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Multivariate analysis of taphonomic data in Lower Jurassic carbonate platform (northern Italy)

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Abstract

Taphonomical analysis on skeletal concentrations and taphofacies has been carried out in the Lower Jurassic deposits of the Trento carbonate platform (northern Italy). The interpretation of the taphonomic categories used has been refined applying three statistical processes to the semi-quantitative values of taphocharacter abundance in eight types of skeletal concentrations. Analysis of correlation allowed the taphocharacters to be subdivided into four genetic categories: (1) palaeobiological processes on shelly ground; (2) palaeobiological activity on the substrate; (3) mechanical processes induced by currents; (4) infilling processes induced by currents. Cluster analysis on the eight types of skeletal concentrations defined six genetic processes. Moreover, principal-components analysis offered three factors which explained 75% of the variance. Factor 1 shows the contribution of hydrodynamic vs. bioturbation processes in the genesis of the resulting skeletal concentration. Factor 2 displays the degree of transport undergone by bioclasts before burial. Finally, factor 3 points out the dominance of superficial taphodistortion and colonization of the substrate, or deeper colonization in the substrate. Numerical analysis on taphonomical data has been proved to be a powerful tool for palaeoenvironmental studies, thereby aiding in the understanding of the shell beds genetic processes. ***To cite this article: J.E. Caracuel et al., C. R. Palevol 4 (2005).***

Résumé

L'analyse taphonomique effectuée sur des concentrations coquillières et des taphofaciès a été réalisée sur des dépôts du Jurassique inférieur provenant de la plate-forme carbonatée de Trente (Nord de l'Italie). L'interprétation des catégories taphonomiques utilisées a été précisée en appliquant trois procédés statistiques aux valeurs semi-quantitatives de l'abondance de taphocaractères à huit types de concentrations coquillières. L'analyse de corrélation a permis de diviser les taphocaractères en quatre catégories génétiques : (1) processus paléobiologiques sur un niveau coquillier ; (2) activité paléobiologique sur le substrat ; (3) processus mécaniques induits par les courants ; (4) processus de colmatage induits par les courants. L'analyse de

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groupe appliquée aux huit types de concentrations squelettales définit six processus génétiques. En outre, l'analyse en composantes principales fournit trois facteurs, qui expliquent 75% de la variance. Le facteur 1 montre la contribution de l'hydrodynamisme par rapport à la bioturbation dans la genèse de la concentration coquillère résultante. Le facteur 2 montre le degré de transport subi par les bioclastes avant l'enfouissement. Enfin, le facteur 3 met en évidence la dominance de la distorsion taphonomique superficielle et de la colonisation du substrat, ou de la colonisation plus profonde du substrat. L'analyse numérique des données taphonomiques apparaît comme un outil puissant dans les études paléoenvironnementales, qui aide considérablement la compréhension des processus génétiques responsables de l'accumulation des couches coquillères. ***Pour citer cet article : J.E. Caracuel et al., C. R. Palevol 4 (2005)***.

Keywords: Numerical analysis; Taphofacies; Skeletal concentration; Taphonomic categories; Lower Jurassic; Trento carbonate platform; Northern Italy

Mots clés : Analyse numérique ; Taphofaciès ; Concentrations coquillières ; Catégories taphonomiques ; Jurassique inférieur ; Plate-forme carbonatée de Trente ; Nord de l'Italie

Version française abrégée

La formation de l'Hettangien–Pliensbachien dénommée Calcari Grigi (région de Trente, Nord de l'Italie) se divise en quatre membres (inférieur, moyen, supérieur et Massone Oolite), dont deux (membres moyen et supérieur) ont été pris en compte dans cette étude. Neuf sections stratigraphiques (Fig. 1), couvrant la partie supérieure et inférieure de la plate-forme, ont été analysées pour évaluer l´application des analyses numériques aux caractères taphonomiques caractéristiques et préciser la genèse de huit types de concentrations coquillières. Vingt caractéristiques taphonomiques ont été reconnues, analysées et subdivisées en quatre catégories selon les processus dominants qui ont contribué à leur genèse : (A) distorsion taphonomique, (B) diagenèse précoce, (C) agents biologiques et (D) agents physiques (Tableau 1).

Les concentrations coquillières analysées, induites par des agents hydrodynamiques ou biologiques, sont fréquemment superposées, menant à un chemin taphonomique complexe, avec des taphocaractères variables (certains hérités de phases antérieures). Dans ce contexte, la puissance discriminatoire de l'analyse numérique (matrice de corrélation, analyses de classification hiérarchique et analyse en composantes principales), parmi les taphocaractères reconnus, peut aider à interpréter l'origine et l'histoire de cette concentration coquillière. Le groupe de données utilisé pour l'analyse numérique se compose de valeurs d'abondance semi-quantitatives de chaque taphocaractère pour chaque concentration coquillière. Les variables étaient au nombre de 16 (Tableau 1, sauf pour A3, A4, B2, B3).

L'analyse des corrélations (Tableau 2) a favorisé le regroupement de taphocaractères, antérieurement uniquement analysés qualitativement [16], selon leurs processus génétiques : (1) des taphocaractères induits par des processus taphonomiques actifs sur le fond de la mer (A1–A2) ; (2) des taphocaractères produits par une activité paléobiologique sur le substrat (B1–C1–C2–C3–C4–C5) ; (3) des processus mécaniques induits par des courants (D1–D2–D3–D4) ; (4) des processus de colmatage induits par des courants (D5–D6–D7–F). Comme on s'y attendait, des corrélations inverses sont apparues entre des variables des groupes 1 et 2 et des variables des groupes 3 et 4.

L'analyse de classification hiérarchique sur les 16 taphocaractères a donné des résultats compatibles avec ceux de l'analyse des corrélations (Fig. 2). De plus, l'analyse de classification hiérarchique faite sur les huit concentrations coquillières les regroupe selon les processus génétiques dominants subis : (a) une action en cours induite par des vagues normales ou de faibles tempêtes (SkC1a-1b); (b) des courants profonds et forts (SkC2-4) ; (c) un dépôt de tempestites induit par les ouragans ou tsunami (SkC5) ; (d) une action persistante de courants répétitifs sur les faciès riches en bioclastes (SkC3) ; (e) un événement de remplissage sédimentaire des terriers développés en profondeur (SkC6) ; (f) un taux élevé de bioturbation dans des conditions à faible énergie (SkC6a).

L'analyse en composantes principales a mis en évidence trois facteurs, qui expliquent 75% de la variance (Fig. 3). Le facteur 1 indique la contribution des processus hydrodynamiques ou le taux de bioturbation dans la genèse de la concentration coquillière résultante. Ces paramètres ont été inversement corrélés, comme indiqué précédemment, par l'analyse de corrélation. Le facteur 2 a, pour sa part, été interprété comme le degré de transport subi par les dépôts bioclastiques avant leur sédimentation. Il est contrôlé par le résultat positif ou négatif des taphocaractères liés respectivement à la fragmentation, à la désarticulation, au regroupement et au caractère allochtone de la roche bioclastique ou à l'exposition prolongée de sédiment bioclastique immobile dans le substrat. Le facteur 3 a été interprété comme la dominance de taphodistorsion superficielle et de colonisation superficielle du substrat (y compris le sol coquillier), s'il est positif, et d'une colonisation plus profonde dans le substrat, s'il est négatif.

D'après les résultats statistiques de l'analyse en composantes principales, de la classification hiérarchique et de la matrice de corrélation, le cadre paléoenvironnemental dans lequel chaque concentration coquillière s'est développée peut être mieux envisagé (Fig. 4). Cette méthodologie s'est avérée être un outil performant pour les études sédimentologique, taphonomique et ichnologique, aidant ainsi à la compréhension des processus génétiques, dans les couches, de fines intercalations de roche dure.

1. Introduction

This paper evaluates the performance of numerical analyses applied to taphonomic characters for characterizing and approaching the genesis of eight types of skeletal concentrations in the Pliensbachian Calcari Grigi Formation (Trento Platform, Southern Alps). The analysed skeletal concentrations, induced either by hydrodynamics or biological agents, are frequently superimposed (discrete, conflicting, constructive and cooperating background and episodic taphonomic signatures, *sensu* Brett [3]) leading to a complex taphonomic path, with variable taphocharacters (some inherited from prior phases). In this context, the discriminatory power of the numerical analysis within the recognized taphocharacters may assist in interpreting the origin and history of these skeletal concentrations. The quantitative data processed through statistical analysis enabled more effective analysis of the similarities and differences between them [15,16].

2. Geological setting

The Calcari Grigi Formation is constituted by shallow-water, well-stratified platform carbonate deposits that developed in the Trento area (northern Italy) during the Hettangian–Pliensbachian (Fig. 1). This formation is subdivided into four members (Lower, Middle, Upper and Massone Oolite), two of which (Middle and Upper Members) were considered in this study. The Middle Member is composed of oolitic beds with high-energy events. Oolitic beds are interbedded with peloidal, muddy beds (low-energy deposits) and thick stromatolitic LLH laminae. The Upper (or Rotzo) Member, formed by lagoon deposits, is characterized by thinner stratification; it has a large fossiliferous interval with well-developed burrows of *Thalassinoides*, useful for recognizing shallowing and upwardly decreasing burrow parasequences [11,17]. For an extensive discussion on geological settings, sedimentary stratigraphy, palaeontology, taphonomic stratigraphy and palaeoenvironmental models, see [1,2,4,5,10,11,14,16,17].

The dataset used for the statistic analysis was collected from nine stratigraphic sections (Fig. 1) covering the outer and the inner part of the platform: AML (40-m thick, Monti Lessini area), AVS (26-m thick, near Rovereto), AVG I (20-m) and AVG II (25-m, both in the Valgola area, close to Folgaria), RPC (24-m, in the area of the Coe Pass) and AVB (35-m thick), RVB (23-m), SVB (27-m), PVB (40-m) sections, which constitute a unique composite section in the Folgaria–Valbona area. Except the AVB (Middle Member), all the sections belong to the Rotzo Member, covering its lower and upper parts.

3. Taphocharacters of the skeletal concentrations

Twenty taphonomic characters were recognized, analysed, and subdivided into four categories according to their dominant process: (A) taphonomic distortion, (B) early diagenesis, (C) biological agents, and (D) physical agents [7,8] (Table 1).

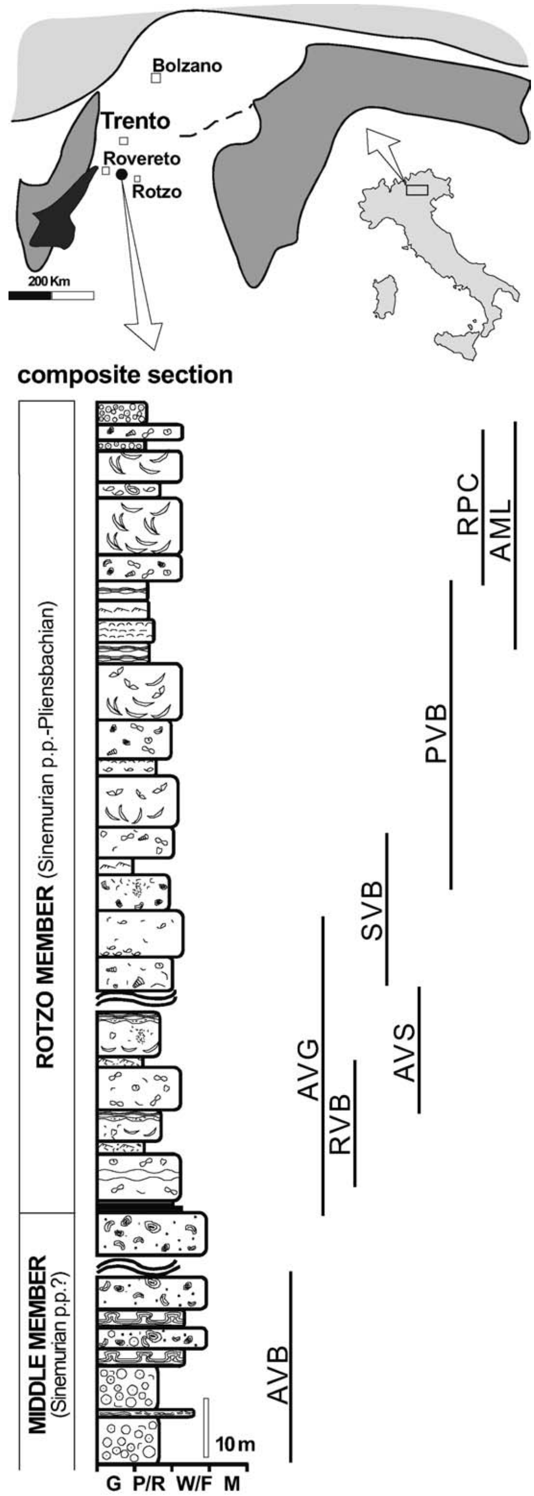

Fig. 1. Location of the study area and composite stratigraphic column of the upper part of the Middle Member and the Rotzo Member, based on 9 sections: AVB, AVGI, AVGII, RVB, AVS, SVB, PVB, AML and RPC.

Fig. 1. Emplacement de la zone d'étude et de la colonne stratigraphique composite de la partie supérieure du membre moyen et du membre Rotzo, basé sur 9 sections : AVB, AVGI, AVGII, RVB, AVS, SVB, PVB, AML et RPC.

These taphonomic characters, together with the analysis of the sedimentary structures, were used to point out eight types of skeletal concentrations, characterizing a particular environmental setting dominated by distinctive palaeobiological or physical processes. For further information about the following skeletal concentrations, see [11,16,17].

Wave-induced wackestones (fair-weather deposits) (SkC1a) show mud-supported fabric with physical and biogenic processes. Shells are reoriented and distributed on the seafloor by fair-weather wind-driven currents with no allochthonous bioclasts.

Wave-induced wackestones (storm-wave deposits) (SkC1b) are mud supported (up to 10-cm thick) with apparently chaotic clasts distribution (crushing and biogenic reorientation). Surface and deep burrowing is abundant. The principal genetic agents are strong wave currents, inducing great transport and fragmentation of shells.

Combined-flow bivalve packstones (waves + currents) (SkC2) are up to 15-cm-thick, bioclast-supported and composed of broken bioclasts. Erosive base and cross-laminations are present and bioclastic ripples are common. Taphocharacters of the categories A and B are absent or extremely rare, while deep and superficial burrowing occurs.

Winnowed beds with shelter porosity (shell concentration) (SkC3) are bioclast-supported, up to 15–30-cm thick, laterally continuous and comprised exclusively of bivalves with convexity-up. This developed in a stable environment, with weak and persistent tidal currents, not having sufficient strength to group shells or to transport them beyond their native environment.

Storm-wave base deposits (SkC4) are 10–40-cm-thick bioclast-supported packstones made up of allochthonous and autochthonous shells. This coarser-grained deposit was formed in a deeper and higher-energy setting than those of the SkC2. Bored and encrusted reworked shells are quite abundant, as is pre-event bioturbation (well-preserved networks of *Thalassinoides*).

Table 1. Taphonomic characters analysed
Tableau 1. Caractères taphonomiques analysés.

A. TAPHONOMIC DISTORTION	
A1: bioerosion of shells	Boring into shells by predators apparently during the residence time of bioclasts on the substrate (or taphonomically active zone).
A2: encrusting	Organic (or inorganic) processes which develop carbonatic films (1–5-mm thick) that envelopes bioclasts partially or totally.
A3: fractures, deformations	Induced by burial stress on bioclasts or by the pressure exerted by superficial burrowers such as fish during biostratinomy.
A4: taphodistortion s.s.	Fragmentation, displacement and other types of distortions induced on shells by the activity of necrophagous organisms.
B. EARLY DIAGENESIS	
B1: aerobic biodegradation	Slow soft-body decay on low oxygenated (and/or rapid burial) conditions that favours the crystallization of block calcite cements inside the shells.
B2: dissolution	Skeletal loss under non-equilibrium conditions between mineralogy and structures of the shells and chemical composition of waters.
B3: vadose cementation	Cement developed about 10cm above the stromatolitic domes of the Middle Member and similar to the “pedogenetic cementation” described for the Dolomia Principale Fm.
C. BIOLOGICAL AGENTS	
C1: superficial burrowing, biogenic reorientation	Surficial bioturbation characterized by the sedimentary development of bioturbation textures and the absence of preserved walls or networks. Trace-makers may be mainly worms, molluscs and fishes.
C2: deep burrowing, active burrow infilling	Burrowing which preserves walls and 3D networks infilled actively by sediment (mainly *Thalassinoides suevicus*).
C3: chewing	Crowding shells by predatory and scavenging activity, often minutely fragmented and grouped in mottled concentrations or redistributed by currents.
C4: fecal peloid concentration	Concentration of fecal peloids in winnowed shell beds, where fine-grained sediment were swept away, or in muddy beds, where micropeloids infill the shells and the burrows.
C5: biogenic advection	Activity of burrowers (conveyors) that cause a vertical transport of bioclasts towards the overlying beds, determining strong reworking.
D. PHYSICAL AGENTS	
D1: fragmentation, disarticulation, grouping by transport	Reflect the action of currents, strength and persistence, together with type, form, weight and thickness of shells.
D2: abrasion	Resulting from the continuous rubbing of grains transported by currents, causing erosive facets, the form and number of which depends on the abrasive potential of grains and on the shell structure.
D3: reorientation	Affects shells that can freely move on the seafloor, being reoriented by uni- or bidirectional currents, according to their shape until reaching a hydrodynamically stable position.
D4: winnowing of mud	Produced by persisting currents strong enough to transport away fine-grained sediment, but only oriented bioclasts.
D5: shelter porosity, convexity up	Disarticulated bivalves with convexity-up orientation indicate a hydrodynamically stable position for uni-bidirectional currents (concavity-up orientation is instable even for weak currents, $< 10\ cm\ s^{-1}$).
D6: mud infilling, geopetal cement	Partly mud-filled shells indicating sucking in currents by partly buried shells transporting mud inside. Mud may also fill complete burial shells, penetrating from predation holes, abrasion or dissolution.
D7: passive burrow infilling	Burrow holes filled by sediment transported by high-energy events such as storms or hurricanes. The infilling is generally coarse-grained sediments and may be directly graded (tubular tempestites).
D8: Allochthonous fauna	Quantification of the percentage of skeletal remains produced in surrounding areas and transported by current activity.

Cannibalistic deposit, land-seaward transport of skeletals (SkC5) is formed by very high energy events (e.g., tsunamis) [6]. Bioclasts from different environments are swept from the seafloor, causing the heterogeneity and low sorting. Superficial bioturbation developed after the high-energy event dislocating and homogenizing the deposits, forming mottled disposition of bioclasts under the skeletal concentration. Main taphocharacters are those related to the extreme high-energy condition, such as disarticulation and fragmentation, and iso-orientation and imbrication of bioclasts onto cross lamination.

Infilling of crustacean burrows (tubular tempestites) (SkC6) determines muddy beds made of peloidal and bioclastic packstones, similar to the 'tubular tempestites' [18], which represent the forced bioclastic infilling of abandoned burrows of crustacean decapods [20]. Skeletal remains are transported and fragmented by repeated storms or hurricanes in a muddy subtidal environment, and during the intense wave action the coarsest and heaviest detritus falls into the burrows [19].

Superficial and deep burrowing (SkC6a) is generated by the action of organisms that formed 3D burrows or homogenize the substrate, dislocating continuous shell beds and reorienting bioclasts. These are generally mud-supported, deposited in conditions with abundant encrusters and boring. Biological characters are here well-represented (crushing, reorientation of shells during scavenging).

4. Numerical analysis and their interpretation

The dataset used for the numerical analysis consists of the semi-quantitative values of abundance, ranging from 0 (absent) to 5 (dominant), of every taphocharacter in each skeletal concentration. This dataset takes into account that the record of taphonomic distortions can be inherited in those skeletal concentrations (mainly in SkC1b, 5 and 6) with widespread bioclast transport. Moreover, taphocharacters A3, A4, B2, and B3 were only occasionally recorded, since they were scarcely preserved or not clearly identifiable, and thus, they were not considered for the numerical analysis. The software used for the statistic analyses was STATISTICA for Windows, Release 4.0 (Statsoft Inc.). Running variables were 16 (Table 1, except for A3, A4, B2, B3).

4.1. Correlation matrix

Analysis of the correlation matrix allowed the subdivision of the taphocharacters into two groups (positive or negative correlation index; Table 2). The taphocharacters A1, A2, B1, C1, C2, C3, C4, C5, which correlated positively with each other (except C2 vs. C4), are interpreted as induced by the action of organisms. Similarly, the taphocharacters D1 to D7, which correlated negatively in most cases with the remainder, are related to physical processes such as uni-bidirectional currents.

The correlation matrix evidences further relationships among taphocharacters that may be interpreted from a palaeoecological standpoint. One of the highest positive correlations occurred between the variables A1 and A2, which are processes that take place on shelly ground. Although some encrusters and borers live inside

Table 2. Correlation matrix for the 16 selected variables in the 8 cases studied. Positive and negative values indicate direct and inverse correlation among variables. Statistical significance of the result for values < 0.05. Key for taphocharacter abbreviations as in Table 1

Tableau 2. Matrice de corrélation pour les 16 variables sélectionnées pour les 8 cas étudiés. Des valeurs positives et négatives indiquent une corrélation directe et inverse parmi les variables. Signification statistique du résultat pour des valeurs < 0,05. Légende des abréviations des taphocaractères comme dans le Tableau 1.

A1	A2	B1	C1	C2	C3	C4	C5	D1	D2	D3	D4	D5	D6	D7	D8	
1.00	0.76	0.00	0.22	0.26	0.34	0.49	0.35	–0.23	–0.52	–0.46	–0.22	0.00	–0.10	0.46	–0.55	**A1**
	1.00	0.38	0.54	0.24	0.61	0.37	0.52	–0.61	–0.69	–0.34	–0.66	–0.14	0.06	0.18	–0.46	**A2**
		1.00	0.67	0.26	0.56	0.12	0.53	–0.68	–0.70	–0.15	–0.74	–0.43	0.20	–0.15	0.28	**B1**
			1.00	0.19	0.92	0.22	0.68	–0.52	–0.55	–0.05	–0.81	–0.06	0.46	–0.43	–0.23	**C1**
				1.00	0.14	–0.39	0.22	–0.14	–0.29	0.15	–0.32	–0.72	0.52	0.59	0.17	**C2**
					1.00	0.34	0.80	–0.47	–0.53	–0.01	–0.79	–0.06	0.39	–0.38	–0.27	**C3**
						1.00	0.46	–0.34	–0.51	–0.62	–0.18	0.27	–0.28	–0.12	–0.37	**C4**
							1.00	–0.42	–0.53	0.06	–0.70	–0.39	0.21	–0.08	0.04	**C5**
								1.00	0.83	0.51	0.79	0.25	–0.31	0.11	0.20	**D1**
									1.00	0.63	0.71	0.29	–0.19	–0.13	0.23	**D2**
										1.00	0.10	–0.30	0.09	–0.07	0.52	**D3**
											1.00	0.36	–0.50	0.21	0.12	**D4**
												1.00	–0.22	–0.54	–0.60	**D5**
													1.00	–0.19	–0.21	**D6**
														1.00	0.18	**D7**
															1.00	**D8**

the substrate, and their activity is not inhibited by burial [13], the strong presence of these taphocharacters in a skeletal concentration indicates a low sedimentation rate, leading to a long residence time of bioclasts on the substrate [9,12]. Another high positive correlation is evidenced among taphocharacters caused by the biological activity as C3 and C4 (redistribution of bioclasts), and C1 and C5 (superficial–deep burrowing).

Category D (physical processes, [16]) groups, by high positive correlation, most of the taphocharacters produced by mechanical processes under both high-energy events and weak-persistent currents. Taphocharacters D1 to D4 positively correlate well and with D8, indicating high-energy processes, necessary to transport bioclasts beyond their original palaeoenvironment. Such other taphocharacters as D5, D6 and D7 are linked to cementation or mud-infilling processes induced by weak and persistent currents.

4.2. Cluster analysis

Cluster analysis is used to group both variables and cases, hierarchized according to their percentage of similarity. The cluster analysis was run on the 16 variables and on the 8 cases (Fig. 2).

Cluster analysis on the 16 variables grouped C1, C2, C3, D1, D2, and D3 with a maximum distance with respect to the remainder. Some taphocharacters were strongly linked as C1 and C3, which depended on the activity of burrowers, or D1 and D2 caused by the continuous action of currents. Other variables, such as C2 and D3, which are usually related (bioclasts reorientation by burrowers), were weakly linked. This is interpreted as a generalized control of the shell reorientation by physical processes.

In the other groupings, the highest similarity was between A1 and A2, interpreted as long-lasting residence time of shelly grounds on the substrate, and B1 and C5, induced by high sedimentation rate. Other interpretable groupings were the variables D4 and D5, which are related to bypassing of fine-grained sediment due to persistent mild currents that reoriented shells without transporting or breaking them.

Cluster analysis on the eight cases characterized six dominant genetic processes. Skeletal concentrations SkC1a and 1b showed closely comparable taphonomic features, both being generated by wave currents, normal waves for SkC1a and weak storms for 1b. SkC5 was moderately linked to SkC1a and 1b, perhaps because SkC5 derives from cannibalistic processes (physical processes) toward the inner parts of the platform, inheriting taphonomic features of SkC1a and 1b together with new characters, such as the presence of allochthonous fauna.

Skeletal concentrations SkC2 and 4 also show a strong similarity, since both are generated by high-energy, deep subtidal currents. These conditions differ from those of SkC1a and 1b, induced only by weak oscillatory flows. The remaining skeletal concentrations have large distances in the cluster diagram due to their peculiar origin. SkC3 is formed by persistent currents on shelly-rich substrates, while SkC6 requires deep burrowing ([17]) immediately before high-energy events. Conversely, SkC6a is formed under low-energy hydrodynamic conditions, with intense superficial and/or deep bioturbation.

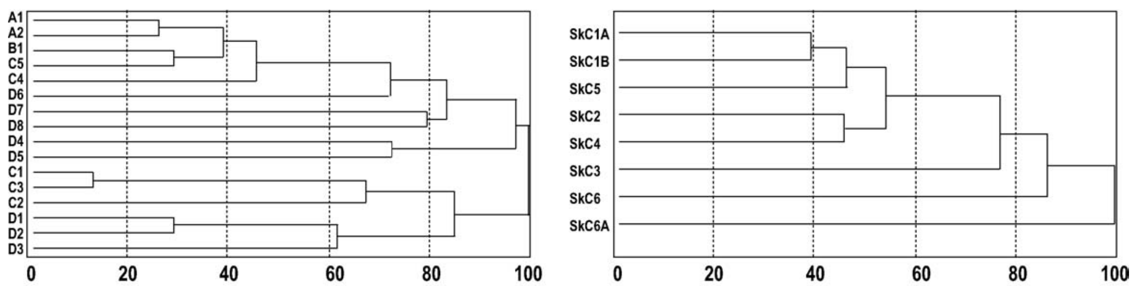

Fig. 2. Tree-diagrams representing the cluster analysis carried out on the 16 variables (left) and 8 cases (right). Missing data were case-by-case deleted. Selected joining rule was weighted pair-group average showing Euclidean distance, $(D_{link}/D_{max}) \times 100$. See text for explanation.

Fig. 2. Arborescences représentant l'analyse de classification hiérarchique réalisée sur les 16 variables (gauche) et 8 cas (droite). Les données manquantes ont été supprimées au cas par cas. La règle de regroupement choisie était la moyenne des groupes de paires pesées montrant la distance euclidienne, $(D_{link}/D_{max}) \times 100$. Se reporter au texte pour plus d'explications.

4.3. Factorial analysis (principal components)

Factorial analysis was applied to the 8 cases by calculating a correlation matrix with the 16 variables, identifying 5 factors that explained 91% of the variance (the first three explained 75%). The factor-score coefficients show the positive or negative weight of each variable for a given factor. Therefore, the taphonomic or ichnologic significance of a factor is that of the variables that contribute the highest value.

Factor 1 explains 40% of the variance. The variables that contribute positively (D1, D2, D3, D4, D5, D7, D8) and negatively (A1, A2, B1, C1, C2, C3, C4, C5, D6) are related, respectively, to hydrodynamic processes as well as to rate and type of organic activity in the substrate (Fig. 3). Thus, factor 1 controls the relationship of the taphocharacters with respect to the current activity or the bioturbation rate, which generally correlate inversely, as already shown by the correlation-matrix analysis. The variables determining factor 2 (20% of the variance) are A1, A2, C4, D4 and D5 (positively) and D8, D3, and C2 (negatively). This factor, therefore, groups the taphocharacters according to the indications they give about bioclast transport; high negative values may be interpreted as long-distant transport, while high positive values mean low (or nil) capability to transport bioclasts for taphocharacters as A1 and A2 (that requires long-lasting residence time of motionless bioclasts on the substrate) or C4, D4 and D5 (sweeping away of only fine mud). For factor 3 (15% of the variance) variables C1, C3, D2, D3, D5 and D6 are positive in weight while variables A1, A2, C2 and D7 are negative. Factor 3 may be interpreted as the dominance of superficial taphonomic and ichnologic processes (positive values) or depth colonization of the substrate (negative values).

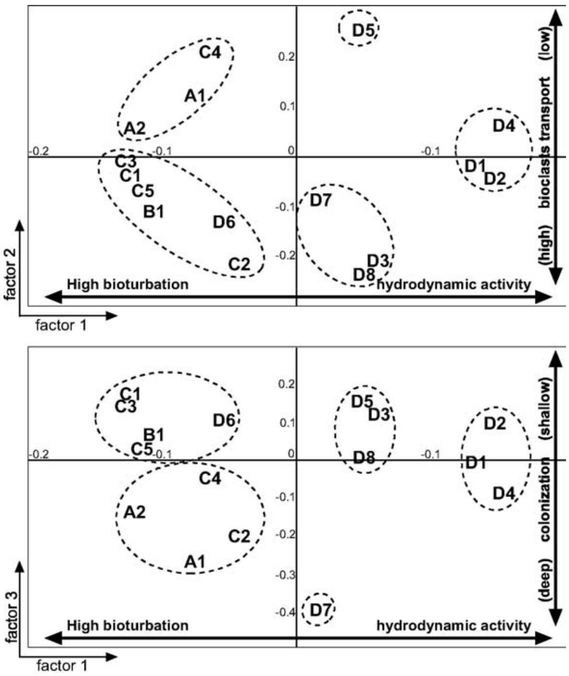

Fig. 3. Two-axe graphs for Factor 1 vs. Factor 2 (upper) and Factor 1 vs. Factor 3 (lower) from the principal-components analysis. The position of the variables provides information concerning their weight in the definition of the factors. Taphocharacters with similar genetic interpretation are grouped together.

Fig. 3. Graphique à deux axes pour le facteur 1 par rapport au facteur 2 (supérieur) et pour le facteur 1 par rapport au facteur 3 (inférieur), basé sur l'analyse en composantes principales. La position des variables donne des informations sur leur poids dans la définition des facteurs. Les taphocaractères ayant une interprétation génétique similaire sont regroupés entre eux.

According to the interpretation of factor 1 as the rate of bioturbation and/or hydrodynamic conditions, SkC6a is the skeletal concentration in which bioturbation was the dominant process (highest negative value). Secondarily, bioturbation contributed to SkC1a and 5 as an inherited character. Conversely, SkC6, 3 and secondarily 2 and 4 showed positive values that evidence genetic processes related to active hydrodynamic conditions (Fig. 4). Factor 2 was interpreted as low/high bioclasts transport in every skeletal concentration. Less bioclast transport was calculated in SkC3, 6a and 1a. On the contrary, active bioclast transport resulted in SkC5, 6 and 1b. With respect to factor 3 (superficial or deep substrate colonization) only SkC6 and 6a reached negative values, indicating a large development of deep burrowing.

5. Conclusions

Results from the three statistical data analyses were compatible and interpretable from a sedimentological, taphonomical and ichnological standpoint. Moreover, they refined the analysis of the taphonomic characters and the interpretation of the resulting skeletal concentrations. The correlation analysis favoured grouping of taphocharacters, previously analysed only qualitatively [16], according to their genetic processes: (1) taphocharacters induced by taphonomic processes

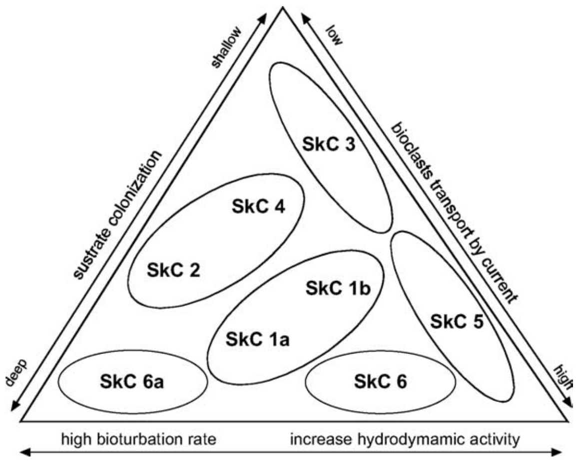

Fig. 4. Synthetic representation of the genetic processes involved in the eight skeletal concentrations, according to the statistical analysis of the 16 taphocharacters analysed.

Fig. 4. Représentation synthétique des processus génétiques impliqués dans les huit concentrations coquillières, selon l'analyse statistique des 16 taphocaractères analysés.

active on shell ground (A1–A2); (2) taphocharacters produced by palaeobiological activity on the substrate (B1–C1–C2–C3–C4–C5); (3) mechanical processes induced by currents (D1–D2–D3–D4); (4) infilling processes induced by currents (D5–D6–D7–D8). As expected, inverse correlations appeared between variables of groups 1 and 2 and variables of groups 3 and 4.

The cluster analysis on the 16 taphocharacters gave results compatible with those of the correlation analysis. Moreover, the cluster analysis on the eight skeletal concentrations grouped them according to the dominant genetic processes undergone: (a) current action induced by normal waves or weak storms (SkC1a, 1b); (b) high-energy, deep subtidal currents (SkC2, 4); (c) cannibalistic phenomena induced by very high-energy events (SkC5); (d) persistent current action in bioclastic-rich facies (SkC3); (e) passive sediment infilling of open burrows due to high-energy events (SkC6), and (f) high bioturbation rate under low-energy conditions (SkC6a).

The principal-components analysis offered three factors that explained 75% of the variance. Factor 1 indicates the contribution of hydrodynamic processes or the bioturbation rate in the genesis of the resulting skeletal concentration. These parameters were inversely correlated, as previously shown by the correlation analysis. Factor 2, instead, was interpreted as the degree of transport undergone by bioclasts before burial. It is controlled by the positive or negative scores of the taphocharacters related to fragmentation, disarticulation, grouping and bioclast allochthony or to the long-lasting exposure of motionless bioclasts in the substrate, respectively. Factor 3 was interpreted as the dominance of superficial taphodistortion and superficial colonization of the substrate (including shelly ground), when positive, and deeper colonization in the substrate, when negative.

According to the statistical results from the correlation-matrix, cluster and principal-components analyses, the palaeoenvironmental setting in which every skeletal concentration developed can be better approached. This methodology has been demonstrated to be a powerful tool for sedimentological, taphonomical and ichnological studies, thereby aiding in the understanding of the genetic processes of shell beds.

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