitat for the abundant infaunal echinoids. This quiet environment was sporadically disturbed by low energy sedimentary events that slightly reworked the substrate (SkC3) and transported material from very shallow-water areas (SkC8). The second taphofacies (TfB) was characterized by the abundance of SkC3 and scarcity of SkC1, and showed a slight increase in water energy. SkC8 could be present too, as evidence of transported material. The third taphofacies (TfC) was characterized by SkC4 to 7 and was recorded in bioclastic rudstone/packstone beds (lithofacies LB). The abundance of transported assemblages and the change in lithology clearly indicated increasing water energy, in particular of sedimentary events. The last taphofacies (TfD) is characterized by cross-bedded grainstones and fine-grained fragmented bioclasts (SkC9–10) that recorded high-energy background conditions. Therefore, from taphofacies 1 to taphofacies 4, a marked increase in the water energy of both background processes and sedimentary events could be inferred. This might be related to the development of different sub-environments on a generally shallow, open platform, due to repeated minor sea-level changes that produced a series of shallowing- and coarsening-upward sequences.

The reconstruction of the distribution of the taphofacies in the platform of the Sácaras Formation showed a clear distal to proximal trend, with taphofacies A typical of the more distal part of the platform and the lowest part of the shallowing-upward sequences. Taphofacies B and C represented the gradual transition to the shallow-water, shifting sand dunes recorded by taphofacies D, present at the top of the sequences.

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