1 **SPATIAL AND TEMPORAL DISTRIBUTION OF MICROBIAL CARBONATES AND**
2 **OF SKELETAL AND NON-SKELETAL GRAINS IN A PENNSYLVANIAN**
3 **CARBONATE PLATFORM (VALDORRIA, NORTHERN SPAIN)**

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13
14 **ABSTRACT**

15
16 The Valdorria carbonate platform, in northern Spain, features a well-preserved
17 and continuous outcrop of a Bashkirian platform to basin transect. During the Asatauian
18 (late Bashkirian), the platform growth changed gradually from a progradational to an
19 aggradational mode, recording 10 most likely short-eccentricity-controlled cyclothem.
20 The facies of the platform-top and slope have been mapped, and the architecture of each
21 cyclothem schematically reconstructed. The distribution of microbial carbonates

(microbially mediated precipitates), skeletal (grazers/burrowers, corals/filter feeders, algae, foraminifera, *Osagia*-like oncoids and *Thartarella-Terebella* worm tubes) and non-skeletal grains (faecal pellets) has been quantified for the transgressive–regressive periods of deposition (transgressive, maximum flooding, early and late regressive intervals) of each cyclothem.

This study shows that the distribution of microbial carbonates and of skeletal and non-skeletal grains along a carbonate platform transect is variable through time and mainly governed by a set of measurable interconnected factors regulating the local palaeoenvironments: the water depth and the wave energy (facies) along the platform profile (inner, outer, break, slope) during periods of sea-level fluctuations (transgressive to regressive intervals of deposition). Auloporid corals, siliceous sponges, phylloid algae and *Osagia*-like oncoids are characteristic of a low-energy environment situated from estimated palaeo-water depths of 25 to 80 meters below sea level (mbsl onward) that formed in the outer platform during the maximum-flooding intervals. *Anthracoporella*–*Archaeolithoporella* boundstone is characteristic of the moderate-energy environments created in the horizontal inner-platform during the transgressive intervals. Microbially mediated precipitates are reliable indicators of the slope and *Masloviporidium*(?) indicator of low-energy environments of the upper slope. On the platform-top, *Ungdarella* and *Donezella* are more abundant during the early regressive interval than during any other interval. Stacheoids are mainly present in the water depth range of 10 to 60 mbsl, tournayellids from 15 to 35 mbsl and archaediscids from 15 to 75 mbsl, all in low- to moderate-energy conditions. Rugose corals are common in the water depth range of 5 to 35 mbsl, either during the transition from the early to the late regressive intervals, as solitary forms or forming boundstone, or during periods of higher sea-level stand, as solitary forms in floatstone. Fenestellids, fistuliporids and

trilobites occur mainly in the slope, but are also common in the platform top during the maximum flooding and/or the early regressive intervals. *Archaeolithoporella* is a reliable indicator of the platform top deposits, but its abundance is closely linked to the presence of adequate substrates. A high abundance in the assemblage of gastropods, endothyrids, palaeotextulariids, bradyinids and fusulinids characterize the platform top shallow-water coated-grain grainstones formed under high-energy currents during the late regressive intervals. Tetrataxids act as encrusters on microbial precipitates of the slope or on phylloid algae and *Archaeolithoporella* of the platform top, but is also observed as nuclei of coated grains. Brachiopods are more abundant in low- to moderate-energy and 35 to 55 mbsl environments that prevailed during the transgressive intervals. Faecal pellets were commonly observed in low-energy environments, from 50 to 325 mbsl, at the platform break and in the slope, and the same applies for *Thartarella-Terebella* worm tubes that are virtually absent in high-energy deposits. Finally, crinoids, lasiodiscids and tuberitinids are randomly distributed and are not indicative of any specific environment.

The here well-constrained distribution patterns of microbial carbonates and of skeletal and non-skeletal grains in Valdorria outcrop hold the potential to serve as a reference for interpretation of depositional environments of other platforms using biota associations and depositional texture, particularly in regions where the platform geometry is not preserved or is not fully exposed.

1. INTRODUCTION

Many studies of the distribution of organisms in upper Palaeozoic carbonate-platform deposits are based on analyses of rock texture because the geometry, water depth, and/or facies belts of many outcrops cannot be accessed (Rácz, 1964;

Davydov and Krainer, 1999; Wahlman, 2002; among others). In spite of the fact that Pennsylvanian cyclic carbonate platform-top strata are widespread and well-studied across the world (see: Weller, 1930; Moore, 1931; Wanless and Weller, 1932; Heckel, 1986, 1994, 2008; Klein, 1992, 1994; Samankassou, 1997; Forke *et al.*, 1998; Malinky and Heckel, 1998; Proust *et al.*, 1998; Della Porta *et al.*, 2002b, 2004, 2005; Olszewski and Patzkowsky, 2003; Stamm and Wardlaw, 2003; West *et al.*, 2003; Kabanov *et al.*, 2006; Heckel *et al.*, 2007; Kabanov and Baranova, 2007; Blomeier *et al.*, 2009; Kabanov, 2010; Corrochano *et al.*, 2012a, b), only few studies have investigated the distribution of skeletal and non-skeletal grains within the transgressive–regressive trends of cyclothems (Heckel, 1986; Samankassou, 1997; Forke *et al.*, 1998; Della Porta *et al.*, 2005; Kabanov *et al.*, 2006; Blomeier *et al.*, 2009), or their lateral distribution across platform-to-basin profiles (West *et al.*, 2003; Della Porta *et al.*, 2005).

The Bashkirian Valdorria carbonate platform (Chesnel *et al.*, 2016a) exhibits a complete and well-preserved inner-platform to basin transect that allows investigating the lateral distribution of microbial carbonates and of skeletal and non-skeletal grains. The platform-top strata are well exposed along a continuous 2200m-long and 195–240 m-thick outcrop. These strata are grouped into 10 stacked ~123ky, most probably orbitally forced, transgressive–regressive cyclothems (Chesnel *et al.*, 2016b). This architecture is ideal for evaluating and quantifying the lateral distribution of microbial carbonates and of skeletal and non-skeletal grains in an inner-platform to lower-slope transect and their vertical distribution linked to the sea-level fluctuation within a sequence stratigraphic framework.

The aim of this study is to provide detailed data on the lateral and vertical distribution of selected carbonate components. Microbial carbonates and of skeletal and non-skeletal grains, including grazers/burrowers, corals/filter feeders, algae,

foraminifera, microbially mediated precipitates, *Osagia*-like oncoids, *Thartarella*-
Terebella worm tubes and faecal pellets have been identified and evaluated at different
levels. Their distribution scheme may facilitate the interpretation of depositional
environments, particularly bathymetry and wave energy, when applied to other
outcrops in which the geometry is poorly or not preserved. A further goal is to
demonstrate the importance of the effect of variations of palaeo-water depth and wave
energy on the distribution of carbonate components along the platform transect,
especially during transgressive-regressive intervals of deposition. This study can
provide further insights into variations of other parameters that are difficult to
constrain, such as temperature, salinity, pH, turbidity, light penetration or nutrient
availability. For example, in a low-energy facies prevailing in palaeo-water depth of 25
mbsl, the abundance of a carbonate component could differ if deposition occurred during
the maximum-flooding interval in the inner platform or during the early regressive
interval in the outer platform. This difference, apparently not related to water depth or
wave energy, could result from the creation of specific ecological conditions related to
changes in the local salinity, temperature or other parameters such as pH, turbidity, light
penetration or nutrient availability. Results of the present study provide insight into the
interpretation of large-scale sedimentary systems known only through well logs and
seismic profiles, in particular to constrain the depositional regime from lithofacies
and/or to predict the composition of rocks in distinct settings. The method of evaluating
both the lateral and the vertical distribution of components across a carbonate platform
may serve as an example for studies in other time windows.

2. GEOLOGICAL SETTING

The Cantabrian Zone is the foreland fold-and-thrust belt of the arc-shaped Variscan orogen in the North of Spain (Fig. 1A; Pérez-Estaún *et al.*, 1988; Gutiérrez-Alonso *et al.*, 2004). Prior to the tectonic deformation and during most of the Carboniferous, the zone formed part of a marine foreland basin several hundreds of kilometres wide in which microbial-dominated high-rising carbonate platforms developed (Eichmüller, 1985; Bahamonde *et al.*, 1997a, b, 2000, 2007, 2015; Della Porta *et al.*, 2002a, b, 2003, 2004, 2005; Kenter *et al.*, 2002, 2005; Merino-Tomé *et al.*, 2014; Chesnel *et al.*, 2016a). The Valdorria carbonate platform forms part of the Valdeteja Formation (Wagner *et al.*, 1971; see also Eichmüller, 1985) and developed during most of the Bashkirian in the southern branch of the Cantabrian Zone, in the Bodón-Ponga Unit (Fig. 1A; Alonso *et al.*, 2009). It is exposed in the Gayo thrust sheet, forming a continuous kilometre-long outcrop with nearly vertically rotated strata that show a W-E-oriented seismic-scale cross section of the platform (Fig. 1B-C), particularly of the eastern platform margin and the slope. Three progradational to aggradational growth phases (Fig. 1B-C) were recognized by Chesnel *et al.* (2016a). Phase I, dated to the Akavasian–Askynbashian, is dominated by a microbial-algal-bryozoan eastward-prograding platform-margin–slope. Phase II, the focus of the present study, dated to the Asatauian, shows 2 km-long progradation of the east platform margin combined with platform aggradation leading to the development of thick platform-top deposits. Primary horizontally bedded inner-platform strata, up to 6° eastward-dipping outer-platform strata (with respect to the original horizontal bedding in the horizontal-bedded Barcaliente Formation), platform-break and slope strata can be recognized (see Chesnel *et al.*, 2016a and their Fig. 2). These deposits exhibit 10 well-defined kilometre-wide cyclothems ranging in thickness from 3 to 60 m (Fig. 1C; see Chesnel *et al.*, 2016b).

Phase III, dated to the Asatauian to Vereian transition interval, exhibits a 535 m-thick aggrading microbial-boundstone body that lacks clear stratal patterns or facies changes.

3. METHODS

The relative abundances of microbial carbonates and of skeletal and non-skeletal grains were estimated in a total of 339 thin sections taken along 10 stratigraphic sections measured in a well-exposed and continuous 2200-m-long and 195–240 m-thick outcrop representing an inner-platform to lower-slope transect of the eastern margin of the platform, and covering all the cyclothems comprised in Phase II (Fig. 1B-C). All *in situ* and reworked components were visually counted in a 7.5 cm² thin-section surface (Tab. 1). To minimize the number of criteria and to avoid over- and under-estimation of large and small grains, visual estimations were preferred to the common point-counting and volume percentage methods (see Tab. 1). However, a visual volume percentage method was preferred for microbial carbonates, occurring as boundstone, crusts or patches of clotted peloidal micrite and, therefore, impossible to evaluate by counting (absent = 0%; rare = 1–25%; common = 26–50%; abundant = ≥51%). For each defined interval of deposition (transgressive, maximum flooding, early and late regressive intervals) and for the 10 cyclothems of Phase II, the distribution was represented laterally on schematic reconstructions of the platform sedimentary profile, following mean relative abundance estimations (Tab. 2).

The variations in shape (length and thickness) of the 10 cyclothems were reconstructed on the basis of a detailed mapping of stratal surfaces and lithofacies and of a detailed correlation of the logged stratigraphic sections (see Chesnel *et al.*, 2016a and their Fig. 2). This approach allowed correcting the effects of minor faulting

and of subtle changes in the bedding attitude revealed by the gently curved pattern of the horizontal-bedded strata. The underlying isopachous Barcaliente Formation was considered as the palaeo-horizontal substrate. The obtained cyclothem architectures allowed characterizing the sedimentary profile for each cyclothem along the studied inner-platform to slope transect.

The palaeo-waterdepth, expressed as metres below sea level (mbsl), was then estimated geometrically along the transect of each interval of deposition, inferred from palaeo-waterlevel above the horizontal inner-platform-top area. Aware of recent conclusions about the care to be taken in establishing facies/water-depth relations (Purkis and Vlaswinkel, 2012), estimations of the waterdepth on the innerplatform were performed following the facies and lithofacies descriptions and interpretations in Chesnel *et al.* (2016a), along with the relative thickness or absence of typical deposits (Tab. 3) and estimated values for the amplitude of Bashkirian eustatic sea-level fluctuations(Rygel *et al.*, 2008).

Four algal types and the worm tubes have been quantified at the genus level (*Ungdarella*, *Archaeolithoporella*, *Masloviporidium*(?), *Donezella* and *Thartarella-Terebella*). The algae resembling the former genus *Stacheoides* are grouped here under the generic name “stacheoids”. All other components are grouped at a higher rank, such as family for the bryozoans (fenestellids and fistuliporids) and auloporid corals. Most of the foraminifera are grouped under the following informal names: fusulinids, tetrataxids, tournayellids, lasiodiscids, tuberitinids, archaediscids, endothyrids, palaeotextulariids and bradyinids, which commonly include high-rank taxonomic categories (families, superfamilies or even orders). Besides the order (rugose coral, dasyclads), other higher ranks used also refer to the class (trilobites, gastropods, crinoids) and the phylum (brachiopods). Other widely descriptive and generic names

are used (siliceous sponges, phylloid algae, *Osagia*-like oncoids, microbially mediated precipitates and faecal pellets).

The percentages of relative abundance of microbial carbonates, skeletal and non-skeletal components were calculated along the entire Phase II platform-top to slope transect (n=339 thin sections) and within each defined platform setting (see Fig. 1B-C; innerplatform: n=83; outerplatform: n=187; platformbreak: n=26; upperslope: n=28; lowerslope: n=15). The mean relative abundance estimations (Tab. 2) of each component were later analysed to obtain relevant information about the distribution across the inner-platform to lower-slope transect, and through the intervals of deposition of each cyclothem.

4. CYCLOTHEM GEOMETRIES

The geometries and the stratigraphic frame obtained for the 10 cyclothems of Phase II along the studied inner-platform to slope transect exhibit a horizontal inner platform, an outer platform with a primary dip reaching up to 6° (Tab. 4) and a relatively deep platform break located at 25–75 m below the level of inner-platform strata, similarly to the Sierra del Cuera platform (cf. Della Porta *et al.*, 2004). The width of the outer platform increases from cyclothem C1 to C10. The slope dip tends to decrease with time, but this could be biased by the proximity of the Correcilla thrust fault and by the outcrop orientation with respect to the progradation direction (Chesnel *et al.*, 2016a). The main features of the inner-platform to slope transect for the 10 cyclothems are summarized in Table 4 and discussed below.

Cyclothem 1 (C1) is laterally continuous from platform top to lower slope (Fig. 1B-C). The micro-/lithofacies, mainly composed of skeletal packstone 'sPG' in the inner

to outer platform top and *Donezella*-rich boundstone 'Bd1' at the platform break (for 'sPG, 'Bd1' and all other facies, see Chesnel *et al.*, 2016a for detailed descriptions), do not permit the distinction among the transgressive, maximum flooding and regressive intervals, although the late regressive interval is represented by a thick and continuous coated-grain grainstone 'cG' bed (Fig. 1B). C1 displays a platform margin progradation of 680 m, a decrease of the outer-platform and upper-slope dips with time and a steepening lower-slope dip (Tab. 4). It is noteworthy that during transgression to early regression, the slope height, measured from the platform break to the basin floor reaches 300 m. The slope height of the late regressive interval cannot be accurately calculated due to the lack of clear continuity with basin deposits (Fig. 1C).

In cyclothem 2 (C2), the micro-/lithofacies, mainly composed of nodular mudstone–wackestone 'nMW' in the inner to outer platform top and *Donezella*-rich boundstone 'Bd1' at the platform break, do not permit the distinction among the transgressive to early regressive intervals. Those of the late regressive interval are identified by a lateral variation, from inner platform to platform break, successively composed of coated-grain grainstone 'cG', nodular mudstone–wackestone 'nMW' and *Donezella*-rich boundstone 'Bd1'. The depositional geometry is inherited from that of C1 (Fig. 1C and Tab. 4). The slope evolves towards a gentler dip with time (Tab. 4).

Cyclothem 3 to 5 (C3 to C5) and 6 to 7 (C6 to C7) all comprise the transgressive, maximum flooding, early and late regressive intervals. They form two groups with distinctive geometries (Tab. 4). In the transgressive intervals, their inner to outer platform top is mainly composed of nodular mudstone–wackestone 'nMW' and nodular floatstone 'nFl', and their platform break by a transition from 'nMW' to *Donezella*-rich boundstone 'Bd1'. In the maximum-flooding intervals, their inner to outer platform top is mainly composed of 'nMW' with intercalations of 'nFl' and mudstone-algal mats 'mAM'

(in C3 and C6), and their platform break by a transition from the latest's to 'Bd1'. In the early regressive interval, their inner to outer platform top is mainly composed of skeletal packstone 'sPG' with intercalations of *Ungdarella* boundstone 'Bd3b' (in C6 and C7), and their platform break by a transition from the latest's to 'Bd1'. In the late regressive interval, their inner to outer platform top is mainly composed of coated-grain grainstone 'cG', and their platform break by a transition from the latest to 'sPG' and 'Bd1'. The geometry of the first group exhibits a horizontal inner-platform top and an outer-platform top dipping from about 5 to 6° (Tab. 4). That of the second group exhibits a wider outer-platform top, divided into a western gently dipping area (from about 2 to 3.5°) and an eastern steeper area (from 5 to 5.5°). The upper-slope dip decreases from C3 to C5 and becomes even gentler in C6 to C7 (Tab. 4).

Cyclothem 8 (C8) also exhibits the four intervals of the transgressive–regressive deposits. In the transgressive interval, its inner platform is composed of nodular mudstone–wackestone 'nMW' and *Anthracoporella-Archaeolithoporella* boundstone 'Bd3a', and its outer platform of nodular mudstone–wackestone 'nMW' in the shallower area and of *Donezella*-rich boundstone 'Bd1' in the deeper area. In the maximum-flooding interval, its inner to outer platform top is mainly composed of 'nMW' with intercalations of nodular floatstone 'nFl'. In the early regressive interval, its inner to outer platform top is mainly composed of skeletal packstone 'sPG' with intercalations of *Ungdarella* boundstone 'Bd3b'. The regressive interval exhibits an eroded inner-platform-top area and coated-grain grainstone 'cG' in the outer platform. The overall geometry of C8 is similar to that of C7, also showing a decrease of the outer-platform dip (Table 4).

Cyclothem 9 (C9) records the transgressive interval only in the eastern area of the outer-platform top (Tab. 4), mainly composed of *Donezella*-rich boundstone 'Bd1'.

The maximum-flooding interval is registered in the whole transect, mainly composed of nodular mudstone–wackestone ‘nMW’ with intercalations of *Ungdarella* boundstone ‘Bd3b’ and auloporid boundstone ‘Bd4b’. The regressive interval exhibits skeletal packstone–grainstone ‘sPG’ with intercalations of nodular mudstone–wackestone ‘nMW’ and coated-grain grainstone ‘cG’ in the inner platform. The absence of a typical cyclothem-capping ‘cG’ layer does not permit to divide the regressive deposits into early and late intervals. In the maximum-flooding interval, C9 exhibits a steep western (about 11°) and a very gentle eastern (about 0.5°) outer-platform area (Tab. 4). These dips decrease in the regressive interval to become gentle in the western area and horizontal in the eastern area (Table 4).

Cyclothem 10 (C10) records a transgressive to maximum-flooding interval composed of skeletal packstone–grainstone ‘sPG’ and nodular mudstone–wackestone ‘nMW’ with intercalations of *Ungdarella* boundstone ‘Bd3b’ and auloporid boundstone ‘Bd4b’, and a maximum-flooding to regressive interval mainly composed of ‘nMW’ and siliceous sponge-phylloid algal boundstone ‘Bd2’. A major disconformity cuts the top of C10 across its entire length and features calcrete and karst. Most of the inner-platform deposits of C10 have been eroded and transported to the eastern slope of the platform (see Chesnel *et al.*, 2016a), precluding a reliable assessment of the distribution of organisms.

5. LITHOFACIES DISTRIBUTION WITHIN INTERVALS OF DEPOSITION

5.1. Transgressive intervals

The transgressive intervals are represented by four characteristic lithofacies types. The first two are deposited above the underlying subaerial exposure surface of

previous cyclothemtop (Fig. 2A): 1) up to 10 m-thick *Donezella*-rich boundstone 'Bd1' (Fig. 2B) and 2) up to 30 cm-thick brecciated deposits composed of subangular lithoclasts formed by 'Bd1', nodular mudstone–wackestone 'nMW', and coated-grain grainstone 'cG' with a packstone–grainstone matrix containing sparse rugose corals, brachiopods, crinoids, dasyclads and benthic foraminifera (Fig. 2C). These brecciated deposits are a lateral equivalent of, or grade rapidly into, 3) 'nMW' (Fig. 2D) and, rarely, into 4) *Anthracoporella*–*Archaeolithoporella* boundstone 'Bd3a' (Fig. 2E), reaching a total maximum thickness of approximately 3 m.

Donezella-rich boundstone 'Bd1' was most likely deposited in deep semi-restricted to open platform-top environments, whereas the brecciated deposit is an inward lateral equivalent that was most probably formed due to wave ravinement (Cattaneo and Steel, 2003) in higher-energy shallow environments. The grading into nodular mudstone–wackestone 'nMW' and *Anthracoporella*–*Archaeolithoporella* boundstone 'Bd3a' likely reflects a rapid creation of accommodation space resulting in lower-energy environments (Chesnel *et al.*, 2016a).

5.2. Maximum-flooding intervals

Six lithofacies types were recognized. 1) Nodular mudstone–wackestone 'nMW' exhibits slightly more mudstones than that of the transgressive intervals and comprises the main lithofacies of the maximum-flooding intervals, being up to 30 m in thickness in cyclothem 9 (Fig. 2F). 2) Bioclastic nodular floatstone 'nFl' forms sparse metre-long and centimetre-thick discontinuous to continuous beds that exhibit either variable- or low-diversity bioclasts (i.e., crinoids, brachiopods, phylloid algae, auloporid or rugose corals; see Fig. 2G). 3) Massive mudstone–'undetermined' algal mats 'mAM' are kilometre-long and 0.8 to 1 m-thick beds that are present only in cyclothem C3 and

C6 (Fig. 2F-H; see also Chesnel *et al.*, 2016b). 4) Auloporid corals boundstone 'Bd4b' form sparse patches mainly in the upper deposits of the maximum-flooding intervals (Figs. 2F and 3A). 5) *Ungdarella* boundstone 'Bd3b' are 0.5 to 3 cm-thick discontinuous beds that generally appear in the upper deposits of the maximum-flooding intervals and in the early regressive intervals of cyclothems C6 to C9 (Figs. 2F and 3B). 6) Siliceous-sponge and phylloid-algal boundstone 'Bd2', which form a 5 to 8m-thick unit that includes 15 to 20 cm-thick biostromes (Fig. 3C), occur only near the eroded top of the uppermost cyclothem C10.

Nodular mudstone-wackestone 'nMW' was likely deposited in inner to outer platform across a wide estimated palaeo-water-depth range, from 10 to 100 mbsl, in low-energy environments of the platform-top to platform break setting. By contrast, the bioclastic nodular floatstone 'nFl' is indicative of low- to medium-energy conditions in a more open marine setting. Mudstone-algal mats 'mAM' represents the lowest-energy environment of the platform top and is estimated to have been deposited during very specific periods, at approximately 30–65 mbsl. Auloporid corals boundstone 'Bd4b' is rare and usually surrounded by 'nMW', indicating that its presence is linked to deep and low-energy areas of the platform top. *Ungdarella* boundstone 'Bd3b' was likely deposited under low- to medium-energy conditions. This facies commonly marks the transition to decreasing rates of sea-level rise (see also Gallagher, 1998). The siliceous sponges–phylloid-algal boundstone 'Bd2', which is present in a single area and thought to have been deposited in a relatively deep and low-energy platform-top environment (Chesnel *et al.*, 2016a).

5.3. Early regressive intervals

The early regressive intervals are characterized by a change in bedding type, from nodular to massive (Fig. 3D), and are mainly composed of skeletal packstone–grainstone ‘sPG’ (Fig. 3E-F). The facies ‘sPG’ contains diverse bioclasts: crinoids, brachiopods, rugose corals, calcareous algae (*Donezella*, *Ungdarella*, and stacheoids), bryozoans (fenestellids and fistuliporids) and benthic foraminifera (fusulinids, endothyrids, bradyinids, palaeotextulariids, archaediscids, and tuberitinids). Rarely, the uppermost deposits of the early regressive intervals contain patches of rugose-coral boundstone ‘Bd4a’, which lack other organisms (Fig. 3G).

The skeletal packstone–grainstone ‘sPG’ has been interpreted to be a deposit of moderate- to high-energy environments (Chesnel *et al.*, 2016a) and is estimated to have formed in shallow to deep-water environments of the platform top at an estimated palaeo-water depth between approximately 10 and 50 mbsl. The rare occurrence of rugose-coral boundstone ‘Bd4a’, which is thought to have been deposited in a shallow subtidal environment, supports this assumption (Samankassou, 2003; Merino-Tomé *et al.*, 2009).

5.4. Late regressive intervals

The late regressive intervals are characterized by massive 0.1 to 2 m-thick beds that exhibit coated-grain grainstones ‘cG’ (Fig. 3D). These grainstones are mainly composed of ooids (0.1–1 mm), sparse oncoids with various nuclei, such as chaetetid, rugosa or crinoid bioclasts, and ooid-grainstone or mudclasts (Fig. 3H).

Coated-grain grainstones ‘cG’ have been interpreted to have formed in very shallow and high-energy environments on the platform top, at approximately ≤10 mbsl (Chesnel *et al.*, 2016a). Their occurrence in the deeper outer platform area (up to 50–75 mbsl) is most probably due to exportation during regressive intervals and progradation.

6. LATERAL AND STRATIGRAPHIC DISTRIBUTIONS OF MICROBIAL CARBONATES AND OF SKELETAL AND NON-SKELETAL GRAINS IN PLATFORM-TOP-TO-SLOPE DEPOSITS

The lateral distribution of microbial carbonates and of skeletal and non-skeletal grains for the transgressive, maximum flooding and early and late regressive intervals of deposition has been investigated individually for cyclothems C1, C2, C8, C9 and C10, and for the sets of cyclothems C3-C5 and C6-C7 (Figs. 4 to 13).

6.1. Grazers/burrowers

6.1.1. Trilobites

Trilobites appear in less than 8% of the studied samples (Fig. 14). They are exclusively found as 1 to 3 mm-long reworked skeletal grains (Fig. 15A). Throughout the depositional sequence of Phase II, they are more abundant in the lower-slope area (Fig. 16), below 150 mbsl of estimated palaeo-waterdepth (Fig. 4A-B). In the platformtop (Fig. 16), they occur mostly in nodular mudstone–wackestone ‘nMW’ in the outer-platform and the maximum-flooding intervals (Figs. 7B, 10B, 12B,13B and 17A). Very rare fragments are present in the inner platform, in ‘nMW’ of the transgressive interval and in skeletal packstone–grainstone ‘sPG’ of the early regressive interval of cyclothem C8 (Figs. 10A and 11A), and in coated-grain grainstone ‘cG’ of the late regressive interval of cyclothem C7 (Fig. 9B).

Although trilobites lived in a wide depth range, from shallow- to deep-ramp settings, depending on the species (Amati, 2004), in the studied example the distribution

of trilobites seems to follow specific ecological conditions that appear at overall relatively deepwater depth, as suggested by Gaines and Droser (2003). When occurring on the platform-top, trilobites are particularly common in nodular mudstone–wackestone ‘nMW’ that formed in low- to medium-energy conditions during the maximum-flooding intervals, between 15 to 80 mbsl of estimated palaeo-water depth in the outer-platform. The fragments observed in high-energy settings are likely transported bioclasts.

6.1.2. *Gastropods*

Throughout Phase II, gastropods are rare to common and present in approximately 30% of the studied samples (Fig. 14), usually as whole fossils or as fragments 0.5–2 mm in size (Fig. 15B). They occur in every defined facies types, intervals of deposition and platform settings (Figs. 4, 5A, 6 to 11, 12A and 13), but are more abundant in the platform-top strata than in the slope (Fig. 16). The highest occurrence of gastropods is encountered at estimated palaeo-water depth of 5 to 30 mbsl in the transgressive and late regressive intervals, respectively in nodular mudstone–wackestone ‘nMW’ and in coated-grain grainstone ‘cG’, with a slight increase in abundance towards the inner-platform area (Fig. 17B).

The highest occurrence of gastropods is in medium- to high-energy environments that prevailed in shallow-water (5 to 30 mbsl) areas during the transgressive and the late regressive intervals. The decreasing content observed in the maximum flooding and early regressive intervals is probably associated with deeper-water conditions and associated environmental changes (lower temperature, salinity, nutrient disposition). A previous study of gastropod fauna in Carboniferous black shales deposited at 100 to 200 mbsl (Nützel and Mapes, 2001) showed that these organisms lived in a wide range of

environments. Nevertheless, in our examples, the abundance appears to reflect a negative effect of changes in their preferred ecologic environment governed by deepening and lowering wave energy.

6.2. Corals/filter feeders

6.2.1. *Auloporidae* corals

Auloporidae corals are observed in approximately 2% of the studied samples of Phase II (Fig. 14), generally found in life position in small patches 2–10-cm thick (Fig. 15C). Auloporidae corals occur as boundstone 'Bd4b' within nodular mudstone-wackestone 'nMW', generally in the outer-platform deposits of the maximum-flooding intervals (Figs. 7B, 12B, 13B and 16) and rarely in the inner platform of cyclothem C10 (Fig. 13A). Their first occurrence is in C6–C7 and a peak appears in C9–C10 (Fig. 17C), at estimated palaeo-water depth of 30–80 mbsl.

Auloporidae corals seemed sensible to small changes in their environment. Indeed, the *in situ* framework of the colonies indicates the requirement of relatively low-energy conditions, which apparently mostly prevailed between estimated palaeo-water depth of 30 to 80 mbsl, in the outer platform, and during the maximum-flooding intervals. This distribution, together with the small size of auloporidae and their non-wave-resistant framework, is consistent with descriptions in previous studies (Flügel and Krainer, 1992; Davydov and Krainer, 1999; Samankassou, 2003; Merino-Tomé *et al.*, 2009).

6.2.2. *Rugosa* corals

Rugosa corals are observed in less than 5% of the studied samples (Fig. 14), mostly in the inner- to outer-platform areas (Fig. 16). They display three modes of occurrence: A) as solitary reworked skeletal grains (1 to 2 cm-wide and 1 to 5 cm-long;

Fig. 3F-H), generally observed in the inner to outer platform of the transgressive intervals in nodular mudstone–wackestone ‘nMW’ (Figs. 6A and 10A), and in the transition from the upper deposits of the early regressive intervals to the late regressive intervals in coated-grain grainstone ‘cG’ (Figs. 4B and 9B), at estimated palaeo-water depth of 5 to 25 mbsl. B) as closely packed reworked skeletal grains in floatstones ‘nFI’ (Figs. 2G and 15D), mostly observed in the inner to outer platform of the maximum flooding and early regressive intervals of C6 (Figs. 7B and 8B), at estimated palaeo-water depth of 15 to 35 mbsl. And C), as small bioconstructions ‘Bd4a’ (10 to 30 cm-thick; Fig. 3G) in the upper deposits of the early regressive intervals (Fig. 5A).

Sparse solitary and small bioconstructions of rugose corals are generally found in packstone–grainstone deposits and, thus, indicate moderate to high-energy environments that prevailed in shallow-water area. These conditions were apparently and generally fulfilled in the inner to outer platform during the transition from the early to the late regressive intervals. On the other hand, the unbroken rugose corals found in floatstones, which were deposited during periods of higher sea-level stand, are an indicator of a low-energy environment (Samankassou, 2003; Merino-Tomé *et al.*, 2009). The depth range reported in this study, from 5 to 35 mbsl, is in agreement with that of previous findings (5 to 40 mbsl in Wells, 1957; 10 to 30 mbsl in Stevens, 1966; 5 to 50 in Hill, 1981).

6.2.3. Siliceous sponges

Undifferentiated siliceous sponges are rarely observed in Valdorria (Fig. 14). They are bodies (1 to 20 cm in width and 1 to 5 cm in thickness) mostly found unbroken and in life position forming biostromes along with phylloid algae ‘Bd2’ (Figs. 3C and 15E), associated with nodular mudstone–wackestone ‘nMW’, in the outer-platform area,

and restricted to the maximum flooding to regressive interval of C10 (Figs. 13B, 16 and 17E) at about 45 mbsl.

As for auloporids, the ecological conditions favourable for the development of siliceous sponges seemed very specific. Indeed, the commonly associated nodular mudstone–wackestone ‘nMW’ lithofacies indicates a low-energy environment. This favourable environment apparently prevailed particularly in the flat outer platform area, at about 45 mbsl, during maximum-flooding interval of cyclothem 10. This observation is consistent with previous descriptions of siliceous sponges as organisms that develop principally in restricted to semi-restricted platform tops (Lane, 1981; Hurcewicz and Czarniecki, 1985; Carlson, 1994, Merino-Tomé *et al.*, 2009). A preference for deep or cold settings has also been suggested by Wahlman (2002). In Valdorria, the distribution of preserved siliceous sponges bodies might be affected by taphonomic processes, explaining their apparent absence in the slope. Indeed, the origin of many Carboniferous slope deposits has commonly been linked to carbonate precipitation mediated by microbial communities acting during the decay of dead siliceous-sponge bodies (Neuweiler, 1995; Neuweiler *et al.*, 1999; Warnke, 1995; Della Porta *et al.*, 2002a, 2003).

6.2.4. Crinoids

Crinoids are among the most common organisms in the Valdorria platform (Fig. 14), usually occurring as reworked millimetre-sized skeletal grains (Figs. 2C, D, G, 3F and 15F). They are present throughout the entire platform-to-slope transect, from 5 to 325 mbsl of estimated palaeo-water depth, and occur in every defined facies types and intervals of deposition (Figs. 4 to 13 and 16). However, they show a slight preference for the platform-top area, where they are abundant in 40–58% of samples (Fig. 16). On the platform top, crinoid abundance shows a minor decrease in the maximum-flooding

deposits (Fig. 17F), and a slight increase in the shallow-water deposits of the transgressive and regressive intervals (Fig. 17F).

In Phase II of Valdorria, crinoids did not seem to have to develop in any preferred environment and are not associated to any facies type. Thus, their distribution is not indicative of variations in wave energy, water depth, salinity or light penetration along the platform to slope transect. They live in all 'normal' marine environments, during all periods of deposition, as suggested in previous studies (Davydov and Krainer, 1999; Wahlman, 2002) and noted in many Palaeozoic skeletal carbonate mounds (see discussion in Hebbeln and Samankassou, 2015). However, crinoids appear to prevail in the platform top, from 5 to 80 mbsl of estimated palaeo-water depth, and particularly at the platform-break, where nutrient input was probably the highest. A comparable high abundance around the platform break has also been reported during platform aggradation (Della Porta *et al.*, 2004) and in late Viséan carbonates of Derbyshire (Harwood, 2005).

6.2.5. *Brachiopods*

Brachiopods are commonly found in the Valdorria platform (Fig. 14), usually as whole fossils or bioclasts, measuring from 0.5 to 4 cm (Figs. 2C, 3E and 15G). They are widely distributed across the platform-to-slope transect, from 5 to 325 mbsl of estimated palaeo-water depth, and occur in every defined facies types and intervals of deposition (Figs. 4 to 13 and 16). However, they show a slight preference for the platform-top area, where they are common in more than 50% of samples (Fig. 16). The brachiopod occurrence is highest in the transgressive deposits, reaching a peak at the platform break, at estimated palaeo-water depth of 35 to 55 mbsl (Figs. 6A-B and 17G). In the outer platform, the occurrence of brachiopods is steady through time. Nevertheless,

their occurrence decreases gradually in the inner platform, and abruptly at the platform break, from the transgressive to the late regressive intervals (Fig. 17G).

Brachiopods apparently lived at all depths of the platform-top to slope transect, from 5 to 325 mbsl of estimated palaeo-water depth, but were rare in the deeper-slope environments. Their preferred ecological conditions, observed in nodular mudstone-wackestone 'nMW', seemed to be fulfilled in the low- to moderate-energy environments of the platform top, mainly from 35 to 55 mbsl (10 to 20 mbsl in Harwood, 2005), which developed during the transgressive intervals. Accordingly, in the Tengiz platform, brachiopods were mainly observed in moderate to low energy in open platform or in shallow protected platform in skeletal packstone-grainstone (Kenter *et al.*, 2006). They are rare in very shallow shoal environments of the inner platform that prevailed in the late regressive intervals. Similarly, Merino-Tomé *et al.* (2009) and Martínez-Chacón *et al.* (2010) reported abundant brachiopods in mid-ramp settings of the nearby early Kasimovian Las Llaceras Formation, under open-marine and low-energy conditions. Also, in the Middle Pennsylvanian rock of central Colorado, the density and variability of brachiopods increase with water depth and distance from shore (from 4 to 22 mbsl) (Stevens, 1971). In Valdorria, as elsewhere in the Late Palaeozoic record, brachiopods grew in normal marine water (Davydov and Krainer, 1999; Wahlman, 2002).

6.2.6. *Fenestellid bryozoans*

Fenestellid bryozoans are common components of the Valdorria platform (Fig. 14), generally occurring as millimetre-sized reworked skeletal grains in the platform top and as whole colonies in the slope (Fig. 15H). Although they are well represented throughout the entire depositional sequence of Phase II and across the platform-top to slope transect, in every defined facies types and almost every intervals of deposition

(Figs. 4 to 8, 9B, 10, 11, 12B-C and 13), their occurrence is higher in the slope (Fig. 16) in peloidal micrite boundstone 'pBd'. In the platform top, they are commonly found at the platform break and in the outer platform, below estimated palaeo-water depth of 50 mbsl, with an abundance peak in the maximum-flooding intervals (Fig. 17H). They are, however, sparse in the maximum flooding and early regressive intervals in the inner platform.

Fenestellid bryozoans seemed to grow preferentially in low-energy and relatively deep-water environments that developed in specific periods. Indeed, fenestellid bryozoans, which occurred exclusively at estimated palaeo-water depth greater than 15 mbsl, and were generally abundant below 50 mbsl, grew mainly during the maximum-flooding intervals. This is further supported by the fact that in the platform top, at equal palaeo-water depth, the occurrence of fenestellids is highest in the maximum-flooding intervals compared to other intervals (Fig. 17H). The depositional environments located below the palaeo-water depth of 50 mbsl (in the slope and in outer platform and platform break of the maximum-flooding intervals) most likely matches their preferred trophic conditions and wave energy. As suspension feeders, fenestellids require nutrient-rich low-turbidity water to grow (Walker, 1972; Babcock, 1977; Flügel, 1981; Grünbaum, 1995), which is common in relatively deep settings (Wahlman, 2002). Moreover, thick bryozoan banks, which are not observed in Valdorria, are thought to form near the shelf margin (Nakrem, 2001).

6.2.7. *Fistuliporid bryozoans*

Although fistuliporid bryozoans are present throughout the whole depositional sequence of Phase II, except in C2, they are less abundant than fenestellids (Fig. 14). They generally occur as millimetre-sized reworked skeletal grains in the

platform top (Fig. 15I) and as small centimetre-sized colonies in the slope. They are most abundant in the slope, below estimated palaeo-water depth of 75–100 mbsl (Figs. 4A and 16). However, they are present in the platform top, but relatively rare, mostly occurring below estimated palaeo-water depth of 50 mbsl, in *Donezella*-rich boundstone 'Bd1' and nodular mudstone–wackestone 'nMW' (Figs. 7, 8, 10B, 11A, 12B–C, 13) that formed in the outer platform to platform-break areas during the maximum flooding and early regressive intervals (Fig. 17I). They occur very rarely in the transgressive intervals (Fig. 6B) and late regressive intervals (Fig. 9A), and are nearly absent in areas estimated to be shallower than 10–15 mbsl.

Fistuliporid bryozoans appeared to be sensible to variations of water depth and probably other parameters in their environment. Indeed, fistuliporids, which occurred exclusively at estimated palaeo-water depth greater than 15 mbsl, and were generally abundant below 50 mbsl, mainly grew during the early regressive intervals. Similar to fenestellids, this is supported by the fact that in the platform top, at equal water depth, the occurrence of fistuliporids is highest in early regressive intervals compared to other intervals (Fig. 17I), periods during which their preferred trophic conditions were probably best fulfilled at these depths. In Valdorria, fistuliporids mainly act as encrusters, in agreement with previous observations of fistuliporids interlayered with laminar encrusting red algae or in association with *Tubiphytes*, forming boundstones (Wahlman, 2002). They mainly encrust *Donezella* boundstone and peloidal micrite (Chesnel *et al.*, 2016a) as well as microbially mediated precipitates, in contrast to the observations of other studies (Mundy, 1994).

6.3. Foraminifera

6.3.1. *Tetrataxids*

Tetrataxids occur in 21% of the studied samples (Fig. 14), and are generally found encrusting microbially mediated precipitates or thalli of phylloid algae (Fig. 15J). Most of the tetrataxids are observed in the lower slope (Fig. 16), below estimated palaeo-water depth of 150 mbsl, in peloidal micrite boundstone 'pBd' (Fig. 4A), being rare in the platform-top transgressive to maximum-flooding intervals *Donezella*-rich boundstone 'Bd1' and nodular mudstone–wackestone 'nMW' (Figs. 5A, 6A, 7B, 10, 12B and 13), and sparse in the early to late regressive intervals skeletal packstone–grainstone 'sPG' and coated-grain grainstone 'cG' (Figs. 4B, 8, 9, 11 and 12C). They have also been found, very rarely, encrusted on, and covered by, layers of the alga *Archaeolithoporella*. However, they are observed in all cyclothems of Phase II (Fig. 17J). They are absent in the outer platform and at the platform break during the transgressive intervals. Their abundance increases from the transgressive to the late regressive intervals, except in the inner platform, where they remain rare (Fig. 17J).

The ecological requirements needed for the presence of tetrataxids were apparently not affected, or only slightly, by variations of depths along the platform-top to slope transect. Indeed, tetrataxids were observed from 5 to 325 mbsl of estimated palaeo-water depth, but were rare in the platform-top environments. They can be divided into two main groups that could most probably contain diverse species: (1) encrusters of microbially mediated precipitates seemed to prefer deep-water areas of the slope, below 150 mbsl, which is consistent with that of previous studies reporting higher abundances in deep and low-energy settings (below 200 mbsl; Lees, 1997). The encrustation of microbially mediated precipitates has also been reported by other authors (Cossey and Mundy, 1990; Mundy, 1994); (2) encrusters of phylloid and *Archaeolithoporella* algae found in the platform top, demonstrating that their living environment extended to shallower-water areas (Toomey and Winland, 1973;

Samankassou, 2001; Wahlman, 2002; Gallagher and Somerville, 2003). Other isolated tetrataxids forming rare nuclei of coated grains indicate that their living niches could also have extended to higher-energy environments, as observed by Mamet (1970). Other authors have, however, shown that tetrataxids can be found in diverse environments/substrates (Henbest, 1963; Cossey and Mundy, 1990; Poncet, 1992; Gallagher, 1997, 1998; Merino-Tomé *et al.*, 2009), and that the main limiting factor for their distribution may be the type of substrate (Vachard *et al.*, 2010).

6.3.2. *Tournayellids*

Tournayellids are present in approximately one-third of the studied samples (Fig. 14), usually found unbroken (Fig. 15K), most probably because of their small size (250 to 500 μm). Their abundance is relatively high in the platform top compared to the slope (Fig. 16). They occur throughout all settings, depths and described facies in the platform top (Figs. 4 to 11, 12B-C and 13), slightly increasing in abundance in the outer platform, while decreasing in the inner platform and platform break, from the transgressive to the regressive intervals (Fig. 17K).

In the Valdorria platform, tournayellids did not seem to have strong palaeoecological preferences. They were apparently present in low- to high-energy environments and in a wide range of estimated palaeo-water depth, from 5 to 100 mbsl. They are, however, mostly present in the narrow depth range of 15 to 35 mbsl corresponding to environments of medium energy. This narrow depth range might explain the observed opposite trends in abundance from the transgressive to the regressive intervals, decreasing in the inner platform and increasing in the outer platform. This finding is consistent with previously reported shallow-marine environments of deposition within wackestone to ooid packstone (Armstrong and Mamet,

1974) and carbonate/shale (Brenckle, 1997). However, it contrasts with previous interpretation stating that tournayellids probably inhabited the entire inner area of Mississippian ramps (Vachard *et al.*, 2010).

6.3.3. *Lasiodiscids*

Whereas lasiodiscids are commonly observed in the matrix of phylloid-algal boundstone in Phase III (Chesnel *et al.*, 2016a), they are rare in Phase II of Valdorria (Fig. 14), absent in C3 to C5 and in C10 (Fig. 17L). They generally occur as loose grains (Fig. 15L), not associated with any specific water depth, facies or interval of deposition (Figs. 4, 5B, 6B, 7B, 8B, 9B, 10A, 11A and 12B). However, they are slightly more frequent in the upper slope than in the platform top (Fig. 16). Their distribution in the intervals of deposition along the platform break, outer platform and inner platform is apparently random and does not follow any recognizable trend (Fig. 17L).

The random distribution of lasiodiscids suggests that the palaeoecological conditions needed for their presence were wide, extending from low- to high-energy environments, and apparently not affected by variations of the water depth along the platform setting during the changing periods of deposition. A similar distribution pattern lacking any preferred location, has been reported on the Sierra del Cuera platform (Della Porta *et al.*, 2005) and, for certain species, it may be due to a planktonic lifestyle (Rauzer-Chernousova & Chermnykh, 1990). However, it is still not clear if lasiodiscids were sessile or planktonic.

6.3.4. *Tuberitinids*

Tuberitinids are the most common foraminifers and organisms in the Valdorria platform, being present in approximately 95% and abundant in 72% of the studied

samples (Fig. 14). They are observed as loose grains in the matrix or attached to various substrates (Fig. 15M). Ubiquitous throughout all cyclothems in Phase II (Figs. 4 to 13 and 17M), they are however more abundant in the platformtop than in the slope (Fig. 16). They arecommon to abundant at all depth, in all platform settings, in every defined facies and in all intervals of deposition. They exhibit a lowdecrease atthe platform break from the transgressive to the regressive intervals of deposition and in the inner-platform in the late regressive intervals of deposition (Fig. 17M).

Observed in all types of platform-top to slope environments, from 5 to 325 mbsl of estimated palaeo-waterdepth, and in almost every studied samples, tuberitinids did not seem to have ecological preferences, and their occurrence seems independent of variations in waterdepth and wave activity along the platform setting,or to any other parameter. This isconsistent with previous studies reporting tuberitinids from deep-subtidal marginal environments, outer platform mounds and base of slope apron, in mudstone–wackestone, algal-foraminifera-crinoid packstone, bioclastic grainstone and microbial boundstone–floatstone (Harwood, 2005).

6.3.5. *Archaediscids*

Archaediscids are common foraminifera in the Valdorria platform (Fig. 14), present in all cyclothems in Phase II (Fig. 17N) and generally occurring as loose grains (Fig. 15N). They are more abundant in the platformtop than in the upperslope, specifically from 15 to 75 mbsl of estimated palaeo-water depthand are absent in the lowerslope. They are not associated to any specific facies or interval of deposition (Figs. 4 to 13 and 17N). They exhibit a decreasing trend in the platform-break deposits from the transgressive to the regressive intervals and a slight increasing trend in the inner-to-outer-platform deposits (Fig. 17N).

In the Valdorria platform, archaescids show a distribution similar to that observed in the Sierra del Cuera platform (Della Porta *et al.*, 2005), being more abundant in platform-top areas, from 15 to 75 mbsl of estimated palaeo-water depth, and in low- to medium-energy setting. In Valdorria, no thorough observations indicate that the small changes of ecological condition created through the transgressive–regressive periods of deposition played an important role on their presence and distribution. However, Gallagher (1997, 1998) estimated that the thickness of the test wall could play a role in their resistance to wave energy, based on the observation that archaescids are rare in algal-dominated faunas rich in crinoid and bryozoan thickets. Contrarily, Haynes (1965) and Brenckle *et al.* (1987) reported archaescids in symbiosis with algae and explained that their lenticular shape may be an adaptation to high-energy environments.

6.3.6. *Endothyrids*

Endothyrids are present in approximately 48% of the studied samples (Fig. 14), mainly as loose grains (Fig. 150). They are more abundant in the platform top than in the slope (Fig. 16), not associated to any specific facies (Figs. 4 to 13). Endothyrids are most common in the transgressive and the regressive intervals, showing a marked decrease across the whole platform-top transect in the maximum-flooding intervals (Fig. 170). They reach their highest abundance in the outer platform between estimated palaeo-water depths of 5 to 55 mbsl, mainly in the late regressive intervals (Fig. 170).

In Valdorria, endothyrids are observed in all environments of the Phase II platform top. However, their ecological preferences seem to be located in the shallow to medium depth, from 5 to 55 mbsl, observed in the outer platform during the late part of the regressive intervals. Similarly, Della Porta *et al.* (2005) in Sierra del Cuera platform observed the deposition of endothyrids primarily within skeletal–algal packstone–

grainstone and algal-skeletal packstone of the outerplatform, as well as in coated-grain grainstone. It is noteworthy to mention that in Valdorria the distribution of endothyrids appears to be negatively affected by sea-level rise leading to deeper and lower-energy environment (Skipp *et al.*, 1966; Idris and Azlan, 1989) during the maximum-flooding intervals. Consistently, a number of studies reported endothyrids in high-energy shallow environments (Ferguson, 1963; Skipp, 1969; Armstrong and Mamet, 1974, 1979; Haynes, 1981; Gallagher, 1998). This, however, contrasts with previous interpretations that the distribution of Endothyroidea is driven mainly by the type of substrate (Vachard *et al.*, 2010).

6.3.7. *Palaeotextulariids*

Palaeotextulariids are among the most common organisms of the Valdorria platform, being present in 63% of the studied samples (Fig. 14) and in all cyclothems of Phase II (Figs. 17P). They usually occur as loose whole or broken grains (15P), common to abundant in the whole platform-top, not associated to any specific facies (Figs. 4 to 13 and 18), and in all intervals of deposition (Fig. 17P). The highest abundance in the inner and outer platform is observed in the late regressive intervals, being present in 100% of the coated-grain grainstone 'cG' samples, which are estimated to have accumulated at palaeo-waterdepth of 5 to 10 mbsl. A decrease in their abundance is observed in the maximum-flooding intervals of the inner-platform area.

Palaeotextulariids occur across a wide depth range in the platform top, from 5 to 75 mbsl of estimated paleo-waterdepth. However, they are more common in the shallow subtidal environments of the inner-platform area, as reported by Gallagher (1997, 1998) and Gallagher and Somerville (2003) elsewhere. A similar distribution has also been reported for the Sierra del Cuera platform (Della Porta *et al.*, 2005), where

744 palaeotextulariids are common in algal–skeletal packstone and skeletal–algal
745 packstone–grainstone from deep to moderately deep environments of low- to moderate-
746 energy; they are also abundant in shallow high-energy, coated grainstone deposits. This
747 is in accordance with previous studies findings that the main limiting factor for their
748 distribution may be the type of substrate (Vachard *et al.*, 2010). This, however,
749 significantly contrasts with Stevens (1966) assertion that palaeotextulariids probably
750 lived at overall greater depths (50 to 70 mbsl), or with Stevens (1971) who did not
751 encounter palaeotextulariids from 0 to 15 mbsl and rarely from 15 to 22 mbsl.
752 Additionally, the decrease observed in the inner platform maximum-flooding intervals
753 remains difficult to explain, and would better be due to a combination of unfavourable
754 ecological conditions in terms of water depth, salinity, temperature, pH, wave energy,
755 nutrient availability and/or other parameters.

756 757 6.3.8. *Bradyinids*

758 Bradyinids are common organisms of the Valdorria platform (Fig. 14), reported in
759 all cyclothems of Phase II (Fig. 19A). They usually occur as loose whole or broken grains,
760 certainly due to their relatively large size (0.5–3 mm; Fig. 15Q), and are present in the
761 whole platform top, in all intervals of deposition, from 5 to 75 mbsl in every defined
762 facies (Figs. 4 to 11, 12B-C and 13). As for palaeotextulariids, the highest abundance in
763 the inner platform is observed in the late regressive intervals, being abundant in 100% of
764 coated-grain grainstone ‘cG’ samples, estimated to have accumulated at palaeo-
765 water depth of 5 to 10 mbsl (Fig. 19A). They are also abundant in the transgressive and
766 regressive intervals of the inner platform. However, they are nearly absent in the
767 maximum-flooding intervals of this setting (Fig. 19A). Bradyinids also show an

increasing trend in abundance in the outer-platform setting from the transgressive to the late regressive intervals.

Bradyinids occur in low- to high-energy environments, across a wide depth range in the platformtop setting, up to 75 mbsl of estimated palaeo-waterdepth, and in all intervals of deposition. The ubiquity of bradyinids in the late regressive coated-grain grainstone 'cG' deposits of the innerplatform, which clearly indicate agitated very shallow-water environments (5–10 mbsl of estimated palaeo-waterdepth), is in agreement with data from Gallagher (1998) and Della Porta *et al.* (2005), but in disagreement withStevens (1971), according to whom they are rare from 15 to 22 mbsl and absent from 0 to 15 mbsl. Additionally, their relatively high abundance observed in the upperslope(Fig. 4A) could be due to sediment transport from the platformtop, or to the fact that their distribution may be driven by the type of substrate (e.g. algae, Vachard *et al.*, 2010). The increase in abundance observed in the regressive intervals could be due to increasing wave energy associated to decreasing sea level. The decrease observed in the inner-platform maximum-flooding intervals remains difficult to explain, and would better be due to a combination of unfavourable ecological conditions in terms of water depth, salinity, temperature, pH, wave energy, nutrient availability and/or other parameters.

6.3.9. *Fusulinids*

Fusulinids are among the most common foraminifers and organisms in Phase II of Valdorria (Fig. 14), particularly in the platformtop where they occur in 81–84% of the samples (Fig. 18). They are present in all cyclothems of Phase II (Fig. 19B), generally occurring as unbroken loose grains (Fig. 15R). Their abundance in the inner- and outer-platform facies follows similar trends to those of endothyrids, palaeotextulariids and

bradyinids, being present from 5 to 75 mbsl, more common in the late regressive intervals and decreasing in number in the maximum-flooding intervals of the innerplatform(Figs. 4 to 13 and19B). The highest abundance is observed in the innerplatformduring the transgressive and late regressive intervals, being abundant in 100% of these samples.

Fusulinids occurprincipally in agitated environments, particularly in very shallow coated-grain grainstone 'cG'. However, theyalso occur in a wide range of estimated palaeo-water depth in the platform top, from 5 to 75 mbsl. This distribution is consistent with many other studies (Ross, 1961; van Ginkel, 1973; Toomey, 1983, Davydov and Krainer, 1999; Villa and Bahamonde, 2001; Della Porta *et al.*, 2005). Depending on the species and/or on the time slice of occurrence, fusulinids were apparently capable of living in all platform-top environments (Ross, 1965, 1969; Stevens, 1966, 1971; Dingle *et al.*, 1993; Gallagher, 1998; Baranova and Kabanov, 2003), but were most probably affected by changing water conditions, such as temperature, salinity, pH, turbidity or currents (Ross, 1969). Depending on the assemblage, fusulinids can also indicate cyclic recurrence and a response to sea-level and regional climate change (Khodjanyazova, 2014). In Valdorria, similar to palaeotextulariids and bradyinids, fusulinids increase in abundance in the regressive intervals, which could be due to increasing wave energy associated to decreasing sea level. The observed decrease in the maximumflooding inner-platform deposits, but not in outerplatform or platformbreak cannot be conclusively linked to increasing waterdepth or lower-energy, and would be better explained by local changes linked to unfavourable,yet unknown conditions.

6.4. Algae

6.4.1. *Dasyclads*

Dasyclads are rare organisms in the Phase II of Valdorria (Fig. 14), occurring as loose grains (Fig. 20A-B), predominantly in the inner-to-outer-platform areas (Fig. 18), in the nodular mudstone–wackestone ‘nMW’ of the transgressive intervals and in the skeletal packstone–grainstone ‘sPG’ of the early regressive intervals (Figs. 6B, 8A, 10A, 13B and 19C). They occur rarely in the coated-grain grainstone ‘cG’ of the late regressive intervals (Fig. 5B) and in the nodular mudstone–wackestone ‘nMW’ of the maximum-flooding intervals (Figs. 7 and 10B). They commonly form lenses of boundstone with a packstone matrix (specifically, *Anthracoporella* associated with the encrusting alga *Archaeolithoporella*; facies ‘Bd3a’) in the brecciated deposits of cyclothem C8 transgressive inner-platform interval.

In Valdorria, dasyclads are mostly restricted to moderate-energy and shallow-water environments, forming *Anthracoporella*–*Archaeolithoporella* boundstone lenses during the transgressive intervals. This finding contrasts with previous studies in the Carnic Alps and other settings, where *Anthracoporella* skeletal mounds formed widely in low-energy conditions (Flügel, 1987; Mamet *et al.*, 1987; Mamet, 1991; Krainer, 1995; Samankassou, 1998, 2001; Davydov and Krainer, 1999; Samankassou, 2003; Merino-Tomé *et al.* 2009). Nonetheless, Samankassou (2003) reported that *Anthracoporella* mounds grew during rising sea level, as observed in Valdorria. However, dasyclads remain poor indicators of a specific water depth range, or of any other parameters (Fig. 19C).

6.4.2. Phylloid algae

Phylloid algae are rare organisms in the Valdorria platform during Phase II (Fig. 14), occurring only in the platform top and mostly in outer-platform to platform-break settings (Fig. 18) of cyclothem C6, C9 and C10 (Fig. 19D). They reach their peak in the

outerplatform of the maximum-flooding interval of C10, forming boundstones along with siliceous sponges (facies 'Bd2'; Figs. 3C, 13, 19D and 20C), at estimated palaeo-waterdepth of 45 mbsl. They occur rarely as loose grains in the nodular floatstone 'nFl' (Fig. 20D) in the transgressive intervals (Fig. 6B) and in the other maximum-flooding intervals (Fig. 12B).

In the Valdorria platform, phylloid algae are characteristic indicators of a relatively deep and open platform top in a low-energy area, particularly when forming boundstones along with siliceous sponges (Chesnel *et al.*, 2016a). This observation is consistent with that of previous studies that interpreted the depositional area of phylloid algae as primarily including low-energy and well-lit water, but it contrasts with the usually accepted shallow-water setting (Toomey and Winland, 1973; Flügel, 1977; Toomey *et al.*, 1977; West, 1988; Roylance, 1990; Davydov and Krainer, 1999; Wahlman, 2002; Samankassou, 2003; Merino-Tomé *et al.*, 2009). The depth range (45 mbsl) is also consistent with previous estimations for the initiation of bioherms growth (30–40 mbsl; Soreghan and Giles, 1999), or for that of the modern analogues of *Halimeda* bioherms, which mainly grow at 20–50 m depth (Roberts *et al.*, 1988). Phylloid algae are also known to have developed in water depths ranging from 7 to >20 mbsl (Stevens, 1971).

6.4.3. *Ungdarella*

Ungdarella is relatively common in Phase II of Valdorria (Fig. 14), increasing in abundance from cyclothem C2 upward (Fig. 19E). It occurs nearly exclusively in the platform top (Fig. 18), from 5 to 75 mbsl, either as whole loose grains (0.1–1 cm-wide), or forming boundstone beds (facies 'Bd3b'; Figs. 3B and 20E). The alga increases in abundance in the early regressive intervals over the whole platform-top transect (Fig. 19E), especially from cyclothem C6 upward (Figs. 8B, 11A and 12C). It is also abundant

in the maximum-flooding intervals of cyclothems C9 and C10 (Figs. 12B and 13A). Its occurrence decreases in the late regressive intervals, reaching proportions similar to those observed in the transgressive intervals, except in cyclothem C8 where they are abundant (Fig. 11B) and in the innerplatform where they are almost absent (Figs. 5 to 8A, 9B, 10 and 13B). Their presence is also negligible in the innerplatform and platformbreak of the maximum-flooding intervals (Fig. 19E).

In the Valdorria platform, *Ungdarella* grew and formed boundstone beds in a wide estimated depth range from 5 to 75 mbsl, as observed in a review of Upper Carboniferous–Lower Permian deposits by Wahlman (2002). *Ungdarella* is found in settings of normal marine, low- to moderately agitated conditions, and occurs more commonly at the top deposits of the early regressive intervals, similarly as reported by Gallagher (1998). Consequently, in Valdorria, the most favourable conditions (temperature, salinity, pH, turbidity, light penetration) for the growing of *Ungdarella* were apparently fulfilled during the early regressive intervals, independently of wave energy and water depth variations along the platform top transect. Besides, the alga also seems to dislike the lowest- and highest-energy conditions encountered in the inner platform and at platform break during the late regressive and the maximum-flooding intervals, which contrasts with reports by Gallagher and Somerville (2003) where *Ungdarella* is thought to occur in a high-energy environment in the Visean of Ireland.

6.4.4. *Stacheoids*

Stacheoids are rare in Phase II of Valdorria (Fig. 14), occurring as loose algal thalli often reaching a width of 2–3 mm (Fig. 20F). Most of these organisms are present in the platform top (Fig. 18), mainly from 10 to 60 mbsl, and mostly in the outer-platform to platform-break areas, in nodular mudstone–wackestone ‘nMW’, *Donezella*-rich

boundstone 'Bd1' and skeletal packstone–grainstone 'sPG' (Figs. 6 to 8, 10, 11A, 12B-C and 13A). Their abundance strongly decreases at the platformbreak from the transgressive intervals upward (Fig. 19F). Stacheoids are virtually absent in the regressive intervals across the platformtop (Figs. 5B and 19F).

Stacheoids grew under low- to medium-energy conditions and were observed in a wide range of estimated palaeo-waterdepth along the platform-top transect, from 5 to 100 mbsl. However, they seemed to mainly occur between 10 and 60 mbsl, depths that were reached in the outer platform during the transgressive to the early regressive intervals and at the platform break during the transgressive to the maximum-flooding intervals. Besides, stacheoids seemed to have disliked the shallower water of the inner platform, the agitated environments of the coated-grain grainstone 'cG' and, in a wider range, the ecological conditions developed along the whole platform top during the late regressive intervals.

6.4.5. *Archaeolithoporella*

Archaeolithoporella is rare in Phase II of Valdorria (Fig. 14), mostly restricted to the inner to outer platform area, and nearly absent at the platform break and in the slope (Fig. 18). Its abundance increases in the upper cyclothem, reaching a maximum in cyclothem C8 and C10 (Fig. 19G). *Archaeolithoporella* appears from 5 to 100 mbsl, more abundantly distributed in the transgressive inner-platform deposits (Fig. 10A), encrusting dasyclads or brachiopods, and contributing to the formation of *Anthracoporella-Archaeolithoporella* boundstone 'Bd3a' (Fig. 2E). It can also be sparsely to commonly distributed in the maximum flooding outer-platform to platform-break nodular mudstone–wackestone 'nMW' deposits (Figs. 7A-B, 12B and 13B), encrusting auloporids, phylloids and siliceous sponges, and contributing to the

formation of *Osagia*-like oncoids (Fig. 20M-N). It is overall rare in the late regressive intervals (Figs. 5B and 11B) and absent in the early regressive intervals.

Archaeolithoporella is overall rare in Valdorria. This alga grew mainly in low- to high-energy and in shallow and deep environments, all along the platform top, during the transgressive, maximum-flooding and late regressive intervals. Its absence in the early regressive intervals could be explained by the absence of adequate substrates, the alga acting mainly as an encruster. This distribution is consistent with previous studies of *Archaeolithoporella* in reefs and/or high-energy environments (Flügel, 1981; Sano *et al.*, 1990; Wahlman, 2002) or developing in a reef to fore-reef under well-lit to poorly lit, low- to high-energy environments (Mazzullo and Cys, 1978).

6.4.6. *Masloviporidium*(?)

Masloviporidium(?) is present only in 4% of the studied samples (Fig. 14) and occurs nearly exclusively in the upper-slope setting (Fig. 18), between 75 and 250 mbsl of estimated palaeo-water depth (Fig. 4 and 5A). It commonly forms boundstones composed of delicate branches surrounded by a peloidal micrite matrix (facies 'pBd'; Fig. 20I-J). The alga is rarely observed at the platform break, within the transgressive interval of cyclothem C3, in nodular mudstone–wackestone 'nMW' (Fig. 6A), and very rarely in the inner platform deposits, within the early regressive intervals of cyclothem C3, C6 and C8, as broken thalli, in skeletal packstone–grainstone 'sPG' (Figs. 8 and 11A). It decreases in abundance from cyclothem C1 to C5 and is virtually absent in cyclothem C6 through C10 (Fig. 19H).

The *in situ* delicate framework of *Masloviporidium*(?) colonies indicates a relatively low-energy environment. However, the very rare occurrence of *Masloviporidium*(?), as broken grains, in skeletal packstone–grainstone 'sPG' is consistent with descriptions of

this alga in previous studies (Groves and Mamet, 1985). Besides, considering their abundance at water depth of 75 to 250 mbsl, which is mainly observed in the upper-slope setting, a relatively low light penetration and a reduced temperature and salinity (compared with the platform top) were probably required to fulfil their preferred growing ecological conditions. Furthermore, the high difference of abundance and style of occurrence observed between the upper slope and the inner platform could be explained by: (1) exportation of floating remains towards the platform top, (2) by two possible preferred growing environments, or (3) by the presence of two distinct species, yet undetermined.

6.4.7. *Donezella*

Donezella is the most common alga and a ubiquitous organism in Phase II of Valdorria, occurring in 67% and common to abundant in 58% of the studied samples (Fig. 14). It occurs at estimated palaeo-depths of 5 to 325 mbsl, in all described facies, and is particularly abundant in the outer-platform and platform-break settings, within *Donezella*-rich boundstone 'Bd1', but is also frequent in other facies of the inner-platform and in the peloidal micrite-rich boundstone 'pBd' of the slope samples (Fig. Figs. 4 to 13 and 18). It can occur *in situ* or as loose broken algal thalli (Fig. 20K-L). In the platform top, the peaks of abundance of *Donezella* are reached in the early regressive intervals, although it is commonly observed in other deposits (Fig. 19I).

The ubiquity of *Donezella* in Phase II of Valdorria agrees with previous findings showing that the alga is capable of living in various environments, from shallow to deep water, on the platform top and on the slope and in low- to high-energy settings (Della Porta *et al.*, 2002a). However, the present study documents an increase in abundance along the platform top in the early regressive intervals, suggesting that *Donezella* may

have had a preferred ecological environmentsomewhatcontrolled by relative sea-level fluctuation and its effect on other parameters other than water depth and wave energy.

6.5. Other microbial carbonates, skeletal and non-skeletal components

6.5.1. Osagia-like oncoids

The *Osagia*-like oncoids are rare in Phase II of Valdorria (Fig. 14), occurring as rounded to ovoid loose grains, 0.5–2 cm in width, and forming principally around different nuclei, such as mudclasts or bioclasts (brachiopods, phylloids or red algae; Fig. 20M-N). They occur mainly in nodular mudstone–wackestone ‘nMW’, from 25 to 75 mbsl of estimated palaeo-water depth, in the outer platform, within the maximum-flooding interval deposits (Figs. 7B, 8B, 12B, 13B and 19J). They are, however, sparse in the outer-platform within the transgressive interval deposits of cyclothem C8 (Fig. 8A). *Osagia*-like oncoids occur from cyclothem C6 through C10, and reach a peak in cyclothem C8–C9 (Fig. 19J).

The facies in which *Osagia*-like oncoids occur (‘nMW’) indicates a low-energy environment. Their presence, mainly in the depth range of 25 to 75 mbsl and along the outer-platform setting, is also most probably linked to the requirement of other specific conditions (temperature, salinity, and pH) that were apparently fulfilled mostly during the maximum-flooding intervals. This low-energy and relatively deep environment of deposition is in agreement with interpretations of Peryt (1981, 1983) and Bowman (1983).

6.5.2. Microbially mediated precipitates

Microbially mediated precipitates are rare in the studied area (Fig. 14), only occurring in the slope deposits (Fig. 18) of cyclothem C1 (Figs. 4 and 19K), which were

the main slope deposits sampled. They are found in the slope peloidal boundstone 'pBd', in a range of estimated palaeo-waterdepth between 100 and 325 mbsl, forming horizontal or domical mats measuring 0.5 to 2 cm in width (Fig. 200-P). They are often encrusted by tetrataxids, fenestellid and fistuliporid bryozoans and are associated with *Donezella* and *Masloviporidium*(?).

Microbially mediated precipitates apparently grew only in low-energy environmentssituated from 100 to 325 mbsl, and are thus particularly good indicators of a slope setting. Besides, their occurrence seems independent of the sea level fluctuations. Their absence on the platform top could indicate unfavourable conditions, such as higher wave energy, salinity, temperature or light penetration. The distribution of microbially mediated precipitates in the platform-to-slope profile of Valdorria is in accordance with the findings of Della Porta *et al.*(2002a, 2004), Kenter *et al.* (2002, 2005), Weber *et al.* (2003), Bahamonde *et al.*(2004, 2007) and Collins *et al.* (2013) in the Sierra del Cuera, Picos de Europa and Tengiz platforms. This result is also consistent with findings on thrombolitic fabrics by Wahlman (2002).

6.5.3. *Thartarella-Terebella* worm tubes

Worm tubes are a common feature in Phase II of Valdorria (Fig. 14). They are found across the entire platform transect(Fig. 18),from 10 to 325 mbsl of estimated palaeo-water depth, in every defined facies types (Figs. 5 to 8 and 10 to 13). Theymeasure250–500 μm in diameter (Fig. 20Q). *Thartarella-Terebella* worm tubesappear to be mostly restricted to the depth range of 25 to 50 mbsl (Figs. 5 to 8 and 10 to 13) encountered in the outer platform and atthe platformbreak(Fig. 18). Their abundance exhibits a general decrease from the transgressive through the late

regressive intervals (Fig. 19L), being very rare to absent along the inner to outer platform of cyclothem C8 in coated-grain grainstone 'cG' (Fig. 11B).

Present in a wide depth range, from the platform top to the slope, in every defined facies types and in all intervals of deposition, *Thartarella-Terebelladid* did not seem to live in specific environments. However, the decrease in abundance observed in the platform-top deposits, and their scarcity in coated-grain grainstone 'cG', could be the result of increasing energy and reworking of fragile components, including worm tubes. *Thartarella-Terebella* worm tubes have been widely described as frame builders in boundstone deposits in low-energy settings (Fagerstrom, 1987; Samankassou, 2003, Merino-Tomé *et al.*, 2009) in association with sponges (Warnke, 1995) or *Donezella* (Choh and Kirkland, 2006). However, even if they occur in the slope deposits, such associations were not observed in Valdorria.

6.5.4. Faecal pellets

Faecal pellets are overall rare in Phase II of Valdorria (Fig. 14). Their presence increases from the platform top towards the slope (Fig. 18), where they occur more commonly in peloidal micrite boundstone 'pBd' (Fig. 4), from 50 to 325 mbsl. They are rare in other facies types (Figs. 4 to 8A, 11B, 12B-C and 13C). Their occurrence does not follow any particular trend, being slightly more common at the platform break during the transgressive and late regressive intervals (Fig. 19M). They usually measure 0.2 to 1 mm in size (Fig. 20R).

Present in a wide depth range, from the platform top to the slope, in every defined facies types and in all intervals of deposition, the common occurrence of faecal pellets seems however to indicate a platform break-to-slope setting situated from 50 to 325 mbsl. Their distribution appears to reflect deep and low-energy environments,

somehow independent of the dynamics of sea-level change. This distribution could reflect semi-specific conditions needed for the presence of the source organisms, but could also be biased by a partial conservation along the platform transect. Indeed, in modern high-latitude seas, where conditions are different, a causal relationship between the distribution of faecal pellets, the temperature, the water depth and the salinity has been documented (Martens and Krause, 1990).

7. DISCUSSION

7.1. Vertical distribution of microbial carbonates and of skeletal and non-skeletal grains across Phase II

The ten studied platform top cyclothem (C1 to C10), along with their upper- and lower-slope deposit equivalents (Fig. 4 to 13), exhibit an invariably high proportion of crinoids and tuberitids (Figs. 17), which are the two most common organisms in Phase II. Gastropods, brachiopods, fenestellid bryozoans, archaedicids, endothyrids, palaeotextulariids, bradyinids, fusulinids, *Donezella* and *Thartarella-Terebella* worm tubes exhibit different abundances, but all with almost constant proportions through the 10 cyclothem (Figs. 17 and 19).

The vertical extent and abundance of certain microbial carbonates and of skeletal and non-skeletal grains that have been mostly recorded in the slope, such as microbially mediated precipitates, which do not extend above C1, *Masloviporidium*(?), faecal pellets and maybe lasiodiscids, might be significantly biased by the portion of the platform margin represented in the studied outcrop (Fig. 1C). In fact, these components were previously reported up to the youngest deposits of Phase II in the eastern slope area (Chesnel *et al.*, 2016a). It has to be noted that samples originating from the lower-slope

deposits are only available for C1 and C2 whereas those from the upperslope cover from C1 through C5.

A progressive upward increase of calcareous algae is recorded in Phase II: stacheoids, *Ungdarella*, *Archaeolithoporella* and dasyclads extend from C2 through C10 and phylloid algae from C6 to C10, most of them being more common in the uppermost cyclothems. Similarly, *Osagia*-like oncoids and auloporid corals extend from C6 through C10 and auloporid corals are more common in C9 through C10 (Figs. 17 and 19).

The distribution of recognizable entire or fragments of siliceous sponges, only observed in the outer-platform deposits of cyclothem C10, might be affected by a taphonomic bias. Their possible presence in the Valdorria platform slopes could be inferred by the dominant microbial-boundstone facies, which has been linked to the carbonate precipitation mediated by microbial communities acting during the decay of siliceous sponge bodies as shown in the Sierra del Cuera platform (Della Porta *et al.*, 2002a). However, the abundance of beds exhibiting siliceous sponge spicules in the toe-of-slope deposits of Sierra del Cuera, indicating a certain abundance of siliceous sponges in the slope, were not observed in Valdorria. This suggests that microbial-boundstone facies could probably grow in settings devoid of siliceous sponge body matrices.

7.2. Influence of environmental factors in the distribution of microbial carbonates and of skeletal and non-skeletal grains

The lateral (from innerplatform to lowerslope) and vertical (from cyclothems C1 through C10) distribution of microbial carbonates and of skeletal and non-skeletal grains in the Upper Bashkirian (Asatauian) deposits of the Valdorria platform appear to have been controlled by variations of palaeoecological environments driven by distinct and major interconnected factors, namely variations of water depth and wave energy

1092 along the platform transect (inner and outer platform, platform break, upper and lower
1093 slope) during transgressive–regressive periods of sea-level fluctuation. The effect of
1094 other parameters, such as light penetration, turbidity, salinity, pH, temperature and
1095 nutrient availability can be inferred but not quantified accurately at the current stage of
1096 research.

1097 In the present study, microbially mediated precipitates occur only in the slope
1098 setting, from 100 to 325 mbsl, seemingly unaffected by the sea-level fluctuation and the
1099 differences in wave energy, light penetration, turbidity, salinity and temperature along
1100 the slope. Furthermore, microbially mediated precipitates have been reported in Phase
1101 III of Valdorria, which is thought to have been deposited in palaeo-water depth between
1102 50 and 300 mbsl (Chesnel *et al.*, 2016a). This wide depth range shows that the water
1103 depth neither is an important parameter affecting their distribution.

1104 Faecal pellets, observed from 15 to 325 mbsl, occur mostly in the slope setting.
1105 Thus, their distribution suggests that their deposition is virtually independent from the
1106 water depth and the wave energy, but that their great abundance is probably linked to
1107 the environments observed along the slope, independently of the sea level fluctuation
1108 observed on the platform top deposits.

1109 *Masloviporidium(?)*, observed from 15 to 250 mbsl, mostly occur in the upper-
1110 slope. Thus, the growth of *Masloviporidium(?)* seems to be partially affected by variations
1111 of wave energy and water depth along the slope. Besides, this restriction to the upper
1112 slope was also probably due to a negative effect of light penetration, salinity and
1113 temperature. Inversely, the transgressive–regressive periods of deposition and the
1114 associated sea-level fluctuations do not seem to affect their preferred ecological
1115 environment, namely the slope.

1116 Archaediscids, common to abundant, were observed mainly from 5 to 100 mbsl
1117 on the platform top to platform break/upper slope. Tournayellids were episodically
1118 common to abundant, mostly from 5 to 70 mbsl, and lasiodiscids were usually rare to very
1119 rare, observed principally from 20 to 50 mbsl. Both Tournayellids and lasiodiscids
1120 appear to occur mainly on the platform top, from the inner platform to the
1121 platform break. The distribution of these foraminifers lacks a strong link to cyclic changes
1122 of water depth and energy conditions during the transgressive–regressive phases of
1123 deposition. Their ideal living environments, along the platform top to platform
1124 break/upper slope, were probably affected neither by variations of light penetration,
1125 turbidity, salinity, pH, temperature, nor by nutrient availability. Lasiodiscids were found
1126 as loose individuals, not attached to other components, indicating a possible planktonic
1127 lifestyle that was, however, restricted to the platform-top setting.

1128 *Archaeolithoporella* is rarely observed in Valdorria, present mainly on the
1129 platform top from 5 to 85 mbsl of estimated palaeo-water depth. Similarly to
1130 tournayellids, lasiodiscids and archaediscids, this alga does not seem to have a preferred
1131 environment for their growth, affected by variations of water depth, wave energy and
1132 other parameters during the transgressive–regressive periods of deposition. But in
1133 contrast to lasiodiscids, *Archaeolithoporella* is clearly sessile and exclusively found
1134 attached on all other sessile and larger organisms of the platform top except crinoids,
1135 trilobites and gastropods. The alga is most common in the last three cyclothems (C8 to
1136 C10), likely due to the abundance of potential substrates (dasyclads, phylloids, *Osagia*-
1137 like oncoids, auloporids and siliceous sponges).

1138 Crinoids and tuberitinids, which are abundant in all cyclothems, from 5 to 325
1139 mbsl, and in both the platform-top and the slope settings, were clearly not growing in
1140 any specific preferred environment. Their distribution is thus unaffected by variation of

water depth, waveenergy, light penetration, turbidity, salinity, temperature, pH and nutrient availability during the transgressive–regressive periods of deposition. Their ability to live in all environments and conditions certainly played an important role in their broad extent and distribution. The growth of tetrataxids,less common in the Valdorria platform, but observed in a wide depth range, from 5 to 325 mbsl, wasapparently similarly unaffected by variations of the previously cited parameters. However, a systematic description would be necessary to determine if the tetrataxids that occur as loose individuals in coated grainstone, attached to phylloid algal thalli in the platformtop and within microbially mediated precipitates in the slope represent one or several species.

The microproblematic alga *Donezella* is common from the platform-top to the slope settings,from 5 to 325 mbsl, but alsoin all platform-top cyclothems through the transgressive–regressive periods of deposition. Therefore, the alga does not appear to have had a preferred specific environment for growth. However, its abundance, showing a distributionslightly more elevated in the platform-top early regressive intervals, seems to be the sign of a positive effect of the created conditions during these specific periods. The growing of the alga could thus have been affected, at a certain degree, by variationsof water depth, wave energy, light penetration, turbidity, salinity, pH and temperature,in accordance to some previous interpretations (Bowman, 1979: periods of maximum transgression; Della Porta *et al.*, 2002b: periods of relative sea-level rise), but in contrast to the results of several previous studies which failed to show any particular variation (Rich, 1967; Lemosquet and Poncet, 1974; Riding, 1979; Mazzullo, 1981; Poncet, 1991; Samankassou, 2001; Choh and Kirkland, 2006; Corrochano *et al.*, 2012b; Samankassou *et al.*, 2013). This findingmay facilitate the determination of the depositional environment of the multiple *Donezella* mounds occurring in the Upper

Palaeozoic strata of northern Spain and elsewhere, specifically in relation to bathymetry, which is commonly a main issue in carbonate mound research (Hebbeln and Samankassou, 2015).

The large amount of trilobites observed in C1 is likely a bias due to sampling of the lowerslope. However, their higher abundance in C6 through C10 compared to C2 through C5 may be due to the presence of thicker maximumflooding deposits in the former. This greater thickness is probably due to the longer time span needed to fill the higher accommodation space created by the local and rapid increase in subsidence during Phase II (Chesnel *et al.*, 2016a). Indeed, trilobites, which are observed across a wide palaeo-water-depth range, from 5 to 325 mbsl, from theinnerplatform to thelowerslope, and in high- to low-energy conditions, are more common in the maximum-flooding deposits of the platformtop. The lack of a registered effect on their distribution along the platformtransect is certainly due to a lack of determination at the species level. Indeed, previous studies have demonstrated that the setting is important to the species-specific distribution of trilobites (Gaines and Droser, 2003; Amati, 2004; Singh, 2011).

Fenestellid and fistuliporid bryozoans, more abundant on the slope, were also observed on the platform top, appearingto be able to grow in environmental conditionscreated in both these settings.When present on the platform top, they seemed to prefer the deep and low energy environments, from 30 to 70 mbsl,which developedduring the maximum flooding and the early regressive intervals. However, for the same depth range, in the transgressive and late regressive intervals, fenestellids and fistuliporids were generally sparse, rareorabsent. As a result, these organismsseemed to be negatively affected by the environments created during the early and late periods of the transgressive–regressivecycles. Thus, this effect cannot be directly linked to the

water depth, but probably to variations of other parameters, such as nutrient availability, light penetration, turbidity, salinity, pH and temperature. The reasons for the absence of fistuliporids in cyclothem C2 and scarcity in cyclothem C8 remain unclear but may include an effect of sampling or counting, or a lack of favourable conditions.

Thartarella-Terebella worm tubes can be commonly found in both the platform top and the slope, obviously unaffected by the differences in platform setting environments. When present on the platform top, they are common in the transgressive to maximum-flooding intervals, from 15 to 60 mbsl, and become sparse in the same depth range in the regressive intervals. They are nearly absent from 0 to 15 mbsl and are virtually absent in very shallow areas, especially those in which the wave energy is high (e.g. coated grain grainstone 'cG'). *Thartarella-Terebella* worms seemed to be negatively affected by the sea-level fall and disliked the shallow-water and high-energy environments.

Gastropods, rugose corals, brachiopods, endothyrids, palaeotextulariids, bradyinids, fusulinids, dasyclads, *Ungdarella* and stacheoids are all restricted to the platform top. They are also all affected in different ways by the variations in water-depth and wave-energy conditions, and most probably other parameters, along the platform top transect resulting from the transgressive–regressive periods of deposition. Thus, the low occurrence of rugose corals in cyclothem C9 and C10 may be linked to unfavourable water depth and wave energy conditions. The top layers of both C9 and C10 do not exhibit a transition from an early to a late regressive interval, which is, in Valdorria, one of the three deposits in which rugose corals primarily occur. This lack of a transition is probably due to the high subsidence and lower amplitude of the sea-level drop between the two cyclothem, as evidenced by the lower negative shift in the stable-isotope values at surface 9 compared to other surfaces (Chesnel *et al.*, 2016b). The scarcity of rugose

corals in C10 could also be explained by the absence of clear transgressive deposits or by the erosion of the top layers. Their scarcity in cyclothem C1 remains unexplained, as does the absence of dasyclads, *Ungdarella* and stacheoids. Furthermore, in contrast to rugose corals, *Ungdarella* mostly occurs in the upper part of Phase II, from C6 through C10, which is difficult to explain, because deposits of the early regressive intervals are observed in all cyclothems.

Osagia-like oncoids, phylloid algae, auloporida corals and siliceous sponges likely required very specific conditions, which explains their limited occurrence. Indeed, the abundance of these components seem to have been strongly affected by variations, along the platform top, of water depth, wave energy and, to a lesser extent, other parameters during the transgressive–regressive periods of deposition. They were limited to low-energy conditions observed at water depth of about 25–80 mbsl that were encountered during the maximum-flooding and early regressive intervals on the platform top. *Osagia*-like oncoids and auloporida corals occur only in nodular mudstone–wackestone ‘nMW’, whereas phylloid algae and siliceous sponges occur mainly forming boundstone layers ‘Bd2’. Likely, the water depth of deposition, the wave energy and the other parameters that were fulfilled during cyclothems C1 through C5 maximum flooding and regressive intervals did not meet these specific conditions, probably because of a different platform geometry.

8. CONCLUSIONS

1-Phase II of the Valdorria outcrop, which fully exposes platform-top to basin deposits that can be subdivided into 10 cyclothems, constrains the lateral distribution and evolution of microbial carbonates and of skeletal and non-skeletal grains through

time and transgressive–regressive intervals of deposition. Nearly all cyclothems record deposits attributable to transgressive, maximum-flooding, early and late regressive intervals.

2- The observed sequence stratigraphic pattern associated with the prograding–aggrading growth of Phase II permits the reconstruction of the geometry of each cyclothem at the scale of the interval of deposition. The inner platform remains horizontal; the outer platform dips between 0.5 and 6° and increases in length upward through the cyclothems. The slope dip likely decreases upward through the cyclothems, from 22 to 7°.

3- The deposits of each interval of deposition, within each cyclothem, display different assemblages and lateral distributions of microbial carbonates and of skeletal and non-skeletal grains. All these patterns were apparently largely driven by variations of water depth and wave energy, and, to a lesser degree, by the linked variations of temperature, pH, salinity, turbidity, light penetration and nutrient availability, along with changes in platform geometry through time, during the transgressive–regressive periods of deposition. Those grains exhibit the following specific or wide distribution patterns:

- Auloporida corals, siliceous sponges, phylloid algae and *Osagia*-like oncoids are restricted to low-energy environments that developed on the platform top at 25 to 80 mbsl during the maximum-flooding and early regressive intervals of deposition.
- Microbially mediated precipitates show maximum abundance in low-energy environments of the slope, from 100 to 325 mbsl.
- *Masloviporidium(?)* grew mainly in relatively low-energy environment of the upper slope, between 75 to 250 mbsl.

- 1266 • Dasyclads are mostly observed in moderate-energy and shallow-water

1267 environments, forming, in the inner platform, *Anthracoporella*–

1268 *Archaeolithoporella* boundstone lenses during the transgressive intervals.
- 1269 • *Ungdarella* occurred mostly in low- to moderately-agitated conditions of the

1270 platform top, more commonly observed at the top deposits of the early regressive

1271 intervals.
- 1272 • Stacheoids mainly grew under low- to medium-energy conditions at depth of

1273 10 to 60 mbsl that were encountered in the outer platform during the

1274 transgressive to early regressive intervals and at the platform break during the

1275 transgressive to maximum-flooding intervals.
- 1276 • Corals forming boundstones and solitary rugose corals lived in moderate to high-

1277 energy environments that formed in shallow-water area, from 5 to 35 mbsl. These

1278 specific conditions were best fulfilled in the inner to outer platform during the

1279 transition from the early to the late regressive intervals. Other solitary rugose

1280 corals found in floatstones are indicators of a low-energy environment that

1281 developed during periods of higher sea-level stand.
- 1282 • Fenestellid and fistuliporid bryozoans mostly lived on the slope, but were also

1283 observed in the deep and low-energy environments of the platform top, from 30

1284 to 70 mbsl, which developed during the maximum flooding and the early

1285 regressive intervals.
- 1286 • Trilobites are preferentially found in low- to medium-energy and deep-water

1287 environments of the slope, but also of the platform top, especially during the

1288 maximum-flooding intervals.

- 1289 • *Archaeolithoporella* grew in all environments of the platform top. Its occurrence is
1290 strongly linked to the presence of adequate substrates, this alga acting mainly as
1291 an encruster.
- 1292 • Observed in every environments of the platform top, gastropods, endothyrids,
1293 palaeotextulariids, bradyinids and fusulinids preferred the shallow and agitated
1294 conditions and were negatively affected by the conditions created during the
1295 maximum-flooding intervals.
- 1296 • Tournayellids lived in every environments of the platform top, but were mostly
1297 deposited in settings of medium-energy conditions, at 15 to 35 mbsl.
- 1298 • Archæidiscids lived in every environments of the platform top, but were mostly
1299 deposited in low- to medium-energy conditions, from 15 to 75 mbsl.
- 1300 • Tetrataxids grew in two main different environments of the platform top-to-slope
1301 transect: (1) as encrusters of microbially mediated precipitates, in low-energy
1302 environments of the slope, from 150 to 325 mbsl; (2) as encrusters of phylloid
1303 algae and *Archaeolithoporella*, in low- to medium-energy environments of the
1304 platform top, from 15 to 80 mbsl during the maximum flooding and early
1305 regressive intervals of deposition; and deposited (3) as nuclei of coated grains in
1306 high-energy and shallow water areas of the platform top.
- 1307 • Brachiopods lived at all depths of the platform-top to slope transect, but were
1308 mostly observed on the platform top, at 35 to 55 mbsl in low- to moderate-energy
1309 environments that developed during the transgressive intervals.
- 1310 • Faecal pellets deposited in every environments of the platform top-to-slope
1311 transect, but were more commonly observed in low-energy environments, from
1312 50 to 325 mbsl, at the platform break and in the slope.

- *Thartarella-Terebella* worms did not seem to live in restricted environments, but their tubes were very rarely observed in high-energy and shallow-water areas of the platform top.
- *Donezella* grew in every environments of the platform top-to-slope transect, and were slightly positively affected by the conditions created on the platform top during the early regressive intervals.
- Lasiodiscids show a random distribution on the platform top-to-slope transect, in every all environments encountered on the platform-to-slope transect.
- Crinoids and tuberitinids are omnipresent in every defined environment of the platform to-to-slope transect.

The distribution patterns reconstructed from the Valdorria outcrop have the potential to be used as a reference for settings in which the platform geometry is not preserved or exposed.

ACKNOWLEDGEMENTS

The Department of Earth Sciences, University of Geneva, the Swiss National Science Foundation, the Ernst and Lucy Schmidheiny Foundation and Augustin Lombard Foundation are acknowledged for funding of the project. Special thanks to F. Gischig (University of Geneva), E. Iglesias Castaño, M. García Viejo and E. Cabal Díaz (University of Oviedo) for manufacturing the many thin sections analysed in the present study. Giovanna Della Porta and Brenda L. Kirkland are thanked for their constructive reviews that were helpful in improving the revised version of the manuscript. Remarks of a further, anonymous journal referee are acknowledged. We thank Editor Isabel P. Montañez for the comments and her advice.

1337

1338 **FIGURE CAPTIONS**

1339 **Figure 1. (A)** Schematic geological map of the tectonostratigraphic provinces of the
1340 Cantabrian Zone, northern Spain (after Alonso *et al.*, 2009). The studied area is situated
1341 in the Gayo thrust sheet of the Bodón-Ponga Unit. **(B)**Detailed facies distribution
1342 mapped on an orthorectified aerial photograph (PNOA use granted by © Instituto
1343 Geográfico Nacional de España) of the platform-top to slope transect area of Phase II,
1344 showing the cyclicity and the different facies/geometric belts (inner platform, outer
1345 platform, platform break, upper slope and lower slope). Dashed lines indicate major
1346 chronostratigraphic boundaries, and black lines indicate the fault system.**(C)**
1347 Orthorectified aerial photograph (PNOA use granted by © Instituto Geográfico Nacional
1348 de España) of the eastern platform-top to slope transect of Phase II showing the location
1349 of stratigraphic logs and samples (red lines), the subaerial exposure surfaces (black
1350 thick lines) that delimit the 10 cyclothems (C1 to C10), the faults (black thin lines) and
1351 the chronostratigraphic boundaries (yellow lines),based on fusulinid biostratigraphy,
1352 that delimit the three growth phases of the platform (Phases I, II and III). The
1353 Serpukhovian Barcaliente Formation represents the substratum on which the
1354 Bashkirian Valdorria platform (Valdeteja Formation) developed. The Moscovian (Upper
1355 Carboniferous) siliciclastics of the San Emiliano Formation buried the entire platform.

1356

1357 **Figure 2.(A)**Field appearance of the transition from cyclothemsC6 to C7 in the outer-
1358 platform area. Subaerial exposure surface S6 is overlain by a relatively thin (~30 cm)
1359 brecciated deposit (trans. breccia; see Fig. 2C). The transgressive deposit is here
1360 overlain by nodular mudstone–wackestone (nMW) but can be overlain by

1361 *Anthracoporella*–*Archaeolithoporella* boundstone (Bd3a) in the inner-platform area.
1362 Hammer is 33 cm long. **(B)** ‘Bd1’: *Donezella*-rich boundstone. The *Donezella* (Do)-
1363 bounded network is associated with millimetre-sized primary cavities filled with blocky
1364 sparite (BIS). *Donezella* and other organisms are encrusted by micrite (MiC). **(C)** Polished
1365 slab showing the appearance of brecciated deposit composed of subangular lithoclasts of
1366 *Donezella*-rich boundstone (Bd1), nodular mudstone–wackestone (nMW), and a
1367 packstone–grainstone matrix with sparse brachiopods (Br), gastropods (Ga), crinoids
1368 (Cr) and benthic foraminifera (Palaeotextulariids: T). **(D)** ‘nMW’: nodular mudstone–
1369 wackestone. Fine-grained skeletal wackestone with benthic foraminifera: tuberitinids
1370 (Tu), bradyinids (B), endothyrids (En) and crinoid fragments (Cr). **(E)** ‘Bd3a’:
1371 *Anthracoporella*–*Archaeolithoporella* algal boundstone. *Anthracoporella* (Da),
1372 *Archaeolithoporella* (A) and fusulinids (Fu). **(F)** Typical field appearance of beds with
1373 massive mudstone–algal mats (mAM) representing the maximum-flooding intervals of
1374 cyclothems C3 and C6. Massive mudstone–algal mats is underlain by either nodular
1375 mudstone–wackestone (nMW) or nodular floatstone (nFl) and is in turn overlain by
1376 similar deposits and sparse *Ungdarella* boundstone (Bd3b) and/or auloporid
1377 boundstone (Bd4b). Hammer is 33 cm long. **(G)** Polished slab showing the appearance of
1378 rugose coral (Ru) floatstone (nFl). The corallites are all oriented in the same direction in
1379 a wackestone matrix, revealing the existence of a dominant current. Crinoid fragment
1380 (Cr). Scale in millimetres and centimetres **(H)** Polished slab showing the appearance of
1381 mudstone–algal mats ‘mAM’. Mudstone (Mud) and algal mats (A.mats) are closely
1382 packed to form the massive beds of the maximum-flooding intervals (see Fig. 2F).

1383

1384 **Figure 3. (A)** Polished slab showing the appearance of auloporid-coral (Au) boundstone
1385 ‘Bd4b’. Other organisms are rare in the wackestone matrix. Scale in millimetres. **(B)**

Polished slab showing the appearance of *Ungdarella* (U) boundstone 'Bd3b'. The closely packed algal thalli do not leave much space for other organisms. **(C)** Typical field appearance of the siliceous sponge (Sp)–phylloid algal (Ph) boundstone 'Bd2' in the outer-platform area at the top of cyclothem C10. Note the repetitive pattern of nodular beds dominated by sponges and massive beds dominated by phylloid algae. Hammer is 33 cm long. **(D)** Typical field appearance of the transition from nodular mudstone–wackestone deposits (nMW) to nodular–massive skeletal packstone–grainstone (sPG) and to massive coated-grain grainstone (cG) in the outer-platform area. Hammer is 33 cm long. **(E)** Polished slab showing the appearance of skeletal packstone–grainstone 'sPG' in the nodular layers, exhibiting brachiopods (Br) and palaeotextulariids (T). Scale in millimetres. **(F)** Polished slab showing the appearance of skeletal packstone–grainstone 'sPG' in the massive layers, exhibiting crinoid (Cr) and rugose coral (Ru) fragments. Scale in millimetres and centimetres. **(G)** Polished slab showing the appearance of rugose coral (Ru) boundstone 'Bd4a'. The closely packed corallites do not leave much space for other organisms. **(H)** Polished slab showing the appearance of a coated-grain grainstone 'cG' layer rich in oncoids. The oncoids nuclei are mainly chaetetid sponges (Cha) and coated-grain grainstone clasts (cG). Sparse rugose corals (Ru) are also present. Scale in centimetres.

Figure 4. Schematic reconstruction of the stratigraphic architecture of Phase II for C1 showing the lateral and facies related distribution of observed microbial carbonates, skeletal and or non-skeletal grains. Coated-grain grainstone 'cG' — Skeletal packstone–grainstone 'sPG' — *Donezella*-rich boundstone 'Bd1' — Peloidal micrite-rich boundstone 'pBd' — Bioclastic packstone–grainstone 'sPG'. **(A)** Transgressive to early regressive intervals. The water level is estimated to be ~15 m above the horizontal inner-platform

area (see text and Tab. 3 for more information). **(B)** Late regressive interval. The water level is estimated to be ~5 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

Figure 5. Schematic reconstruction of the stratigraphic architecture of Phase II for C2 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-skeletal grains. Coated-grain grainstone 'cG' — Nodular mudstone–wackestone 'nMW' — *Donezella*-rich boundstone 'Bd1' — Rugosa boundstone 'Bd4a' — Peloidal micrite-rich boundstone 'pBd'. **(A)** Transgressive to early regressive intervals. The water level is estimated to be ~15 m above the horizontal inner-platform area. **(B)** Late regressive interval. The water level is estimated to be ~5 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

Figure 6. Schematic reconstruction of the stratigraphic architecture of Phase II for C3 to C7 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-skeletal grains. Nodular mudstone–wackestone 'nMW' — Nodular floatstone 'nFl' — *Donezella*-rich boundstone 'Bd1' — Peloidal micrite-rich boundstone 'pBd'. **(A)** Transgressive intervals of C3 to C5. The water level is estimated to be ~5 m above the horizontal inner-platform area (see text and Tab. 3 for more information). **(B)** Transgressive intervals of C6 and C7. The water level is estimated to be ~10 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

Figure 7. Schematic reconstruction of the stratigraphic architecture of Phase II for C3 to C7 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-skeletal grains. Nodular mudstone–wackestone 'nMW' — Nodular floatstone 'nFl' —

Mudstone–algal mats ‘mAM’ — *Donezella*-rich boundstone ‘Bd1’ — Peloidal micrite-rich boundstone ‘pBd’.(A)Maximum-flooding intervals of C3 to C5. The water level is estimated to be~30 m above the horizontal inner-platform area (see text and Tab. 3 for more information). (B)Maximum-flooding intervals of C6 and C7. The water level is estimated to be~35 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

Figure 8.Schematic reconstruction of the stratigraphic architecture of Phase II for C3 to C7 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-skeletal grains. Skeletal packstone–grainstone ‘sPG’ — *Donezella*-rich boundstone ‘Bd1’ — *Ungdarella* boundstone ‘Bd3b’ — Peloidal micrite-rich boundstone ‘pBd’.(A) Early regressive intervals of C3 to C5. The water level is estimated to be~15 m above the horizontal inner-platform area (see text and Tab. 3 for more information). (B) Early regressive intervals of C6 and C7. The water level is estimated to be~15 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

Figure 9.Schematic reconstruction of the stratigraphic architecture of Phase II for C3 to C7 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-skeletal grains. Coated-grain grainstone ‘cG’ — Skeletal packstone–grainstone ‘sPG’ — *Donezella*-rich boundstone ‘Bd1’ — *Ungdarella* boundstone ‘Bd3b’ — Peloidal micrite-rich boundstone ‘pBd’.(A) Late regressive intervals of C3 to C5. The water level is estimated to be~5 m above the horizontal inner-platform area (see text and Tab. 3 for more information). (B) Late regressive intervals of C6 and C7. The water level is estimated to be~5 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

1461

1462 **Figure 10.**Schematic reconstruction of the stratigraphic architecture of Phase II for C8
1463 showing the lateral distribution of observed microbial carbonates, skeletal and or/non-
1464 skeletal grains.*Anthracoporella-Archaeolithoporella* boundstone 'Bd3a' — Nodular
1465 mudstone–wackestone 'nMW' — Nodular floatstone 'nFl' — *Donezella*-rich boundstone
1466 'Bd1'.**(A)** Transgressive interval. The water level is estimated to be~15 m above the
1467 horizontal inner-platform area (see text and Tab. 3 for more information).**(B)**Maximum-
1468 flooding interval. The water level is estimated to be~35 m above the horizontal inner-
1469 platform area (see text and Tab. 3 for more information).

1470

1471 **Figure 11.**Schematic reconstruction of the stratigraphic architecture of Phase II for C8
1472 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-
1473 skeletal grains.Coated-grain grainstone 'cG' — Skeletal packstone–grainstone 'sPG' —
1474 *Ungdarella* boundstone 'Bd3b' — Nodular mudstone–wackestone 'nMW'. **(A)** Early
1475 regressive interval. The water level is estimated to be~25 m above the horizontal inner-
1476 platform area (see text and Tab. 3 for more information).**(B)** Late regressive interval.
1477 The water level is estimated to be~0 m above the horizontal inner-platform area (see
1478 text and Tab. 3 for more information).

1479

1480 **Figure 12.**Schematic reconstruction of the stratigraphic architecture of Phase II for C9
1481 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-
1482 skeletal grains.Coated-grain grainstone 'cG' — Skeletal packstone–grainstone 'sPG' —
1483 *Ungdarella* boundstone 'Bd3b' — Nodular mudstone–wackestone 'nMW' — Auloporid
1484 boundstone 'Bd4b' — *Donezella*-rich boundstone 'Bd1'.**(A)** Transgressive interval. The
1485 water level is estimated to be~0 m above the horizontal inner-platform area (see text

and Tab. 3 for more information). **(B)** Maximum-flooding interval. The water level is estimated to be ~35 m above the horizontal inner-platform area (see text and Tab. 3 for more information). **(C)** Regressive interval. The water level is estimated to be ~10 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

Figure 13. Schematic reconstruction of the stratigraphic architecture of Phase II for C10 showing the lateral distribution of observed microbial carbonates, skeletal and/or non-skeletal grains. Skeletal packstone–grainstone ‘sPG’ — *Ungdarella* boundstone ‘Bd3b’ — Nodular mudstone–wackestone ‘nMW’ — Auloporid boundstone ‘Bd4b’ — Siliceous sponge–phylloid algal boundstone ‘Bd2’ **(A)** Transgressive to maximum-flooding intervals. The water level is estimated to be ~25 m above the horizontal inner-platform area (see text and Tab. 3 for more information). **(B)** Maximum flooding to regressive intervals. The water level is estimated to be ~35 m above the horizontal inner-platform area (see text and Tab. 3 for more information).

Figure 14. Percentage of samples in which the studied microbial carbonates, skeletal and/or non-skeletal grains are abundant, common, rare and absent in the western outcrop of Phase II of Valdorria. The total number of studied thin sections is n=339. Note that tuberitinids are the only organisms abundant in more than 50% of the samples.

Figure 15. (A) Trilobite bioclast from the platform top. **(B)** Gastropod. **(C)** Auloporid coral. **(D)** Solitary rugose corals from the floatstone facies ‘nFl’. **(E)** Undetermined siliceous sponges. Note the red matrix, which is most likely due to its proximity to the calcrete from surface S10, and the centimetre size of the sponges. **(F)** Crinoid ossicles in a high-energy coated-grain grainstone ‘cG’. **(G)** Unbroken brachiopod from the platform

top. **(H)**Fenestellid bryozoan bioclast from the platform top. **(I)**Fistuliporid bryozoan from the platform top, encrusted on a lithoclast. **(J)***In situ* tetrataxid encrusted within microbially precipitated layers from the slope area. **(K)**Tournayellids from the slope or platform-top areas. **(L)**Lasiodiscids from the slope area. **(M)***In situ* encrusted tuberitinids. **(N)**Archaeodiscid. **(O)**Endothyrid. **(P)**Palaeotextulariid. **(Q)**Bradyinid. **(R)**Fusulinid.

Figure 16. Percentage of samples in which grazers/burrowers (trilobites and gastropods), corals/filter feeders (auloporids, rugosa, siliceous sponges, crinoids, brachiopods, fenestellids and fistuliporids) and foraminifera (tetrataxids, tournayellids, lasiodiscids, tuberitinids, archaeodiscids and endothyrids) are abundant, common, rare or absent in the different sub-environments of the western outcrop of Phase II of Valdorria. Results are based on following numbers of thin sections studied: inner-platform area (inner plat.), n=83; outer-platform areas (outer plat.), n=187; platform break (break), n=26; upperslope (up. slope), n=28; lowerslope (lo. slope), n=15.

Figure 17. Relative abundance of grazers/burrowers (trilobites and gastropods), corals/filter feeders (auloporids, rugosa, siliceous sponges, crinoids, brachiopods, fenestellids and fistuliporids) and foraminifera (tetrataxids, tournayellids, lasiodiscids, tuberitinids, archaeodiscids, endothyrids and palaeotextulariids) in the platform-top to slope transect of the Phase II outcrop, in the transgressive (T), maximum flooding (MF), early (eR) and late (lR) intervals of deposition, and for the whole Phase II (cyclothem C1 to C10). 0=absent; 1=rare; 2=common; 3=abundant.

Figure 18. Percentage of samples in which foraminifera (palaeotextulariids, bradyinids and fusulinids), algae (dasyclads, phylloid algae, *Ungdarella*, stacheoids, *Archaeolithoporella*, *Masloviporidium*(?) and *Donezella*), microbial and other components (*Osagia*-like oncoids, microbially mediated precipitates, *Thartarella*-*Terebella*-like worm tubes and faecal pellets) are abundant, common, rare and absent in the different sub-environments of the western outcrop of Phase II of Valdorria. The following numbers of thin sections were studied: inner-platform area (inner plat.), n=83; outer-platform areas (outer plat.), n=187; platform break (break), n=26; upslope (up. slope), n=28; lowerslope (lo. slope), n=15.

Figure 19. Relative abundance of foraminifera (bradyinids and fusulinids), algae (dasyclads, phylloid algae, *Ungdarella*, stacheoids, *Archaeolithoporella*, *Masloviporidium*(?) and *Donezella*), microbial and other components (*Osagia*-like oncoids, microbially mediated precipitates, *Thartarella*-*Terebella*-like worm tubes and faecal pellets) in the platform-top to slope transect of the Phase II outcrop, in the transgressive (T), maximum flooding (MF), early (eR) and late (lR) regressive intervals of deposition, and for the whole Phase II (cyclothems C1 to C10). 0=absent; 1=rare; 2=common; 3=abundant.

Figure 20. (A-B) Dasyclads. **(C)** Phylloid algae (Ph) from the siliceous sponge-phylloid algal boundstone 'Bd2'. **(D)** Phylloid algae (Ph) in floatstone with a brachiopod (Br) and an encrusted tetrataxid (Te). **(E)** *Ungdarella* thalli from the *Ungdarella* boundstone 'Bd3b'. **(F)** Stacheoid. **(G-H)** *Archaeolithoporella*. **(I-J)** *Masloviporidium*(?) from the slope boundstone 'pBd'. Note the several millimetre-long delicately branching algal thalli.

1558 **(K)***Donezellalunaensis*. **(L)***Donezellalutugini*. **(M)***Osagia*-like oncoid with a brachiopod
 1559 (Br) as the nucleus. **(N)***Osagia*-like oncoid with an algal thallus (A?) acting as nucleus.
 1560 Note the encrusted tetrataxid (Te).**(O-P)**Microbially mediated precipitates from the
 1561 slope area. Note the encrusted tetrataxids (Te) on or within the layers. **(Q)**Worm tube
 1562 known as *Thartarella-Terebella* from the platform-top. **(R)**Faecal pellets (Fp) from the
 1563 slope area.

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Lithofacies, microfacies & other stratigraphic features

Bd1 <i>Donezella</i> -rich boundstone.	nMW Bd3a Nodular mudstone–wackestone or floatstone,	sPG Skeletal packstone–grainstone
Bd2 Siliceous-sponge & phylloid-algal boundstone	nFI Bd4b dasyclad & auloporiid boundstones	Bd4a & rugosa boundstone
pBd Peloidal-micrite-rich-microbial-algal-bryozoan boundstone (slope)	mMA Mudstone–algal mats	Bd3b <i>Ungdarella</i> boundstone
bPG Bioclastic packstone–grainstone (calciturbidites) &	Br1 Red-stained breccias	cG Coated-grain grainstone
bMW mudstone–wackestone rich in radiolarians (basin)	mBd Microbial boundstone (Phase III)	Br2 Breccia (down slope)
		Calcrete
		Karst

A. C1 transgressive to early regressive intervals

B. C1 late regressive interval

abundant common to abundant sparse to abundant common sparse rare very rare

A. C2 transgressive to early regressive intervals

B. C2 late regressive interval

A. C3 to C5 transgressive intervals

B. C6 to C7 transgressive intervals

A. C3 to C5 maximum-flooding intervals

B. C6 to C7 maximum-flooding intervals

A. C3 to C5 early regressive intervals

B. C6 to C7 early regressive intervals

A. C3 to C5 late regressive intervals

B. C6 to C7 late regressive intervals

A. C8 transgressive interval

B. C8 maximum-flooding interval

A. C8 early regressive interval

B. C8 late regressive interval

A. C9 transgressive interval

C. C9 regressive interval

B. C9 maximum-flooding interval

A. C10 transgressive to maximum-flooding intervals

B. C10 maximum-flooding to regressive intervals

A. Trilobites

B. Gastropods

C. Aulopodids

D. Rugosa

E. Siliceous sponges

F. Crinoids

G. Brachiopods

H. Fenestellids

I. Fistuliporids

J. Tetrataxids

K. Tournayellids

L. Lasiodiscids

M. Tuberitnids

N. Archæodiscids

O. Endothyrids

P. Palaeotextariids

A. Bradyinids

B. Fusulinids

C. Dasyclads

D. Phylloids

E. Ungdarella

F. Stacheoids

G. Archaeolithoporella

H. Masloviporidium(?)

I. Donezella

J. Osagia-like oncoids

K. Microbially mediated precipitates

L. Thartarella-Terebella-like worm tubes

M. Faecal pellets

Skeletal, composite or non-skeletal grains counted per thin section (7.5 cm²)	Relative abundance estimation	Code number used for percentages calculations
0	Absent	0
1	Rare	1
2 to 4	Common	2
≥5	Abundant	3

Table 1. Relative abundance estimations per thin section.

In % of thin sections	>50%	<50%	
Number of counted	0	1	Very rare
skeletal, composite or	1	0	Rare
non-skeletal grains	2 to 4	0 to 1	Common
	0 to 1	2 to ≥ 5	Sparse
	≥ 5	0 to 1	Sparse to abundant
	2 to 4	≥ 5	Common to abundant
	≥ 5	2 to ≥ 5	Abundant

Table 2. Relative abundance estimation per interval of deposition (in one stratigraphic section).

Interval of deposition	Cycles (C)	Facies or feature observed in horizontal inner platform area (Present study; Chesnel <i>et al.</i> , 2016a)	Thickness of facies in inner platform (m)	Mean water level above inner platform (m)
T	C9	None — ‘Bd1’ in outer platform	-	0
	C3 to C5	Brecciated deposits to ‘nMW’	0.3 to ~5	~5
	C6 to C7	Brecciated deposits to ‘nMW’ — ‘Bd1’ in outer platform	0.3 to ~9	~10
	C8	Brecciated deposits to ‘nMW’ with ‘Bd3a’ — ‘Bd1’ in outer platform	0.3 to ~3	~15
T to MF (und.)	C10	‘nMW’ with ‘Bd3b’ to ‘sPG’	~25	~25
T to eR (und.)	C1 to C2	‘sPG’ or ‘nMW’	8–15	~15
MF	C3 to C5	‘nMW’ or ‘nMW’ to ‘mAM’ to ‘nMW’	~1 to ~5	~30
	C6 to C9		~6 to ~15	~35
MF to R (und.)	C10	‘sPG’ to ‘Bd2’	~10 to ~15	~30
eR	C3 to C7	‘nMW’ to ‘sPG’	~2 to ~15	~15
	C8		>~15	~25
R (und.)	C9	‘nMW’ with ‘Bd3b’ + ‘cG’	~10	~10
lR	C1 to C7	‘cG’ (rarely ‘sPG’)	~0.5 to ~2	~5
	C8	None — ‘cG’ in outer platform	-	0

Table 3. Mean water level estimations per interval of deposition.

Cyclothem	Interval of deposition	Slope				Platform			
		lower	upper		outer	inner		East	West
			East	West		East	West		
C1	T/eR	520[12.5]	680 [13.9]		380 [2.3]			>200 [0]	
	lR	520 [n.d.]	680 [n.d.]		380 [1.4]			>200 [0]	
C2	T/eR	>130 [22.3]	390[22.3]	680[9]	380 [0.4]			>200 [0]	
	lR	n.d. [n.d.]	1070 [n.d.]		380 [0.4]			>200 [0]	
C3	T	n.d. [n.d.]	>650 [9.9]		725 [5.3]			200 [0.1]	>200 [0.6]
	MF	n.d. [n.d.]	>650 [n.d.]		725 [5.4]				
	eR	n.d. [n.d.]	>650 [n.d.]		725 [5.8]			200 [n.d.]	>200 [0.7]
	lR	n.d. [n.d.]	>650 [n.d.]		725 [5.9]			200 [-2.6]	>200 [-0.7]
C4	T	n.d. [n.d.]	>650 [n.d.]		725 [5.9]			200 [-2.6]	>200 [-0.6]
	MF	n.d. [n.d.]	>650 [n.d.]		725 [5.8]				
	eR	n.d. [n.d.]	>650 [n.d.]		725 [6]			200 [-2.6]	>200 [n.d.]
	lR	n.d. [n.d.]	>650 [n.d.]		725 [6]			200 [-2.6]	>200 [n.d.]
C5	T	n.d. [n.d.]	>650 [n.d.]		725 [6.1]			200 [-2.6]	>200 [0]
	MF	n.d. [n.d.]	>650 [n.d.]		725 [5.8]			200 [-2.6]	>200 [0]
	eR	n.d. [n.d.]	>650 [n.d.]		725 [5.8]			200 [0]	>200 [0]
	lR	n.d. [n.d.]	>650 [n.d.]		725 [5.4]			200 [1.2]	>200 [0]
C6	T	n.d. [n.d.]	>520 [7.1]		855 [5.5]			200 [0.9]	>200 [0]
	MF	n.d. [n.d.]	>130 [n.d.]		1245 [5]	200 [2.4]		>200 [0]	
	eR	n.d. [n.d.]	>130 [n.d.]		1245 [5]	200 [3.4]		>200 [0]	
	lR	n.d. [n.d.]	>130 [n.d.]		1245 [5.2]	200 [3.1]	>100 [n.d.]	>100 eroded	
C7	T	n.d. [n.d.]	>130 [n.d.]		1245 [5.2]	200 [3.1]		>200 [-0.6]	
	MF	n.d. [n.d.]	>130 [n.d.]					>200 [n.d.]	
	eR	n.d. [n.d.]	>130 [n.d.]		1245 [5.5]	200 [2.2]		>200 [0.4]	
	lR	n.d. [n.d.]	>130 [n.d.]		1245 [5.6]	200 [2.4]		>200 [0.4]	

Table 4. Platform geometry parameters for cyclothem 1-10 (C1 to C10) include approximated length in metre and [bottom dip] in degrees for each interval of deposition; n.d.=no data. T=transgressive interval. MF= maximum-flooding interval. e/lR= early/late regressive intervals. Outer platform dips were calculated on the unfaulted western half side of the platform top (see Fig.2)

C8	T	n.d. [n.d.]	>130 [n.d.]	1245 [5.3]	200 [2.9]	>200 [0]	
	MF	n.d. [n.d.]	>130 [n.d.]	1245 [5.2]	200 [2.2]	>200 [0]	
	eR	n.d. [n.d.]	>130 [n.d.]	1245 [5]	200 [2.2]	>200 [0]	
	IR	n.d. [n.d.]	>130 [n.d.]	945 [3.3]	300 [n.d.]	>400 eroded	
C9	T	n.d. [n.d.]	>130 [n.d.]	945 [2.3]	300 [n.d.]	200 [1.2]	>200 [0]
	MF	n.d. [n.d.]	n.d. [n.d.]	>1420 [0.4]	180 [11.3]		
	R	n.d. [n.d.]	n.d. [n.d.]	>1420 [0]	180 [3.5]	>400 [n.d.]	
C10	T/MF	n.d. [n.d.]	n.d. [n.d.]	>1420 [0]	180 [3.7]	>400 [n.d.]	
	MF/R	n.d. [n.d.]	n.d. [n.d.]	>1420 [0.4]	180 [≥3] eroded	>400 [n.d.] eroded	

Table 4. Following.