Axis 2

micrite

Axis 1

lithoclastic content

Axis 2

light penetration

Axis 1

turbidity

Axis 4

Axis 6

Axis 5

Group	Facies	Cluster	Subcluster	Textures
non-microbial	Grainstones			Grainstone (rarely packstone)
	intraclast rudstones	A		rudstone
	Wackestone-packstone	B		wackestone-packstone
microbial	micropeloidal	C		micropeloidal cement-supported (more rarely intraclastic and matrix-supported)
	intraclast-bioclastic-peloidal	D	D1	intraclastic matrix-supported
			D2	bioclastic matrix- and cement supported
			D3	peloidal matrix-supported
	Micropeloidal-skeletal	E	E1	micropeloidal matrix- and cement-supported
			E2	micropeloidal cement-supported
			E3	micropeloidal-bioclastic matrix-supported
			E4	micritic and micropeloidal matrix-supported (rare cement-supported textures)
			E5	micropeloidal matrix- and cement-supported
			E6	micropeloidal matrix-supported (rare micritic, peloidal cement-supported)
	Dasycladale-rich	F		diverse
	Micritic	G	G1	micritic
			G2	micritic

	Aphralysiacean-cyanobacterial micritic	H		micritic and micropeloidal matrix-supported
	Automicritic	I		micritic (rare peloidal matrix-supported and wackestone)
Mixed	Allomicritic	J		micritic and wackestone-packstone
	Calcifoliids-denezellid	K		mostly micritic and packstone

Cement	Allomicrite	Automicrites	Non-skeletal
high (blocky)	absent	absent	high (ooids, oncoids)
absent	low to high	absent	high (intraclasts)
absent	high	absent	low to moderate (intraclasts)
high (radial fibrous+blocky)		moderate % of micropeloids	low
moderate (radial fibrous+blocky)	low	moderate % of microbial micrites and micropeloids	high (intraclasts)
moderate (radial fibrous+blocky)	low	moderate % of micropeloids, peloids and microbial micrite	moderate (intraclasts)
moderate (radial fibrous+blocky)	low	high % of peloids	low
moderate (radial fibrous+blocky)	absent	high % of micropeloids	absent
moderate (radial fibrous+blocky)	low	high % of micropeloids	low
low (radial fibrous+blocky)	high	moderate % of microbial micrite and micropeloids	low
low (radial fibrous+blocky)		moderate % of microbial micrite and micropeloids	low
low (radial fibrous+blocky)	low	high % of micropeloids	low
low (radial fibrous+blocky)	low	moderate % of microbial micrite and micropeloids	low
high (blocky)	low	low	low to high (oncoids)
low (radial fibrous+blocky)	low	high % of microbial micrite and low % of micropeloids	low
low (radial fibrous+blocky)	low	high % of microbial micrite and moderate % of micropeloids	low

low (blocky)	low	high % of microbial micrites and low % of micropeloids	low
low (radial fibrous+blocky)	high	moderate % of microbial micrites and micropeloids	moderate to high (quartz, intraclasts)
low (blocky)	high	moderate % of microbial micrites and micropeloids	moderate % of quartz grains
low	high	low % of microbial micrites and micropeloids	low to high (quartz, intraclasts)

Skeletal	predominant Formation
low to moderate (mostly donezellids, crinoids, brachiopods, foraminifers)	
absent to low (mostly brachiopods, cyanobacteria)	common in Roc de Murviel (RM), rare in Roque Redonde (RR) and Coteau de Bergue (CB)
high (mostly calcifoliids, donezellids, crinoids, brachiopods, foraminifers)	RM
moderate (varied)	RR
moderate (mostly fenestellids and crinoids)	RR and CB
high (mostly crinoids, fenestellids, foraminifers, calcifoliids)	RR
moderate (mostly cyanobacteria, red algae, crinoids and brachiopods)	CB, RR and RM
moderate (mostly the cyanobacteria <i>Ortonellopsis</i>)	CB, RR and RM
low to moderate (varied)	Common in RR, very rare in RM and CB
low to moderate (varied)	Common in RR, very rare in RM
low (varied)	Common in RR, intermediate in RM and rare in CB
low (varied)	Common in RR, intermediate in RM and rare in CB
high (mostly calcifoliids, aphralysiaceans and donezellids)	RM
high (dasycladales)	RM
low (varied)	Common in RR and CB, rare in RM
moderate to high (mostly fenestellids, crinoids and calcifoliids)	Common in RR and rare in CB and RM

high (mostly aphralysiaceans, cyanobacteria, dasycladales)	CB and RM
low to high (mostly crinoids, donezellids, fenestellids, ostracods and foraminifers)	Common in RR, intermediate in RM and CB
low to high (varied)	RM
high (mostly calcifoliids and donezellids)	RM

**Environmental controls on the development of Mississippian microbial
carbonate mounds and platform limestones in southern Montagne
Noire (France)**

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Associate Editor – Jody Webster

Short Title – Environmental controls on microbial mounds and limestones

ABSTRACT

Late Mississippian carbonates in southern Montagne Noire are dominantly domical to laterally-accreted microbial mounds in some formations, as well as stratiform microbial limestones occurring in hundreds of olistoliths within a flysch basin, constituting pieces of a giant puzzle that are used to help reconstruct a platform in a region that is no longer preserved. Petrographic data of limestone samples from 14 continuous long sections of olistoliths have been analyzed statistically, using multivariate clustering (Q-mode) of the components/matrix/cement and canonical correspondence analysis (CCA) that allow the reconstruction of the environmental parameters of carbonate microbial communities

in space and time. Clustering analysis separated microbial and non-microbial facies. The calculation of indices along the various axes from canonical correspondence analysis allows recognition of the controlling factors of the mounds and microbial growth as being turbidity, light penetration, bathymetry and storms. Turbidity and light penetration are the primary factors controlling the morphology of the microbial limestones. Representation of the light penetration and bathymetry indices on the stratigraphical sections define two vertical environmental gradients. Light penetration can be subdivided into euphotic, euphotic-dysphotic and dysphotic-aphotic conditions. The representation of the bathymetry allows the subdivision of samples into a deeper outer ramp, external mid-ramp and internal mid-ramp. The curve distance from the section base = f (index) suggests a cyclicity for the platform that cannot be compared with the onlap curve defined from other cratonic areas (Moscow Basin), and thus, the cyclic succession of the Montagne Noire is interpreted to have been mostly tectonically-controlled. Integration of the data allowed the reconstruction of the original Mississippian carbonate platform, where, up to the Mikhailovian, it appears to correspond to a platform morphology, with narrow shallow water facies and wide turbiditic systems, whereas the width of shallow-water settings expanded during the Venevian to the Protvian, forming a ramp or distally-steepened ramp with widespread microbial limestones.

Keywords automicrites, canonical correspondence analysis, Carboniferous, ecological gradient, multivariate clustering, ramp.

INTRODUCTION

The Carboniferous rocks of the southern Montagne Noire are the result of the Variscan Orogeny, involving the collision of Gondwana and Laurussia during the late Viséan up to the latest Serpukhovian (or earliest Bashkirian). Here, several nappes and klippen (Fig. 1) have transported carbonate blocks southward from positions farther to the north before final emplacement (Engel *et al.*, 1982; Franke *et al.*, 2011). These movements allowed the preservation of partially intact successions of late Tournaisian-late Viséan age, comprising predominantly carbonate ramp (Cózar *et al.*, 2017) and some siliciclastic flysch complexes, where olistoliths (up to hundreds of metres in diameter)

commonly contain limestones of the Coteau de Bergue, Roque Redonde and Roc de Murviel formations (Poty *et al.*, 2002; Vachard *et al.*, 2017). The stratigraphic succession is a composite succession, measured and reconstructed from the largest olistoliths, which contain the longest partial sections, and the successions are not exactly the same for each structural unit (Fig. 2). For such a reconstruction, detailed biostratigraphic control was necessary, which in this type of shallow-water limestone facies is based mostly on foraminifers (Vachard *et al.*, 2016b, 2017). The absence of a preserved *in situ* platform in the northern Montagne Noire, combined with the occurrence of rather uniform microbial facies, significantly complicates the reconstruction of the platform.

The Coteau de Bergue, Roque Redonde and Roc de Murviel formations are composed mostly of micropeloidal fabrics (*sensu lato*), commonly recorded in Mississippian bioconstructions and of widely accepted microbial origin (Chafetz, 1986; Monty, 1995; Neuweiler and Reitner, 1995; Pratt, 1995; Pickard, 1996; Neuweiler *et al.*, 1999; Riding, 2000), but see Shen & Neuweiler (2017) for a different opinion. Similar microbial textures are currently recorded in stressed and hypersaline environments, peritidal settings, lakes, caliches and patch reefs (e.g. Friedman *et al.*, 1974; Macintyre, 1985; Chafetz, 1986; Mann and Nelson, 1989; Kobluk and Crawford, 1990; Reitner, 1993; Gerdes *et al.*, 2000). Micropeloidal mounds of the Montagne Noire are characterized also by a common and diverse biota (e.g. Aretz, 2002a; Vachard *et al.*, 2016a,b).

Owing to the uniformity of the microbial facies and their random distribution within the sections, facies analysis does not allow significant environmental interpretation beyond that of an overall platform setting. In order to obtain palaeoecological trends within fauna and flora, multivariate statistical analyses were undertaken. Principal component analysis (PCA) and correspondence analysis (CA) were performed previously as ordination methods but were discarded because they show marked horseshoe-type patterns and Guttman effects, which suggest an overimposition of different factors (Guttman, 1953; Goodman, 1991) and thus they provide little value for discrimination of the diverse environmental controls on the microbial communities. Hennebert and Lees (1991), Lees and Miller (1995) and Devuyst and Lees (2001) demonstrated environmental gradients using CA as an

ordination method for the Waulsortian Banks of Belgium, England and Ireland, and developed the relay-index (RI) method based on a marked arch or Guttman effect. Nevertheless, as the authors recognized (e.g. Hennebert and Lees, 1991), their RI gradient was an amalgamation of multiple factors, such as bathymetry, turbidity and light penetration.

The main change within the microbial communities that contributed to the development of domical and laterally-accreted mounds in the Coteau de Bergue and Roque Redonde formations as opposed to the thin stratiform deposits in the Roc de Murviel Formation is not understood. Similar examples of both types of microbial deposits in a single succession are also known in other Mississippian successions of the Western Palaeotethys, such as in Scotland (Pickard, 1992), England (Gutteridge, 1995), SW Spain (Cózar & Vachard, 2003; Cózar *et al.*, 2006) and the Central Moroccan Meseta (Cózar *et al.*, 2008).

The aims of this study are: (i) to characterize and individualize facies associated with the Roque Redonde and Roc de Murviel formations, in order to; (ii) identify different environmental or palaeoecological factors that controlled the faunal/floral assemblages within the microbial communities, thus helping disentangle the ecological factors. The ultimate aim for those analyses is to decipher (iii) the controlling factors on the types of microbial growth communities; and (iv) the stratigraphical distribution of the controlling factors. Finally, these factors are used as a tool to (v) aid the reconstruction of the, as yet, poorly understood basin.

STRATIGRAPHICAL AND SEDIMENTOLOGICAL CONTEXT

The succession developed from the Devonian up to the base of the Mikhailovian (Upper Viséan) has been interpreted as a predominantly carbonate ramp (Cózar *et al.*, 2017), where microbial carbonates are recorded only exceptionally in the upper part of the succession. The analyzed sections are included in the Coteau de Bergue, Roque Redonde and Roc de Murviel formations (Table S1; Figs S1 to S14), where the general lithological features were described in Vachard et al. (2017).

The Coteau de Bergue Formation is composed of thickly-bedded dark grey limestones, several metres thick (Fig. 3A), slightly better stratified in the upper part of the formation (0.5 to 1 m thick). Thus, the morphology of the microbial mounds are considered as large tabular mounds (*sensu* Gutteridge, 1995). Macrofossils are rare, as are cavities. Large stromatactis-like cavities (decimetric to decametric scales) are present only in the middle part of the formation, whereas small fenestrae (of millimetric scale) are more randomly distributed in the succession. Small fenestrae could be associated with post-burial diagenetic processes generating birdseye-like structures (Gerdes *et al.*, 2000), but the origin of the large cavities is still a matter of discussion (see Bourque and Boulvain, 1993; Neuweiler *et al.*, 1999). Strong schistosity within the limestone does not allow a reliable study of the orientation of the bedding planes and orientation of the cavities. Limestones are composed mostly of micrites and common cyanobacteria fossils. A carbonate breccia, 1 to 2 m thick, occurs in the upper part of the formation. Foraminiferal biostratigraphy yielded an Aleksian to Venevian age for the formation. Youngest beds in faulted contact with this formation correspond to oolitic bars of the Serpukhovian (Tarusian Substage), but no micritic or micropeloidal facies were identified. Owing to the scarcity of bioclasts, paucity of micritized grains and calcareous algae, and the abundance of cyanobacteria, these mounds were interpreted as probably growing mostly in dysphotic to aphotic conditions (Vachard *et al.*, 2017). No lithostratigraphic contact between the Coteau de Bergue and Roque Redonde formations was observed in outcrop, but a lateral equivalence is assumed due to its similar biostratigraphy and the co-occurrence of the same tectonic unit in olistoliths (Fig 2).

The Roque Redonde Formation is composed of thickly-bedded to massive pale grey limestones (Fig. 3B to C). Locally bioclastic-rich beds, coral biostromes and carbonate breccias are present. Common cavities (as small fenestrae or larger stromatactis-like cavities) and sparse bioclastic content occurs throughout. Cavities commonly show smooth to flat bases and irregular to digitate tops and are filled by different cements and infillings. Larger cavities are commonly parallel to bedding planes or with gentle dips, less than 5°. However, bedding planes are seldom recognized on outcrops (e.g., Fig. 3C), and they are rarely associated with lithological changes or any particular hydrodynamic-sedimentary feature. The main challenge in the field is to establish the thickness and morphology of large individual carbonate mounds, mostly in those sections where bedding planes are inconspicuous. Three main mound types are

166 recognized, which are: (i) small, stacked and coalesced domical mounds, ranging from a
167 few metres up to rarely 10 m thick (Figs S7 to S9); (ii) laterally-accreted to large tabular
168 mounds (*sensu* Gutteridge, 1995), 5 to 15 m thick (Figs S4 and S6); (iii) individual
169 mounds that are 15 to 30 m thick, and form a predominant tabular dome with slight
170 palaeorelief on top (Figs 3A, S8 to S11). Flank facies are not recognized, and the
171 breccias recorded in the succession do not appear to be related directly to the flanks or
172 caps of the mounds. The base of the formation was rarely recorded and was assigned to
173 the late Viséan (Aleksian Substage), whereas the most important development occurred
174 during the uppermost Viséan to early Serpukhovian (Venevian and Tarusian substages,
175 and rarely up to the lower part of the Steshevian Substage). The formation was
176 interpreted as having developed in an outer platform to shelf break setting (Vachard *et*
177 *al.*, 2017).

178
179 The Roc de Murviel Formation is composed of dark grey to brown well-bedded
180 limestones interbedded with shales and argillaceous mudstones (Fig. 3B). The
181 limestones are thin-bedded, usually less than 1 m thick, with stratiform growth. They
182 comprise micropeloidal facies alternating with argillaceous micrites containing
183 micropeloidal bands and nodules, at centimetric to decametric scale. Stromatactis-like
184 cavities are absent and only small-sized fenestrae occur. Locally, macrofossils are
185 common (brachiopods, gastropods, crinoids), but colonial rugose corals are a notable
186 feature of those facies, being present as monospecific and polyspecific coral biostromes
187 and coral bioherms (patch reefs), as well as sparse solitary corals in the carbonate
188 mounds (extensively described by Aretz, 2002a; Aretz and Herbig, 2003; Aretz and
189 Webb, 2006). The formation was assigned mostly to the mid-late Serpukhovian
190 (Steshevian and Protvian), whereas facies assigned to the late Viséan and lowermost
191 early Serpukhovian (Aleksian to Tarusian) are rarely recorded. The formation was
192 interpreted to be developed in inner platform to lagoonal settings (Poty *et al.*, 2002;
193 Aretz and Herbig, 2003).

194
195 The growth initiation phase of large mounds is rarely recognized because the
196 carbonate bodies are mostly located directly on shales due to their olistolitic
197 emplacement, and only two sections of the Roque Redonde Formation contain the initial
198 phase of mound growth. In Les Pascales North section, the massive limestones are
199 developed above well-bedded micritic beds, similar to mud mound textures of the

Waulsortian banks (see Lees and Miller, 1995), but also related to microbial activity. In the Roc de Murviel section, the massive limestone succeeds a bioclastic/oolitic packstone/grainstone (Fig. 3C) showing hummocky cross-stratification, that formed the stabilized substrate necessary for the growth of the microbes (Keupp *et al.* 1993). These oolitic facies are also recognized in blocks of debris flows but are very rare. Owing to the rarity of this facies, it is difficult to assume that all mounds nucleated on this type of oolitic facies, although such deposits could favour the development of mounds by creating a pre-existing palaeotopography as a hard substrate that the microbes could colonize.

A palaeokarst was interpreted at the boundary between the Roque Redonde and Roc de Murviel formations by Poty *et al.* (2002). In the Château-Vailhan area, the Tour de Castellas section exposes facies attributed to the Roc de Murviel Formation, but with slightly higher shale and quartz content, and there, the base of the section is dated late Viséan in age (Mikhailovian-Venevian substage; Fig. 2). In addition, the Roc de Murviel Formation also occurs in the Castelsec South section from the Tarusian. The occurrence of those facies, dated as old as the late Viséan, as well as those others dated as Tarusian (e.g., Figs S2 and S14), confirms the synchronous deposition of the Coteau de Bergue, Roque Redonde and Roc de Murviel formations nearly up to the lower part of the Steshevian, and thus, the formations co-existed on the original platform (Fig. 2).

The top of the Roc de Murviel Formation is transitional into shales and oolitic beds of the La Serre de Péret Formation. That formation is considered to have been deposited mostly in deltaic environments and can be correlated to the deltaic siliciclastic successions located west of Cabrières town (Aretz, 2016; Vachard *et al.*, 2017).

METHODOLOGY

The lower part of the succession assigned to the Mikhailovian substage is not included in the database, because it is composed mostly of oolitic grainstones and bioclastic packstones, considered shoals and bars, and interpreted as the stabilized substrate prior to the growth of the carbonate mounds.

In total, more than 6000 thin sections were studied for different purposes in the area. Sampling undertaken by the authors corresponds mainly to four phases (spanning five decades); (i) thesis work of Vachard (1974); (ii) Ph.D. thesis work of Aretz (2002a); (iii) the Ph.D. thesis work of Pille (2008); and (iv) a recent sampling campaign (since 2014). 1800 thin sections belonging to the 401 selected levels of the 14 most continuous sections (Figs S1 to S14) were used for this study. Less well-exposed sections or those with thinner successions, due mostly to their occurrence in smaller olistoliths, also were discarded from this analysis (the location of all stratigraphic sections was documented in Vachard *et al.*, 2016a, 2017).

Database

Two hundred points were counted for each thin section using a petrological microscope by the senior author in order to analyze the percentage of matrix, cements, non-skeletal clasts and skeletal components (e.g. Gischler *et al.*, 2013). As each stratigraphic level is represented by several thin sections (commonly 4 to 6), percentages were recalculated to 100%. Since part of the matrix is the non-microbial facies, allomicrite (or allochthonous micrite) is considered as detrital and mainly derived from skeletal disintegration (Tucker and Wright, 1990). In the microbially-induced facies, allomicrite (where present), microbial micrite (*sensu* Monty, 1995), micropeloids and larger peloids were considered. These latter are usually included under the term automicrites (e.g. Lees and Miller, 1995; Reitner and Neuweiler, 1995; Webb, 1999). This subdivision of the organo-precipitated automicrites is preferred to analyze possible variations in the carbonate mounds. Non-skeletal clasts are confined to pellets (of very low weighting in the database), grapestones, quartz grains, intraclasts, ooids and oncoids. Internal fillings or cements within moderate to large shells have been quantified as matrix or cement (such as in the large coral calices), whereas cements/filling within small cavities of fossils are considered as part of the fossil (such as in massive corals or fenestellid bryozoans). In those cases, where mixed facies exists between non-microbial and microbially-induced facies, the percentage of each facies also was quantified. Samples with less than 20% of microbial textures were associated with the non-microbial clusters, whereas those with more than 60% were usually associated with the microbially-induced facies. Samples with a balanced percentage of microbial and non-microbial facies occur in separate clusters.

Genus and species diversity was studied for the foraminifers, calcareous red algae, calcareous green algae, cyanobacteria, rugose corals, bryozoans, calcispheres and problematic Algospongia (see taxonomic studies summarized in Vachard *et al.*, 2017). However, this detailed taxonomy is not really useful for the statistical comparison due to the disproportionate number of variables, and its low weighting in the database. Thus, the most diverse skeletal components were grouped into: dasycladales green algae, questionable bryopsidales green algae, cyanobacteria and biocalcifications, aphralysiaceans (also related to the cyanobacteria) and red algae. The Algospongia were subdivided into four groups, depending on their more usual taxonomic affiliation, such as the aoujgaliids, commonly considered red algae, the palaeoberesellids, more commonly interpreted as green algae, the calcifoliids, associated with the red algae as well as with the phylloid algae, and the donezellids, interpreted as green or red algae. The foraminifers are considered as a single variable, although more than one hundred genera have been described from the area, as well as 15 genera of calcispheres, although the latter are comparatively rare in the carbonate mounds. Other important facies components were divided into major groups, such as the bryozoans (fenestellid, encrusting and trepostomate) or corals (rugose, tabulate and heterocorals). Other bioclasts are not subdivided (ostracods, crinoids, brachiopods, trilobites, gastropods, bivalves, ammonoids and sponge spicules).

Multivariate clustering

For the first re-grouping of the facies, multivariate clustering (Q-mode) of the components/matrix/cement was performed using the Morisita (1959) coefficient with unweighted pair-group method using averages (UPGMA) to produce a basic dendrogram (Fig. S15), where clusters A to K were individualized. Thus, statistical associations or clusters in the database are an equivalent to facies. The multivariate analysis was performed using the PAST 3.14 program (Hammer *et al.*, 2001). To establish the clusters, only quantitative variables in percentages related to matrix, cements, skeletal components and non-skeletal clasts were used, whereas qualitative variables were not included in this part of the analysis due to the different nature of the data. The Morisita coefficient is one of the more commonly used for quantification of similarities, because it is influenced little by species richness and sample size (Wolda,

1981; Magurran, 1988), and thus, it is suitable for databases with many ‘double zeros’ (Ramette, 2007), which is usual in the database, where the absence of data is more common than the presence of data. The main disadvantage in using this index is that it is influenced by the abundance of the main variable, which in the present study, appears to be the percentages of cement as the dominant variable (Fig. S16). Other authors have used the Morisita coefficient for the recognition of biofacies in the fossil record (e.g., Wu *et al.*, 2015), and thus, matrix or cement percentages did not have the same influence as in this study’s database (Fig. 4).

Canonical correspondence analysis (CCA)

The first variables included in the database as binary data (0 = absent, 1 = present) are the textures, including those typical of the microbial textures (cementstone, micropeloidal matrix-supported and cement-supported, peloidal, intraclastic; sensu Webb, 1996; and Rodríguez-Martínez *et al.*, 2010) and the non-microbial facies (wackestone, packstone, grainstone and rudstone), as well as the micrites (including microbial micrites, as well as mudstones and argillaceous micrites). Variation between those textures into microfabrics where more than one is present is also binary quantified (irregular, thrombotic, grumular, domical and laminar), as well as other features observed in the facies (size of cavities, type of cement, and encrusting and micritization processes) (Table S1).

A canonical correspondence analysis (CCA) was used as an ordination method to compare the quantitative variables as a function of the qualitative variables for each of the main clusters (Figs 5 to 8). This method is a linear combination of environmental variables (Ramette, 2007), which allows the comparison of quantitative variables (usually species) versus well-known environmental parameters. The method seems to be robust even where species display bimodal responses, unequal ranges or unequal maxima along environmental gradients (Ramette, 2007). These factors have established CCA as the most widely used gradient analysis technique for ecological studies (Palmer, 1993). In contrast to modern ecological studies, the geological record allows comparison of qualitative and quantitative variables in order to infer environmental parameters. In these analyses, all those variables that were not present in at least 5% of samples have been filtered out, in order to reduce the noise in the database, because they

do not have a great influence on the analysis (ter Braak and Verdonschot, 1995). In the database for the microbial facies (clusters C to I, Table S1), the textures wackestone-packstone, packstone, grainstone, rudstone and the components: pellets, ooids, oncoids, palaeoberesellids and tabulate corals are removed, because they are not present in at least 5% of samples. Whereas for the CCA in clusters A and B, all textures and microfabrics are removed, as well as micropeloids, peloids, microbial micrite, cemenstone, micropeloidal matrix-supported, micropeloidal cement-supported, peloidal, intraclastic, micritic, grainstones, and in addition the components: pellets, grapestones, ooids, oncoids, quartz grains, bryopsidales, palaeoberesellids, aphralysiaceans, cyanobacteria, red algae, encrusting bryozoans, trepostomate bryozoans, trilobites, bivalves, ammonoids, sponge spicules, rugose corals, tabulate corals and heterocorals. Identification of the controlling factors over the axes in the CCA are based on the palaeoecological dependencies/interpretations of the allochems.

Vertical ecological gradient

Palaeoecological/environmental factors recognized in the CCA are stratigraphically analyzed by means of the projections of the scores on the axes, and recalculated from 0 to 100 in samples and components. These recalculated indices allow vertical evolution of the factors on the microbial rocks from the Montagne Noire to be established. The index was calculated on axes 1 to 4, although only axis 3 (Fig. 9), which is more probably interpreted as bathymetry, shows a stratigraphical evolution of the microbial facies. Axis 2 (Fig. 10), light penetration, is helpful to interpret some of the curves and peaks observed in axis 3. They are called I_3 and I_2 respectively. In contrast, no tendency was observed in axes 1 or 4.

These values are an expression of the CCA, as they show the same gradients over the axes, but they allow a more visual representation over the stratigraphic succession. Distance from the base of the section (axis y (m) = f (index)) also was constructed for each section (on Figs 11 and 12) to better describe the stratigraphic changes in time and space, following the recalculation method that Hennebert and Lees (1991) used to obtain the RI for the Waulsortian banks. As mentioned above, only axis 3 shows a vertical variation, where changes of palaeobathymetry versus time were shown. The calculated I_3 for the palaeobathymetry is subdivided at values of 18 and 30 (Fig. 11).

Values lower than 18, contain sponge spicules, intraclasts, cyanobacteria and donezellids as important components, and, represent the deeper-water setting of the environments. Values higher than 30 contain foraminifers, brachiopods and red algae (peloids have a value of 100; see discussion on axis 3), which are interpreted to represent the shallower water facies in the microbial rocks of the Montagne Noire. Taking into consideration the previously discussed factor, the $I_3 < 18$ is considered to be an outer ramp setting, and $I_3 > 30$ as representative of the internal middle ramp. Whereas values between 18 and 30 most probably correspond to a more external middle ramp with sporadic periods passing into the outer ramp via transitional environments. This interpretation is based on the presence of storms (rather more common in the Roc de Murviel Formation than in Coteau de Bergue and Roque Redonde formations), allowing generalization of a widespread middle ramp setting for the Roc de Murviel Formation. To help in interpreting those settings, the light penetration recognized on axis 2 also was used. It was subdivided into: $I_2 < 17$ typical euphotic conditions, between 17 and 32, transitional conditions between the euphotic and dysphotic, and $I_2 > 32$ questionable environments that are most probably dysphotic, but some levels could reach aphotic conditions (see discussion on axis 2).

FACIES

Facies recorded in the southern Montagne Noire can be characterized by main skeletal components and non-skeletal clasts. The main clusters are separated at higher similarity index (Fig. S15), and are related to the microbial influence, being arranged in two large groups; non-microbial facies and microbially-induced facies. There is also a mixed facies, where a percentage is occupied by microbially-induced facies and other are mostly wackestone-packstone facies, alternating or co-habiting with the microbial communities. The main lithological features are summarized in Table 1.

Non-microbial facies

Only two clusters have been recognized, A and B. Furthermore, there are grainstone horizons (mostly at the base and top of the succession), that were not included in the database, as well as rugose coral biostromes, that were described in detail by Aretz (2002a, 2002b) and Aretz and Herbig (2003).

Intraclastic rudstones (cluster A)

This cluster is composed mostly of large intraclasts (up to centimetres in diameter) of micropeloidal textures (Fig. S17A), although in some cases, bioclastic intraclasts are predominant (Fig. S17B). Intraclasts make up 60 to 90% in volume (exceptionally 100%, with sutured contacts between the clasts; Fig. S17A). The matrix is mostly composed of micrites, varying between 10% and 20%.

Bioclastic wackestones to packstones (cluster B)

This cluster is rather heterogeneous compared to other clusters (Fig. S15). The main feature is the absence or near absence of cements, being composed of a combination of skeletal components and allomicrites, in many cases also with common intraclasts (Table 1). Most samples contain fragmented bioclasts that are well-sorted and are densely packed, which show mostly flat-parallel orientation, although very rarely, cross-lamination occurs (Fig. S17C and D).

Oolitic-bioclastic packstone-grainstones

At Roc de Murviel hill, oolitic grainstones and packstones are recorded in a 3 to 4 m thick level, predominantly with a radial fabric ooids. These oolitic beds are interbedded with microbial facies of the Roque Redonde Formation. The same facies is recorded at La Rouquette (8 m thick; Fig. S17E), and in boulders and olistoliths in the debris flows in Les lentilles de la route and Tourière (Oolites of Roc de Murviel Formation in Vachard *et al.*, 2017). Some levels are intraclastic, kamaenid-rich or oncoidal packstones (Cózar *et al.*, 2017) and with low to moderate percentages of skeletal components (Table 1). Sedimentary structures are common, including fining-upward sequences, cross-stratification and hummocky cross-stratification.

Microbial facies

The microbially-induced facies can be subdivided into several clusters and subclusters, of which cluster E is the most abundant (present in 35% of the levels); C, D and G are also important to characterize the bulk of the mounds (present in 14%, 12% and 16% of the levels, respectively); whereas there are other small clusters (F, H and I) (Fig. S15).

The clusters are a result of multiple variations between matrix and components, but the dominant factor that discriminates the microbial clusters is the cement (Fig. S16). From cluster C through to I there is a decreasing percentage of cement (more or less, but not valid for each subcluster).

Micropeloidal (cluster C)

Cement is the most abundant, ranging from 40 to 70% (rarely 80 to 90%; Figs 4A, S17F to G). Micropeloids are usually present, ranging between 10% and 30% in percentage of the facies, although in some levels, they are scarcer and even absent. Microbial micrites are rare, as well as peloids, and allomicrite is negligible. Bioclastic content is moderate (highly diversified), as well as low percentages of intraclasts (Table 1). Diverse textures include: irregular, patchy and laminar, with domical and grumelar structures being rare.

Intraclastic-bioclastic-peloidal (cluster D)

It is mostly characterized by peloidal and intraclastic textures with a moderate percentage of cement. The sum of the skeletal components and non-skeletal clasts is usually higher than 50%.

Three subclusters (D1 to D3) occur (Fig. S15). Subcluster D1 is characterized by common intraclasts and microbial micrites (Figs S17H and S18A). Stromatactis-like cavities and small fenestrae are relatively scarce compared to other microbial facies. Subcluster D2 mainly regroups samples with higher skeletal content (Table 1; Fig. S18B and C). Subcluster D3 is characterized by abundant peloids (Fig. 4B), although the occurrence of cyanobacteria and red algae in some horizons is also noteworthy.

Micropeloidal-skeletal (cluster E)

It is a similar facies to cluster C, although in this case, the percentage of cement is markedly lower, whereas the combined percentage of micropeloids and microbial micrites is much higher. It is difficult to propose uniform features to characterize cluster E because of variation between samples. However, most samples contain moderate cement, low to absent allomicrite, moderate skeletal content and high microbial micrite content.

Six subclusters occur (E1 to E6). Subcluster E1 is characterized by the abundance of cyanobacteria fossils (Fig. S18D), which, essentially, are the only bioclasts recorded in those levels, except for negligible fenestellid and encrusting bryozoans, crinoids, ostracods and foraminifers. Micropeloids are indistinctly matrix-supported and cement-supported, and microbial micrites are low in percentages compared to other subclusters. Subcluster E2 is characterized by the highest cement percentage of this cluster, accompanied by a relatively high percentage of bioclasts and micropeloids (Figs 4C and S18G). Bioclasts are diverse (Table 1). Subcluster E3 includes those levels with high allomicrite content (*ca* 10 to 30%), wherein in addition to micritic textures, only micropeloidal matrix-supported textures occur. Skeletal components and non-skeletal clasts are more abundant than in other subclusters and are diverse. Peaks of dasycladales, calcifoliids, fenestellids, ostracods, crinoids, foraminifers, as well as grapestone and intraclasts may occur (Fig. S18H). Subcluster E4 regroups all those samples with high microbial micrite content (10 to 35%), as well as those with abundant micropeloids (*ca* 20 to 40%). The abundance in those components is reflected by the common micritic textures, as well as micropeloidal matrix-supported and cement-supported textures (Fig. S19A and B). Subcluster E5 is characterized by the richest content of micropeloids (45 to 60%, rarely 73%) and the lowest percentages of microbial micrite (0 to 14%, up to 23%). Skeletal material is diverse (Fig. S19C). Subcluster E6 is characterized by an abundance of calcifoliids (20 to 50%), in some levels accompanied by abundant cyanobacteria fossils, aphralysiaceans and donezellids (Table 1; Fig. S18E and F).

Dasycladal-rich (cluster F)

This cluster is rarely present and has varied characteristics. Dasycladales can reach 40% (Fig. 4D), and oncoids 20%. Cement and micrite content vary one from another, as well as textures and fabrics (Table S1).

Micritic (cluster G)

The highest proportion of micrite is recorded in this cluster. Microbial micrite ranges from 20 to 70%, in some cases with moderate percentage of micropeloids and allomicrite. The skeletal content is moderate, with fenestellids as the only predominant bioclast.

There are two subclusters, with G1 containing the highest microbial micrite percentage and low to moderate skeletal material (Figs 4E, S19D and E), whereas G2 contains a higher skeletal percentage, including more abundant fenestellid bryozoans, crinoids, calcifoliids, red algae, donezellids and dasycladales (Fig. S19F).

Aphralysiaceans-cyanobacterial micritic (cluster H)

This cluster is rather similar to subcluster G2, rich in microbial micrites and skeletal components (Table 1; Figs 4F and 19G), but it is characterized by the common Aphralysiacean and cyanobacteria fossils. Domical and grumular growths are relatively common.

Allomicritic (cluster I)

This cluster is characterized by low cement (5 to 15%, rarely 20 to 30%). There is also high allomicrite (10 to 40%, but as low as 0%) and high skeletal plus non-skeletal contents (40 to 75%; Table 1; Fig. S4G).

Allomicritic mixed (cluster J)

This is the most heterogeneous cluster, and it is similar to cluster B. The main bulk of this cluster is composed of mixed facies (ca 40 to 50% of microbial facies), with laminar texture (Fig. 4H). Non-skeletal clasts are common and skeletal components are varied.

Calcifoliid-donezellid mixed (cluster K)

This cluster is composed also of mixed facies, where the microbial contribution is 30 to 40% of the total volume. Micropeloids, peloids and microbial micrites may occur, but, allomicrites are comparatively more important. The main contributors to the facies are the skeletal (50 to 70%) and non-skeletal clasts (0 to 30%; Table 1). The skeletal material is usually transported and accumulated in the allomicrite predominantly with packstone texture (Fig. S19H).

ENVIRONMENTAL PARAMETERS

Environmental controls discussed in this section are those that are deduced from the CCA performed on the database using palaeoecological knowledge of the skeletal components, as well as considerations of non-skeletal clasts.

Non-microbial facies

The main characteristic is the presence of intraclasts in the samples that, after removing the matrix, have a weighting of 77% in the variance of the samples over axis 1 (Fig. 5). In contrast, variation over axis 2 is smaller, and it only implies less than 22% of the variance.

The intraclastic rudstones or breccias (cluster A) are apparently the most uniform facies due to their similar percentage in components (Fig. 5), although three subgroups are distinguished. The first subgroup is composed of samples in the upper part of the Malac mound railway section (Coteau de Bergue Formation). They are characterized by an absence of micrite in the matrix and are exclusively composed of intraclasts of the same micropeloidal matrix as in the mound, and with sutured contacts. A second subgroup of breccias is composed of samples from the supposed palaeokarst at the Roc de Murviel section (Roque Redonde Formation), characterized by low percentages of micrite between the intraclasts, with a polymictic composition (Fig. S17A), as well as those from Castelsec quarry (Roc de Murviel Formation), also characterized by low percentages of micrite between the intraclasts, but they present a uniform composition of intraclasts (Fig. S17B), in mostly shallow-water platform-derived grainstones. Finally, the third subgroup of breccias is characterized by higher percentages of bioclasts and micrites and they occur separated from the rest (Fig. 5).

Multiple origins have been described for breccias associated with microbial mounds; nucleation beds, flank facies, intermound facies, off-bank facies, cap beds, debris flows, rock fall, collapse breccias, etc. (e.g. Lees and Miller, 1995; Della Porta *et al.*, 2003; Rodríguez-Martínez *et al.*, 2010; Waters *et al.*, 2017), although breccias of the Montagne Noire are commonly poorly exposed which complicate its interpretation.

Many breccias in the Montagne Noire are not differentiated by any particular feature; typical radiaxial fibrous calcite (RFC) cements around the boulders, or

fragments of cements are not recorded, nor any true matrix-supported breccias, which would suggest more debris flows are recorded. Their interpretation in the Montagne Noire is thus mostly based on the surrounding rocks and environments. Breccias located in the middle of microbial facies, such as in the La Boutinelle, Les Pascales and Tour de Castellas sections, could be interpreted as storm deposits, whereas those associated with olistoliths (Castelsec South) are related to the slope, due to fracturing during transport. On the other hand, the polymictic breccias at Roc de Murviel attributed by Poty *et al.* (2002) to a palaeokarst, could be indirectly produced also during remobilization by strong storms, with or without subaerial exposure.

The bioclastic wackestone to packstone facies (cluster B) is interpreted as outer platform deposits remobilized by storms (wackestone-packstone) to form typical tempestites (packstone), with an increase in the energy level, as well as the accumulation of more photic components in the same levels (foraminifers, Algospongia, dasycladales). The precise position in the CCA is not understood yet, because in the middle of axis 2 are located rudstones of the breccia, which are virtually devoid of bioclasts (Fig. 5). The variable that best explains the presence in axis 2 of packstone-rudstone with positive and neutral values, whereas wackestone-packstone has negative values with an abundance of allomicrite, is an indirect measure of light penetration or turbidity.

Other grainstone levels are considered to be shallow-water facies in the inner platform, affected by waves or tides, such as those oolitic-bioclastic grainstones-packstones from the Oolite de Roc de Murviel Formation at Roc de Murviel and La Rouquette sections, as well as those in the La Serre de Péret Formation at La Serre de Péret section (Vachard *et al.* 2017).

Microbially-induced and mixed facies

Distribution of skeletal components, non-skeletal clasts and matrix in these facies can be explained by five main factors (although, a sixth relevant factor could not be identified), explaining 82.3% of the variance, although factors 1 and 2 combined account for 53% (Figs 6 to 8).

When assessing these mostly physical factors, it has to be recognized that they are commonly interrelated, e.g., temporary material in suspension in the environment leads to turbidity (water clarity), which in turn affects the light penetration of the water column, and furthermore, the light penetration can be linked with the palaeobathymetry.

Turbidity

The dominant factor, axis 1, controlling 29% of the variance, is a quantification of the turbidity in the environments (as a measure of the clay and silt in suspension). The more turbid environments (situated in the negative part of the axis; Fig. 6) contain quartz grains, microbial micrites and allomicrites, as well as bioclasts (sponge spicules, red algae and aoujgaliids). It is noteworthy, that in contrast to many other mounds where the sponge spicules are associated with many well-preserved sponge bodies (e.g. Bourque *et al.*, 1995; Webb, 1999), the presence of sponge spicules in limestones of the Montagne Noire is low, although sponge bodies, have been recognized in places. This fact contrasts with the common sponge spicules in the pre-mound facies, even constituting spiculites in the black bedded chert of the Lydiennes Formation, as well as in green bedded chert of the Colonnes Formation (Cózar *et al.*, 2017). The red algae, mostly belonging to *Archaeolithophyllum* in the studied interval of the Montagne Noire, are well-known constituents of muddy and shallow-water environments (e.g. Toomey, 1979; Toomey and Cys, 1979). There are no detailed palaeoecological studies on the aoujgaliids, but as in Montagne Noire, they are abundant or occur with high biodiversity in muddy environments elsewhere in the Western Palaeotethys (e.g. Somerville *et al.*, 1996). The donezellids are the fourth type of bioclasts in the negative axis, comprising mostly *Kamaenella* and *Praedonezella*. Studies in shallow-water platforms in northern England and Ireland on *Kamaenella* highlighted the greater abundance of this taxon on muddy substrates (Gallagher and Somerville, 2003; Cózar and Somerville, 2005), even overlying microbial mounds (Horbury, 1992). There are no detailed studies on *Praedonezella*, but if it occupied a similar niche as its descendant in the Pennsylvanian, *Donezella*, they are common constituents in mounds and small bioconstructions with micropeloidal textures, but also in mud-rich shallow-water inner platforms (Choh and Kirkland 2006; and references therein). These bioclasts markedly occur associated with micritic textures (Fig. 6). Many of the levels with high values of turbidity are located in samples of the Roc de Murviel Formation.

On the opposite side of the axis are located the trepostomate bryozoans, associated with the cement and micropeloids. Consistently, the predominant textures are the micropeloidal cement-supported and cementstones, with similar presence of radiaxial fibrous and blocky cements (Fig. 6). The occurrence of trepostomate bryozoans does not seem to be very reliable, because they occur in only 22 levels, and one-half of them correspond to mounds in the Roque Redonde Formation characterized by the development of large cavities (stromatactis-like), although a significant number of samples correspond to the basal level of the Les Pascales North section. This group was considered as an opportunistic fauna in mounds (Pickard, 1992), but its interpretation is not sufficiently documented in such bioconstructions.

Gastropods and bivalves are localized and slightly separated from the above described elements (Fig. 6). Like most of the molluscs, they are usually associated with bright environments, and are commonly recorded more abundantly in the mound facies than in off-mound shaley sediments (Pratt, 1995). However, it is of particular interest that Lees *et al.* (1985) and Lees and Miller (1985) noted a relationship between the plurilocular foraminifers preceding the gastropods in the upper part of their phase C, and just before the micritization process in the photic levels of phase D. There is no agreement in the micritization process as a photic marker because this process has been observed down to 871 m depth (Hook *et al.*, 1984), whereas the plurilocular foraminifers in the Mississippian platforms seem to be limited to shallower than 140 m (Gutschick and Sandberg, 1983), in similar photic conditions as the green algae. The most frequent occurrence of those bioclasts is usually in mounds of the Roque Redonde Formation. Those bioclasts are mostly associated with shaley settings, suggesting a low rate of sedimentation, a fact that coincides with a high rate of background sedimentation being a negative factor for the growth of the microbial communities (Pickard, 1992; Keupp *et al.*, 1993; Leinfelder *et al.*, 1993).

Light penetration

The second factor in importance, controlling 24.2 % of the assemblage distribution is represented in axis 2 (Fig. 6), and interpreted as light penetration. This factor shows narrow variations compared to the previous one. Higher photic levels are located in the negative pole of the variance and contain aphralysiaceans, donezellids, cyanobacteria,

dasycladales, aoujgaliids and rugose corals, and also close by red algae. Some of those taxa also can be found in turbid environments (donezellids and aoujgaliids; see above). The traditionally well-recognized photic marker is the dasycladales, in which living species are widespread in tropical to warm-temperate waters, most at 10 to 15 m depths (Berger and Kaever, 1992), whereas other green algae, e.g. the bryopsidales, have been recorded in water depths down to 140 m (Hillis-Colinvaux, 1986). *Koninckopora* is the most widely recorded dasycladal in traditional Mississippian mound models, considered as a photic marker (Somerville *et al.*, 1992, 1996; Lees and Miller, 1995), although other authors interpreted their thalli as platform-derived material (Bridges and Chapman, 1988; Rodríguez-Martínez *et al.*, 2010). This taxon is recorded only in the Roc de Murviel Formation, although other dasycladales are as abundant in the Roque Redonde Formation as in the Roc de Murviel Formation.

Cyanobacteria, aphralysiaceans and red algae are well known to develop at least in dysphotic environments, although, they are also common in shallower euphotic water. The cyanobacteria *Girvanella* is common in shallow water, in protected lagoons in the Mississippian mounds of Northern Ireland, and also the red alga *Archaeolithophyllum* (Somerville *et al.*, 1996), as well as *Aphralysia* in northern England (Adams, 1984). In consequence, there is evidence of the abundance of those taxa in photic conditions in other mounds of relatively similar age. However, in the Montagne Noire, the concentration of most of those taxa in a more photic position of the axis is related to their occurrence in the Roc de Murviel Formation, where *Girvanella*, dasycladales, rugose colonial corals, *Praedonezella* (donezellid) and *Sparaphralysia* (aphralysiacean) are common. Even assuming more turbid environments for this formation, it is clearly a shallower setting than the Roque Redonde and Coteau de Bergue formations, and with higher light penetration, and thus, the assemblages developed completely in euphotic conditions.

Intraclasts are located in the positive extreme, which is interpreted due to its complete independence of the photic level, which coincides with the less photic levels. There is an inverse relationship between the percentage of intraclasts and skeletal content, and some samples with many lithoclasts have virtually no bioclasts at all.

In the positive part of the axis, fenestellid bryozoans, crinoids and trilobites are localized. Associated with these bioclasts are recorded concentrations of *Saccamminopsis*, although in this case, due to the fragmentary nature of this possible bryopsidale, it is most likely transported. The position of the fenestellids and crinoids in the deeper and lower photic levels of most mounds is a common feature known in the literature (e.g. Lees and Miller, 1985, 1995; Bridge *et al.*, 1995; Gutteridge, 1995; Pratt, 1995), with their first appearances ranging from aphotic to dysphotic settings, and also depending on the stage of preservation. Fenestellid sheets and intact crinoids are usually deeper/aphotic, whereas more fragmented material is recorded in higher/shallower dysphotic levels (Lees and Miller 1995; Gutteridge, 1995; Somerville *et al.*, 1996). In the case of the Montagne Noire, the assemblages are usually composed of fragmented bryozoan sheets in the Roque Redonde section (except for marly intervals and bed surfaces where zoaria are larger), suggesting that they occupy dysphotic settings. A possible interpretation of an upper aphotic setting more than dysphotic could be discussed, because strictly, and assuming that the bryopsidales are transported, the rest of the bioclasts could be developed in aphotic settings. However, common foraminifers are recorded close to the axis, and the abundance of those can be only in shallower and more photic settings, mostly because most of the foraminiferal assemblages are composed of autochthonous specimens, and transported specimens are negligible.

A typical aphotic setting might be located only in the positive extreme, with the upper boundary of this setting located above the position of the bivalves in Fig. 6, although those settings in the Montagne Noire might also correspond to dysphotic conditions. From the latter, up to the position of the red algae on the axis, could be readily considered as the dysphotic zone, or even also including the rugose corals, whereas only the left part of the axis could be attributed to typical euphotic conditions.

Bathymetry

The third factor (axis 3 in Fig. 7) controlled 10.5% of the variance. Ignoring the position in the positive extreme of the peloids (a mathematical artifact due to its abundance in some beds of the La Serre section), the remaining bioclasts in this positive axis suggest a relation to bathymetry. This is supported by the idea that quartz grains, brachiopods, red algae and foraminifers are more abundant in the shallower water facies, such as those represented by the typical Roc de Murviel Formation, as well as the hybrid facies

localized in the Tour de Castellás section. In the negative part of the axis, this factor seems to be confirmed by the higher abundance of sponge spicules, intraclasts, aphralysiaceans (in particular *Aphralysia*), microbial micrites, micropeloids, cyanobacteria (in this case *Renalcis* and *Ortonellopsis*) and heterocorals. This latter group is mostly recorded in the typical mound facies of Coteau de Bergue and Roque Redonde formations.

Brachiopods are more commonly present in shales and siltstones than in pure limestones (Gutteridge, 1990, 1995), and they are particularly abundant in platform facies. However, foraminifers and red algae are present mostly in shallow platform facies (Toomey and Cys, 1979; Somerville *et al.*, 1996). A detailed analysis of the foraminiferal families or genera has not been undertaken, but there are high percentages of representatives of the family Lasiodiscidae, ubiquitous Endothyridae and Tetrataxidae in the Roque Redonde Formation, families typically represented in quiet low-energy environments and mound facies (cf. Gallagher, 1998; C3zar and Rodr3guez, 2003). The Roc de Murviel Formation is characterized by common foraminiferal families/subfamilies such as Endothyridae, Archaediscidae, Endothyranopsinae, Palaeotextulariidae and Eostaffellidae, commonly present in subtidal settings (in some cases protected areas behind shoals) (C3zar and Rodr3guez, 2003).

It is noteworthy that most allochems are located in intermediate positions, for instance, fenestellids associated with dasycladales, suggesting that the absolute water depth was not very important, and most of the microbial communities in the Montagne Noire developed in relatively shallow-water settings.

Energy: storms

The fourth factor (9.6 % of the variance) is a measure of the energy in the environment, not of constant, but sporadic energy, which could be attributed to storms. In the positive part of the axis occur quartz grains, aoujgaliids, donezellids and allomicrite, followed by the bryopsidales, heterocorals, ostracods and micropeloids (Fig. 7). Analysis of these components shows that they are mostly concentrated in some horizons, and not uniformly distributed in each horizon. In the following levels, intraclasts, peloids, foraminifers and rugose corals co-occur. These assemblages are typical of the levels in the Roc de Murviel Formation, including also levels in Tour de

Castellas, where levels of higher energy are marked by the above-listed clasts, as well as by the mixed facies. Microbial micropeloids and peloids are the most surprising elements, but they are also rather abundant in the same levels, in some cases showing laminar microfabrics. This suite of components suggests that ostracods, as microorganisms, were also easily transported, just as with the small foraminifers.

On the opposite side, the aphralysiaceans, encrusting bryozoans, red algae and grapestones are located, followed by the trepostomate bryozoans, bivalves and dasycladales. The controlling factor suggests that they were not favoured by unstable conditions in the environment, being widespread in more constant currents. Clearly, they did not flourish under the same current conditions, because some of them seem to be better adapted to more turbulent environments (see factor 5 below), whereas others (e.g., trepostomate bryozoans, dasycladales, grapestones and bivalves), were more abundant in tranquil energy levels, mostly in the typical facies of the Roque Redonde Formation.

Energy: currents

The fifth factor (9 % of the variance, eigenvalue = 0.054342) is also related to the energy of the environment (axis 5; Fig. 8), but in a more restricted sense. In the positive part of the axis the grumelar and domical microfabrics are located, including also components with laminar growth, such as the aphralysiaceans, red algae, encrusting bryozoans, as well as quartz grains, followed by rugose corals, intraclasts, aoujgaliids, donezellids, allomicrite and sponge spicules. The laminar growth exhibited by the fauna situated in the positive extreme can be related to the most energetic currents within the relative quiescence of the microbial communities. In part, they can be compared with laminar growth at the top of reefs, and similarly, such structures have been interpreted as a shallower, more photic and more energetic part of the growth in ancient carbonate mounds (Somerville *et al.*, 1996; Shen *et al.*, 2010). The occurrence of some intraclasts in this assemblage could be partly misleading due to a relative influence or coexistence with the input of the storms in the environments (e.g., quartz grains, aoujgaliids and donezellids) and, furthermore, most of the sponge spicules are also concentrated, although they are in no case abundant. Those assemblages are most typically represented in the Roc de Murviel Formation.

808 Solitary rugose corals are present in the coral assemblages recorded through the
809 carbonate mounds, with local biostromes composed mostly of colonial rugose corals.
810 The colonial rugose corals generated stronger and more rigid structures with the
811 microbial communities and carbonate precipitates anchoring the colonies on the hard
812 substrate. The calcification of microbial communities has been traditionally considered
813 rapid (Pickard, 1992, 1996) and thus, generating rapidly indurated or hard substrates
814 suitable for coral colonization, resulting in variegated types of biostromes and patch-
815 reefs (Aretz, 2002a; Aretz and Herbig, 2003). Furthermore, isolated colonies or
816 fragments of colonies also are recorded in the carbonate mounds. On the other hand,
817 solitary rugose corals are commonly associated with muddy environments and soft
818 substrates (apart from tolerating more turbid and deeper-water environments), because
819 they have no calcified anchoring systems, and they may be partly buried in soft
820 substrates to keep the right growth position (not anchored) or the precipitated small
821 encrustations on hard substrate or bioclasts (Neuman, 1988). Muddy substrates did not
822 occur in the carbonate mounds, and their original soft substrates should have been that
823 of the microbial communities after the early calcification, and thus, the solitary corals
824 were growing penecontemporaneously with the microbes.

825
826 In the negative values of this factor, most bioclasts are concentrated with little
827 variation, including trepostomate bryozoans, bivalves, fenestellid bryozoans and
828 gastropods, together with microbial micrites and grapestones. This is a typical suite of
829 clasts recorded in the Roque Redonde Formation, with many cements, fenestrae and
830 micropeloidal cement-supported fabrics.

831 *Undetermined factor*

832 There is a sixth factor that influenced the assemblages and clasts (4.4 % of the
833 variance), but this factor could not be identified. In the positive part of the axis
834 cyanobacteria, red algae, peloids, intraclasts, micropeloids, microbial micrites and
835 aphralysiaceans are recorded (Fig. 8). In the negative part of the axis quartz grains,
836 aoujgaliids, bryopsidales, sponge spicules, donezellids, allomicrite, dasycladales and
837 heterocorals are recorded.

838
839
840 With the available data on palaeoecology of these precise biota, this order of
841 allochems does not suggest any trend, and it could be assumed that it may correspond to

small variations in factors, such as temperature, oversaturation, or many other factors that could have had an influence on marine biota and carbonate precipitation. Another possibility is the amount of oxygen in the environment, because in the negative part of the axis are most of the biota, whereas in the positive part of the axis only the cyanobacteria are observed, although this factor is not adequately resolved.

ENVIRONMENTAL GRADIENTS

The greatest palaeodepths occur mostly in the Coteau de Bergue Formation, represented in the Malac and Coteau de Bergue sections, and Roque Redonde Formation in Les Pascales South and Tour de Castellás 2 sections, whereas the shallowest settings are recorded in parts of the Roc de Murviel, La Serre, Roque Redonde and Coteau de Bergue sections. In those sections, shallowing-upward or deepening-upward sequences are recognized (Figs 11 and 12).

The Malac section (Fig. S6) contains the greatest palaeodepth, and the section is nearly completely developed in the outer ramp, with more than one-half of the samples containing the highest I_2 values for light penetration, which suggests that some of those could have been developed in aphotic conditions in the Mikhailovian, as well as for the Venevian (Fig. 11B). Similar I_3 values for the palaeobathymetry are recorded in the Coteau de Bergue section (Fig. S5) during the Aleksian, Mikhailovian and Venevian (Fig. 11A). However, there was a progressive shallowing event during the Aleksian, with the top sample reaching inner ramp settings, which also are recorded in the upper part of the Mikhailovian. The lower part of the Mikhailovian shows a rapid deepening event, which is similar to that observed in the Roc de Murviel section, where the oolitic bar represents the inner ramp setting in the upper part of the Mikhailovian and the shales below, the deepening event at the base of the Mikhailovian (Fig. S10). Only in the lower part of the Venevian, is recorded a possible aphotic level, whereas the rest of the section appears to be developed in transitional euphotic-dysphotic settings (Fig. 11A).

Low I_3 values are also recorded in the lower part of the Tour de Castellás 2 and Roc de Murviel sections during the Venevian of the Roque Redonde Formation (Figs 11F

and 12B), and middle Mikhailovian in Tour de Castellás 1 (Fig. 12A). However, analyzing the I_2 for light penetration, the assemblages appear to be developed in the transitional photic zone, suggesting that they were shallower settings than Malac and Coteau de Bergue sections. In addition, in the case of Tour de Castellás 1, microbial facies are commonly interbedded with tempestites, consistent with a much shallower setting within the middle ramp. In Roc de Murviel section, these low values for I_3 also coincide with high I_2 during the Venevian, suggesting that a significant part of the microbial mounds developed in deep-water outer platform and with dysphotic or even aphotic conditions. However, most samples of the Roc de Murviel section seem to be situated in an outer platform, in dysphotic to euphotic conditions. This scenario is rather similar in the section up to the analyzed levels for the Steshevian (Fig. 12B). Locally, at the top of the Venevian and base of the Steshevian, inner ramp deposits occur, which correspond to rapid shallowing events.

Low values of I_3 are observed also in Les Pascales South and La Boutinelle sections during the Mikhailovian and more rarely, during the Venevian in the Château de Cabrières section (Fig. 11C to E). In the case of Les Pascales South, I_3 suggests outer ramp settings for the Venevian and Tarusian, but in all the cases, the transitional euphotic to dysphotic conditions are the same (similar I_2 values). In La Boutinelle section, the low I_3 values during the Mikhailovian occur with multiple intermediate values, as well as samples developed in dysphotic conditions, according to the light penetration I_2 , with one sample reaching a value > 50 (Fig. 11D). This is probably a result of multiple fluctuations on the platform, which are not recorded in most sections containing Mikhailovian rocks. La Boutinelle also represents a deep-water setting in the outer platform, more so than other sections, such as Roc de Murviel during the Mikhailovian, but similar to that environment for the Venevian.

In contrast, the Château de Cabrières section shows fluctuations from the outer ramp (common) up to the inner ramp (rare) during the Venevian, and in terms of light penetration, samples range from dominantly dysphotic to dysphotic-euphotic (Fig. 11E). An important fact observed in the Château de Cabrières section is that, apparently, the Venevian could be represented by at least three main shallowing-upward events. However, due to the thickness of the section, and the low sampling interval, this number cannot be confirmed, but it could be the best criterion for the correlation of the numerous Venevian microbial mounds. In other sections of the Venevian, generally a

single deepening-shallowing cycle is recognized (or two in the Roque Redonde section) that does not occur in deeper environments, as in Coteau de Bergue, Malac and Roc de Murviel sections, where only one cycle is observed. Unfortunately, in most of those sections, it cannot be shown that a complete Venevian interval is present, because usually the base or top is absent. These types of cycles are more likely recorded in mid-ramp than outer ramp. These cycles are interpreted as third-order sequences based on the duration of the Venevian (2 Myrs; Davydov et al., 2012).

Also, the Roque Redonde Formation, Les Pascales North and Roque Redonde sections are mostly composed of samples with I_3 values ranging between 15 and 28, which are interpreted as mostly developed in the outer ramp and reaching more transitional settings frequently (Fig. 11G and H). The occurrence of palaeobathymetric I_3 values close to 30 in the lower part of Les Pascales North suggests a shallower water setting than for the rest of the mounds. It contrasts with some light penetration I_2 values higher than 32, in clearly dysphotic settings, even reaching values of 45 and 50, which could be interpreted as aphotic. However, both extreme values in I_2 and I_3 do not coincide exactly in the same levels (Fig. 11G).

The only unusual I_3 values for the Roc de Murviel Formation are observed in La Serre section, where there are high palaeobathymetric values, indicative of middle ramp settings, but also, higher photic fluctuations are observed from the dysphotic (invariably lower values than could be suggested as aphotic) to nearly euphotic (Fig. 12F).

The succession from the Aleksian to Protvian (Fig. 13) shows multiple deepening-shallowing (DS) cycles. Owing to the absence of a preserved platform, those cycles are difficult to interpret in terms of eustasy or tectonics. The Aleksian shows a shallowing sequence, the Mikhailovian has two DS cycles, the Venevian one, two or three DS cycles (depending on the section), the Tarusian a single deepening sequence that begins in the lower part of this substage, the Steshevian a single shallowing sequence (in this case Tarusian and Steshevian combined represent a DS cycle), and the Protvian a single DS cycle that ended the sedimentation on the platform. Although the Venevian seems to be represented by multiple cycles (which could be the only features to correlate more precisely the mounds), but as in the other substages, two cycles seem to be the most representative (Fig. 13). The most striking feature of those cycles is that the inflection

between the shallowing and deepening occurs in slightly older horizons than the recognized boundaries of the substages. This is true for all the substages, except for the Aleksian, where the change in the trend of the curve appears to occur just at the boundary between the Aleksian and Mikhailovian, and the Venevian in shallower environments. The comparison with the sequences in the South Russian platform (Kabanov *et al.*, 2016), where the control is eustatic, shows that there are 11 sequences in that platform, from the Venevian up to the Protvian (probably high frequency and fourth order sequences), and some sequences coinciding with the substage boundaries (Fig. 13). The platform of Montagne Noire does not show the same sequences, nor inflexions coinciding with the substage boundaries. These facts suggest a tectonic control of the deepening-shallowing sequences, mostly for the Serpukhovian succession of the Montagne Noire, whereas the late Viséan cycles coincide more with stage boundaries, and probably had a stronger eustatic control.

RECONSTRUCTIONS OF THE PLATFORM

Taking into consideration the above-described parameters, the main clusters are primarily conditioned by the amount of cement, and secondarily by the amount of micrite (microbial micrite plus allomicrite; Fig. S16); the palaeoecological factors that controlled the distribution of the main components are subordinate to those major clusters based on matrix percentage. Nevertheless, these palaeoecological factors have also a direct influence on the clusters (Figs S20 to S22).

Cluster C contains most of the samples in the less turbid environments, which also coincides with the levels recording higher proportions of cement. The same fact, although less marked, is valid for clusters D and E. In the case of cluster D, there is a small variation, with moderate to low turbidity environments. In the case of cluster E, the subclusters E2 and E5, which are mostly located in the positive and central part of axis 1 (Fig. S20), suggest that they are also rather cleaner environments. In contrast, the more turbid settings are the locations for clusters G (particularly subcluster G1), H, I and J, as well as subclusters E3 and E4, which essentially share the same values for the three clusters in the positive part of the axis. In that case, the turbidity of the water has a control on the configuration of the clusters. This suggests that the Roque Redonde

Formation developed in less turbid environments, whereas Roc de Murviel and Coteau de Bergue formations were deposited mostly in more turbid settings.

Axis 2 (light penetration) suggests that most of the samples are located in photic to dysphotic zones (negative values of the axis), where clusters H, J, K, most of cluster E, and one-half of the samples belonging to cluster G occur. In contrast, the less photic settings appear to be represented by cluster D (being more or less ordered from less photic D1, D2 to the more photic D3), nearly completely developed in aphotic settings close to the favoured position of the fenestellid bryozoans. Additionally, most samples of clusters C and I appear to correspond to this setting, ranging into the dysphotic setting (Fig. S15). A few samples of cluster G (mostly belonging to subcluster G2) also occur in dysphotic settings. In that case, the light penetration is not apparently a major control on the distribution of clusters. In contrast to the previous factor, the Roc de Murviel Formation was developed in more photic conditions than the Roque Redonde Formation, whereas the Coteau de Bergue Formation developed in alternating conditions.

Bathymetry does not appear to be a relevant factor for the clusters, as G1, G2, H, E4, E5 and D1 subclusters (with higher percentages in microbial micrite) are located in the negative part of axis 3 within deeper water conditions (Fig. S21), whereas D2 (higher skeletal components, with bryozoans and crinoids) and D3 (peloids), I, J and K occur in the positive part, in shallower-water settings. This suggests that the Coteau de Bergue Formation developed continually in deeper water settings, the Roque Redonde Formation in alternating deep to shallow settings, and the Roc de Murviel developed in shallower water settings.

The occurrence of accumulated storm debris suggests that the clusters with higher storm influence are I, J, K (mostly mixed facies, as was interpreted above), and some subclusters of E, such as E2, E3 and E5. In contrast, those with small storm influence are clearly H, but also C and G (Fig. S21). This factor has a higher influence on the Roc de Murviel Formation, but also a certain influence on the Roque Redonde Formation.

The final factor, turbulence, exerts a major control on samples belonging to cluster H (Fig. S22), wherein some of them are situated in a more energetic position of the axis,

but others are located in the negative part of the axis. Samples of clusters I and J also occur in the energetic settings of the positive part of the axis. In lower energy, there is a predominance of samples of clusters G and C, although some of the latter can be recorded in the positive axis. The centre of the axis is occupied by samples of clusters D and E, in intermediate regimens. Thus, this factor has a higher influence on Roc de Murviel and Coteau de Bergue formations, and less influence on the Roque Redonde Formation.

All these factors together with the detailed analysis of the vertical bathymetric and photic gradients suggest that the Coteau de Bergue Formation developed in the deepest water setting, with high turbidity and low light penetration, and relatively low influence of storms and current energy. The Roque Redonde Formation developed mostly at intermediate palaeodepths with low turbidity, variable conditions of light penetration, low influence of storms and current energy (except for some subclusters, E2 to E4). The Roc de Murviel Formation developed in a shallower setting, with high turbidity, high light penetration and high storm and current energy influence.

The change between the small domical and laterally-accreted mounds into thin stratiform microbial platform carbonates in the Montagne Noire is interpreted as a response to multiple palaeoecological factors. These mainly correspond to turbidity and light penetration, and secondarily, bathymetry and energy, which highlight the main differences between the Coteau de Bergue/Roque Redonde and Roc de Murviel formations.

Massive bioconstructions in most large Waulsortian banks were favoured by upwelling currents on the margin of outer ramps, and the same is true for some large late Viséan mounds (see Jeffery and Stanton, 1996b). However, the microbial communities of the Montagne Noire; (i) did not form such large buildups; (ii) are composed of more photic components (even the laterally-accreted mounds), and appear to have developed in shallower water settings from their bases; and (iii) are associated with even shallower water settings in the stratiform beds of the Roc de Murviel Formation. These points suggest that the microbial communities occurred in shallower water on the ramp, and the origin for the nutrients could be related to siliciclastic input. However, for the studied interval, siliciclastic environments are mostly recognized in

the area from the late Serpukhovian, owing to the mélange of siliciclastic materials in the flysch, and it is difficult to recognize possible autochthonous shales and siltstones incorporated in the flysch (Engel *et al.*, 1982, Vachard *et al.*, 2017).

On the other hand, the higher abundance of storm events in the Roc de Murviel Formation also suggests that the previous factor can be simply bathymetry, and that this formation was situated between the storm-weather and fair-weather wave-base levels. This contrasts with the occurrence of storm events in the Coteau de Bergue and Roque Redonde formations, that apart from some breccias in the mounds, have negligible storm influence, with evidence of energy restricted to some remobilised sediments, local disarticulation of bioclasts and local accumulations of some other clasts.

The turbidity or the material input in the basin is a limiting factor for the growth of the microbial communities, and thus, the higher turbidity in the Roc de Murviel Formation is also interpreted as a limiting factor for the development of large buildups within this formation.

The absence of flank facies in the Coteau de Bergue and Roque Redonde mounds is noteworthy. Different orientations of the base of the stromatactis-like cavities suggest slight palaeodips in the buildups. However, the absence of reworked flank facies suggests that mounds did not reach major highs above the sea floor, as has been recognized in the Roc de Murviel section (Fig. 3C). The preservation of these palaeodips was possibly due to the rapid cementation of the microbial communities (Pickard, 1992). The apparent domical form currently observed in some of the mounds thus may be a temporary appearance, only observed in the smaller mounds; they coalesced rapidly with each other forming larger buildups, where lateral growth was also an important component or even more important than vertical growth (Fig. 3C).

Another important point is the absence of intermound facies, where wackestones to grainstones are rare, and mostly restricted to periods associated with the base and top of the succession or storm events. This type of facies is rather abundant in many other mound complexes (e.g. Bridges and Chapman, 1988; Pickard, 1992; Somerville *et al.*, 1992, 1996; Waters *et al.*, 2017), and facilitated the reconstructions of the surrounding environments to the buildups. The virtual absence of this type of facies in the Montagne

Noire suggests that the buildups were growing directly on the shales and siltstones (Fig. 14) that constituted most parts of the platform, also including possibly, the unrecognized inner ramp setting spanning the developments of the microbial communities. In the case of the Roc de Murviel, they were growing at the same time as siliciclastic material was arriving into the area, and even, coral biostromes did not achieve high topographic relief above the sea floor, as suggested by their tabular outcrops. The thick buildups of the Roque Redonde Formation, without significant highs, suggest that it was a balanced growth of the microbial communities with subsidence or eustatic sea-level rises in the area, and that they never reached very deep conditions, nor shallower, as to be periodically affected by storms. They, likewise, did not develop flank facies.

There are two problematic issues to consider that are closely related to the fragmentary outcrops of the olistoliths. First, is the Roc de Murviel Formation invariably in contact with the Roque Redonde Formation and second, did the Roque Redonde mounds form a continuous belt in the outer platform or did they constitute multiple buildups separated by fine siliciclastic sediments? Basically, both questions arise, because of the uncertain role of the shales and siltstones in the platform. The Roc de Murviel Formation is only in contact with the Roque Redonde Formation in two sections, suggesting that although it is possible for a direct transition between the formations, they were probably mostly separated by shales in the platform and most rarely in direct contact. In contrast, there is no evidence that individual buildups of the Roque Redonde Formation were separated by shales or that they constituted an elongate belt parallel to the coast. Furthermore, although some shales and siltstones consumed by the flysch have been recognized, in most cases, they could not be dated, and there is no way to know if contemporaneous latest Viséan-early Serpukhovian siliciclastic sections existed. In the base of the succession, as in Les Pascales South section, buildups are interbedded with shales. In contrast, in the middle part of the Roc de Murviel section, where bedding planes suggest small domical mounds (metric-scale), there is no evidence of siliciclastic facies in between, nor high abundance of siliciclastic rocks within the Roque Redonde Formation. These latter two facts likely suggest that they originally constituted a continuous belt in the outer platform, mostly during the most prolific period for the development of mounds in the Venevian-Tarusian interval (Fig. 14B).

Within the outer platform, there are some stratigraphic sections that might represent the most distal parts, such as Château de Cabrières and Coteau de Bergue, which seem to be mostly developed in dysphotic conditions, and even in some cases reaching euphotic conditions, generally associated with the Coteau de Bergue Formation. These mounds could be developed on the shelf break. This is also valid for some parts of other sections, such as the lower part of the Roc de Murviel and Les Pascales North sections, which seem also to be dominated by the same dysphotic conditions. However, the most puzzling section is that of Malac railway, which apart from predominant dysphotic settings, contains one of the lowest bioclastic content, higher intraclastic content and breccias at the base and top of the mound complex. This is probably the deepest section studied in detail, and it could have been deposited at the shelf break, as well as on the uppermost proximal part of the slope due to the occurrence of the breccias (Fig. 14A and B), although this is the only stratigraphic section that presents such a feature. Unfortunately, stronger schistosity in the entire Roquessels Complex (Fig. 1) does not facilitate determining if changing oriented planes in infillings and supposed flat surfaces represent primary palaeodip feature or the result of epimetamorphism. Thus, a generalized growth of the microbial buildups in the proximal slope does not seem to be plausible, except perhaps in some particular sections (Coteau de Bergue Formation).

In the literature, there is a predominance of microbial carbonate mounds developed on the shelf break platform margin to upper slope (e.g. Ahr and Stanton, 1996; Stephen and Summer, 2003; Della Porta *et al.*, 2003, 2004; Shen *et al.*, 2010; Chesnel *et al.*, 2016). However, the possible reconstruction of the microbial carbonates of the Montagne Noire is closer to the reconstructions of Pickard (1992) or Cózar *et al.* (2006), where siliciclastic input from deltas had a predominant role in the distribution of the carbonate and microbial facies. Indeed, there are similarities with some of the facies types recorded in platform margin models (as facies A of Della Porta *et al.*, 2003 owing to their richer bioclastic content), but there are also notable differences. Internal ramps or slope facies have not been recognized, and thus, the growth of the microbial communities close to the shelf break is difficult to support above the Mikhailovian. Up to the latter substage, coeval rocks in the Montagne Noire are mostly represented by calciturbidites, carbonate breccias, shales and green cherts of the Colonne Formation, deposition attributed to slope and base-slope settings (Fig. 14A), and rarely, bioclastic

platform limestones of the Valuzières Formation (Cózar *et al.*, 2017; Vachard *et al.*, 2017). Mounds probably formed a belt, parallel to the coast up to the Tarusian (Fig. 14B), cut by canyons that fed the turbidites in the basin and developed in the outer ramp, in predominantly euphotic to dysphotic conditions, and rarely affected by storms. In contrast, the development of mounds during the Steshevian is scarce and absent in the Protvian, where the microbial tabular facies of the Roc de Murviel Formation is widespread on the platform (Fig. 14C). In southwest Spain (Cózar *et al.*, 2006), there is a predominance of argillaceous micropeloidal facies, whereas domical mounds are small and isolated, and they did not develop a continuous band over the shelf break. In contrast, in Scotland (Pickard, 1992) there is a continuous band in the shelf break, but it also developed common mounds in shallower settings. In both cases, and mostly for the shallower facies, the morphologies of the shallower microbial buildups were constrained by deltaic deposits. In the case of the southern Montagne Noire, deltaic deposits have been recognized for the late Serpukhovian (Fig. 14C), whereas their presence from older sections has been only inferred (Vachard *et al.*, 2017), and microbial facies and buildup distribution also suggest the occurrence of coeval deltaic systems. These mounds probably grew on the platform between the canyons and deltas that fed the turbidites of the Puech Capel to Fabrègues formations (Fig. 2) in the basin (Vachard *et al.*, 2017) during the late Viséan and early Serpukhovian.

Thus, the area up to the Mikhailovian interval seems to represent a platform morphology, with relatively narrow shallow-water settings, whereas during the Venevian to Protvian interval, it expanded with common shallow-water facies, which are interpreted to correspond to a ramp morphology or distally-steepened ramp.

CONCLUSIONS

The Late Mississippian platform from southern Montagne Noire is reconstructed from hundreds of olistoliths recorded in a flysch basin. Facies are predominantly associated with microbial communities, developing domical to laterally-accreted mounds in the lower part of the succession and thin-tabular or stratiform microbial geometries in the upper part. The petrographic study of 14 well-preserved, long stratigraphic sections within the olistoliths allowed primary subdivision of 35 components, matrix and cement elements, quantified in percentages by means of multivariate clustering (Q-mode). Two

non-microbial facies (clusters A and B), seven microbially-induced facies (clusters C to I) and two mixed facies (clusters J and K) were discriminated.

These factors are coupled with 22 features recognized in the samples, included in the database as binary data, with analysis by means of canonical correspondence analysis (CCA). Logs resulting from that analysis allow recognition of five main controls on the distribution of components, matrix and cement. These factors in decreasing order are interpreted to correspond to turbidity (axis 1), light penetration (axis 2), bathymetry (axis 3), storms (axis 4) and currents (axis 5). The projections of those factors over the axis were recalculated using maximum and minimum values to simplify the range of values from 0 to 100, giving some partial similar indices as those described by previous authors. The most interesting factors are the results of bathymetry and light penetration. Taking into consideration palaeoecological knowledge of the skeletal components, as well as considerations of non-skeletal clasts, axis 3 can be subdivided into deeper outer ramp, transitional zone and shallower mid-ramp settings. Similarly, axis 2 is subdivided into euphotic zone, transitional zone and dysphotic-aphotic zone. These indices are plotted with distance from the base of the logged sections, and give a relative position of samples. Of those, the index for axis 3 (bathymetry) provides a curve that is interpreted as shallowing and deepening cycles, allowing establishment of a preliminary sequence stratigraphy of the succession that cannot be recognized based on field observations. To interpret some of the local settings, information provided by axis 2 is necessary. Comparison of the curve produced by the shallowing and deepening cycles to that of the Russian platform suggests that tectonic control was more important than eustasy in the Montagne Noire platform.

All of the data are integrated in the reconstruction of the original platform which is no longer preserved intact. It evolved from (i) isolated and small mounds developed on a shallow ramp during the late Viséan (Aleksian-Mikhailovian) interval, with recognizable slope facies; to (ii) a significant development of laterally-accreted mounds on an outer ramp, situated below the storm wave-base to shelf break during the latest Viséan to early Serpukhovian (Venevian and Tarusian interval); and finally (iii) a predominance of stratiform microbial beds situated in the middle ramp, between fair-weather wave-base and storm wave-base, with only local mound developments in the outer ramp during the Serpukhovian (Steshevian and Protvian).

ACKNOWLEDGEMENTS

We thank B. Pratt as well as two anonymous reviewers for their helpful comments on the manuscript. Fieldwork for PC IS and IC was funded by the Spanish Ministry of Ciencia, Innovación y Universidades (project CGL2016-78738BTE).

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Captions

Fig. 1. (A) General location of the Montagne Noire in southern France. (B) Structural units and nappes in the Montagne Noire (for details of the units see Engel *et al.*, 1982 and Franke *et al.*, 2011). (C) Geological map of the Mont Peyroux nappe and Cabrières slices (for details see Vachard *et al.*, 2017).

Fig. 2. Lithostratigraphical reconstruction in the different blocks of the Mont Peyroux nappe and écaïlles de Cabrières. Structural blocks based on Vachard (1974).

Fig. 3. (A) Poorly defined bedding planes in a stacked mound in the Malac mound railway section. (B) Roquemallière Hill, with poorly defined bedding planes in the Roque Redonde Formation and the Roc de Murviel Formation in the upper part. (C) Lower part of the Roc de Murviel section looking from the north showing the laterally-accreted mounds of the Roque Redonde Formation; circled areas show outcrops with oolitic grainstones and packstones.

Fig. 4. Typical appearance of the microbial clusters (way-up to the top of the picture; scale bar = 2 mm). (A) Level RR4423, cluster C, intraclastic texture composed of bioclasts (brachiopods, fenestellids are observed) and large intraclasts (i) with micropeloids (m) and rare peloids (p) in the matrix passing into cementstones. The latter contains radiaxial fibrous (RF) and blocky (b) cements. Note the inverted geopetal filling (g) inside the small brachiopod in the lower right part of the picture. (B) Level SE5258, cluster D3, peloidal matrix-supported (p) and intraclastic (i) textures. (C) Level SE5256, subcluster E2, micropeloidal matrix-supported and cement-supported with common fenestrae filled by blocky cements and microbial micrites. (D) Level CsS4557, cluster F, dasycladales cementstone. (E) Level CB5386, cluster G1, microbial micrites with small micropeloidal areas and common cyanobacteria (*Ortonellopsis*) growths. Note the low degree of schistosity. (F) Level SE5252, cluster H, grumelular micropeloidal with oncoidal and domical growths. Cavities filled by micrites, micropeloids and blocky cement. Common encrusting of red algae (*Anchisolenopora*,

AN and *Archaeolithophyllum*, AR) and aphralysiaceans (*Aphralysia*, a), green algae (*Richella*, R). (G) Level RM4503, cluster I, micropeloidal cement supported in the base with cavities infilled by banded micrites. In the upper part, micropeloidal matrix-supported with areas filled by banded micrites similar to intraclasts, with a patchy distribution. (H) Level TC4712, cluster J, argillaceous wackestone to mudstone at the base passing into micropeloidal nodules (N) and bands (b).

Fig. 5. Canonical correspondence analysis (CCA) triplot for the clusters A and B over axes 1 and 2. Note - components in blue; textures and fabrics in red.

Fig. 6. Canonical correspondence analysis (CCA) triplot for the clusters C to K over axes 1 and 2. Note - components in blue; textures and fabrics in red.

Fig. 7. Canonical correspondence analysis (CCA) triplot for the clusters C to K over axes 3 and 4. Note - components in blue; textures and fabrics in red.

Fig. 8. Canonical correspondence analysis (CCA) triplot for the clusters C to K over axes 5 and 6. Note components in blue; textures and fabrics in red.

Fig. 9. Index (I_3) for the main components in the CCA over axis 3 and constituent graphs % = $f(I_3)$.

Fig. 10. Index (I_2) for the main components in the CCA over axis 2 and constituent graphs % = $f(I_2)$.

Fig. 11. Representation of the thickness of each section (in axis y, in metres), and the I_2 values for each sample on axis 2 (light penetration) and I_3 , corresponding to axis 3 (palaeobathymetry, including shallowing-deepening trends) for the Coteau de Bergue Formation (A - Coteau de Bergue and B - Malac sections) and Roque Redonde Formation (C - Les Pascales South, D - La Boutinelle, E - Château de Cabrières, F - Tour de Castellás 2, G - Roque Redonde and H - Les Pascales North sections).

Fig. 12. Representation of the thickness of each section (in axis y, in metres), and the I_2 and I_3 values (in axis x, and only up to 60 m) for axis 2 (light penetration) and axis 3

(palaeobathymetry, including shallowing-deepening trends) mostly for the Roc de Murviel Formation (A - Tour de Castellas 1, B - Roc de Murviel, C - Castelsec South, D - Roquemallière, E - Castelsec North, F - La Serre, G - Serre de Péret) (pale dots in Roc de Murviel and Roquemallière sections belong to Roque Redonde Formation).

Fig. 13. Main shallowing-deepening sequences recognized in the succession. Sequence in the Russian Platform (first column left) based on Kabanov *et al.* (2016).

Abbreviations for the sections: CB - Coteau de Bergue, CsN - Castelsec North, Ma - Malac mound railway, PaN - Les Pascales North, PaS - Les Pascales South, RM - Roc de Murviel, RR - Roque Redonde, ROQ - Roquemallière, Se - La Serre, Sp - Serre de Péret.

Fig. 14. Reconstruction of the platform from the Aleksian to Protvian. FWWB – fair-weather wave-base, SWB – storm wave-base

Table 1. Main lithological features of the clusters in the southern Montagne Noire.

Supporting Information

Table S1. Percentage of components of the selected samples from the southern Montagne Noire, classified after the sections. The distance (m) from the base of the section is y.

Fig. S1. Stratigraphic section of La Boutinelle.

Fig. S2. Stratigraphic section of Castelsec South.

Fig. S3. Stratigraphic section of Castelsec North.

Fig. S4. Stratigraphic section of Château de Cabrières.

Fig. S5. Stratigraphic section of Coteau de Bergue.

Fig. S6. Stratigraphic section of Malac mound.

Fig. S7. Stratigraphic section of Les Pascales South.

Fig. S8. Stratigraphic section of Les Pascales North.

Fig. S9. Stratigraphic section of Roc de Murviel.

Fig. S10. Stratigraphic section of Roque Redonde.

Fig. S11. Stratigraphic section of Roquemallière.

Fig. S12. Stratigraphic section of La Serre.

Fig. S13. Stratigraphic section of La Serre de Péret.

Fig. S14. Stratigraphic section of Tour de Castellás.

Fig. S15. Dendrogram with a multivariate clustering (Q-mode) using the Morisita coefficient with unweighted pair-group method using averages (UPGMA).

Fig. S16. Visual representation of abundance of components/matrix/cement of the clusters C to I.

Fig. S17. Typical appearance of non-microbial facies and clusters C and D (way-up to the top of the picture; scale bar = 2 mm). **(A)** Level RM5434, cluster A, rudstone with micritic, micropeloidal matrix-supported and peloidal textures. Note at the base large broken brachiopod. All the bioclasts are contained within the intraclasts with sutured contact, and there is no matrix. **(B)** Level CsN4556, cluster A, rudstone of large intraclasts composed of grainstone (upper left) and micropeloidal (lower right) (boundary between the lithoclasts marked with white arrows). **(C)** Level SE5268, cluster B, crinoidal-brachiopod argillaceous wackestone with slightly wavy orientation. **(D)** Level CsN4565, cluster B, *Praedonezella* packstone, *Algospongia* are all the small rounded and tubular forms (white arrow), encrusting bryozoans (b) and crinoids (c). Apart from those large skeletal components, the rest of bioclasts are well sorted,

fragmented, and parallel oriented. **(E)** Level R9, La Rouquette, oolitic grainstone with dasycladales and aoujgaliids in the core of the radial ooid. **(F)** Level RR4430, cluster C, coarse-grained bioclastic cement-supported, with thin rim of fibrous cement (arrows) and widespread blocky cements, with encrusting, coatings and oncoidal structures. There are micropeloidal cement-supported textures (m) distributed in patches. **(G)** Level RR4452, cluster C, fenestellid cementstone with rims of radiaxial fibrous (RF) and massive blocky (b) cements. **(H)** Level RM4508, cluster D1, intraclastic micropeloidal matrix-supported passing to the upper part to cement-supported. Large cavities with a thin RF cement passing into large infillings of banded micrites and micropeloids.

Fig. S18. Typical features of clusters D and E (way-up to the top of the picture; scale bar = 2 mm). **(A)** Level RM4509, cluster D1, intraclastic cementstone forming slightly domical structures. In the middle, there are rims of fibrous cements (arrow) and blocky. “Intraclasts” are micropeloidal, with a low density of peloids. **(B)** Level CSn4545, cluster D2, bioclastic peloidal cement-supported, with laminar growths. Rare large stromatactis-like cavities with microbial micrites and RF and blocky cements. Common small fenestrae in the lower part with blocky cement. **(C)** Level CsN4555, cluster D2, peloidal and micropeloidal matrix-supported, highly bioclastic in the lower part (ostracods, foraminifers, dasycladales), with common biofilms around the bioclasts. Cavities are limited to small fenestrae with blocky cement. **(D)** Level CsS4546, cluster E1, micropeloidal cement-supported with common cyanobacteria (*Renalcis*, lower right), many fenestrae and stromatactis-like cavities filled by RF and blocky cements. Fibrous (f) developed rims in some cavities, oolitic-like, previously to the infilling by microbial micrites (am). **(E)** Level SE5250, cluster E6, boundstone of calcifoliids (*Falsocalcifolium*) passing into micropeloidal matrix-supported with common small cavities with micritic infillings and blocky cement. **(F)** Level CsS4540 cluster E6, small olistolith (cluster A) with internal cluster E6, micropeloidal matrix-supported with large stromatactis-like cavities with micropeloidal infillings and blocky cement. Note *Aphralysia* (a) and *Girvanella* (g) encrusting *Fasciella* (f). **(G)** Level CsS4530, subcluster E2, micropeloidal to peloidal matrix-supported with fenestrae filled by blocky and fibrous cements. Microbial micrite is common in the cavities and in the matrix. **(H)** Level SE5269, subcluster E3, micropeloidal matrix-supported with many allomicrite (al). Small fenestrae filled by blocky cement.

Fig. S19. Typical features of clusters E, F and G (way-up to the top of the picture; scale bar = 2 mm). **(A)** Level BOU4626, subcluster E4, micritic textures with a predominance of microbial micrites (au) and allomicrites (al) in the upper part. Note micropeloidal cement-supported textures in the lower left corner, and radiaxial fibrous and blocky cements in the upper right corner. **(B)** Level BOU5378, subcluster E4, micropeloidal matrix-supported with common microbial micrites. Fenestrae are mostly filled by radiaxial fibrous cements. Large shells are gastropods, and grapestones are concentrated in the upper part of the picture. **(C)** Level BOU5376, subcluster E5, micropeloidal cement-supported texture with small fenestrae randomly distributed (filled by blocky cement). **(D)** Level RR4454, cluster G1, microbial micrites with rather abundant bioclasts (mostly fenestellid bryozoans, base of the picture, solitary rugose coral and ammonoids in the left) with large cavities filled by RFC and blocky cement. In the middle of the RFC foraminifers and bryozoans are recorded. **(E)** Level BOU4651, cluster G1, laminar growths and large cavities at the upper part. Patchy distribution of micropeloidal areas embedded in micrites. **(F)** Level CB5383, cluster G2, micropeloidal matrix-supported passing into clotted cement-supported. There are numerous cavities with micritic infilling and blocky cement. Strong schistosity. **(G)** Level SE5266, cluster H, banded microbial micrites with domical growth in some areas and bands of argillaceous dolomicrites. Large cavities with dolomicrites and blocky cements. Large encrusting of bryozoan (b) and aphyralysiaceans (*Sparaphralysia*, S). **(H)** Level CsS4551, cluster K, packstone of *Praedonezella*.

Fig. S20. Canonical correspondence analysis (CCA) for the clusters C to K over axes 1 and 2.

Fig. S21. Canonical correspondence analysis (CCA) for the clusters C to K over axes 3 and 4.

Fig. S22. Canonical correspondence analysis (CCA) for the clusters C to K over axes 5 and 6.