Development of a Mississippian–Lower Pennsylvanian isolated carbonate platform within the basinal griotte facies of the Cantabrian Mountains, NW Spain

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Abstract

The Valdediezma platform consists of upper Tournaisian to lower Bashkirian (Carboniferous) shallow-water carbonates deposited in the core of the Picos de Europa province (Cantabrian Mountains, northwest Spain). Although faulted in several thrust sheets, it is the only preserved platform developed in the Mississippian starved basins of the southern branch of the Variscan Orogen, that is characterized also by pelagic sedimentation. This unusual platform provides an exceptional opportunity to study the lateral variation from the platform to the typical condensed griotte limestones developed in a starved basin, the origin of such a platform in a particularly unfavourable setting for carbonate accumulation, as well as the nucleation of the subsequent widespread Pennsylvanian carbonate platforms of the Cantabrian Mountains. Sixteen carbonate microfacies are differentiated in the Valdediezma Limestone, from shallow-water to slope to basinal environments. The carbonate production is related to the submarine topography and the rapid rates of microbial growth and accumulation, particularly from the upper Viséan to the lower Serpukhovian. A high-elevaton platform and steep southern margin occurred during the deposition of condensed cephalopod-bearing limestones in the basin. A higher rate of carbonate accumulation is recognized from the upper Serpukhovian and younger, with similar thicknesses in shallow- and deeper-water settings. The thickest part of the succession was coeval with the larger subsidence resulting from the migration of the Variscan deformation at the margin of the foreland basin of the Cantabrian Zone. The migration of deformation along the foreland, uplifted and allowed partial erosion the Valdediezma platform during the upper part of the lower Bashkirian. The Pennsylvanian carbonate platform developed on an exhumed Mississippian platform. Tectonic overloading due to the emplacement of nearby thrust

sheets caused the subsidence and burial of the Valdediezma platform in the upper Moscovian.

Keywords carbonates, microbial boundstones, Carboniferous, Variscan Orogen

Declarations

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Introduction

Mississippian rocks of the Cantabrian Zone (CZ; Fig. 1) have been rarely studied from a sedimentological aspect due to the predominantly pelagic to hemipelagic settings during the late Tournaisian–late Serpukhovian, represented by the Alba Formation (Eichmüller and Seibert 1984; Wendt and Aigner 1985; Fig. 2a). Breccias, debris flows and slump deposits have been rarely described in these units, and their occurrence was generally associated with the margins of sedimentary highs where condensed cephalopod-bearing limestones were deposited (Eichmüller and Seibert 1984). Higher up in the succession, during the upper Serpukhovian to lower Bashkirian, laminated limestones of the Barcaliente Formation were deposited in a moderately-deep basin of the foreland margin. Siliciclastic turbidite deposits filled the foredeep on the western margin of the CZ, which were transported from the hinterland to the west (Reuther 1977; Oliveira et al. 2019). Mississippian pelagic nodular cephalopod-bearing limestones (such as those of the Alba Formation) widely occur in the southern branch of the Variscan chain in southern Europe, below younger limestones equivalent to the Barcaliente Formation and/or coeval siliciclastic deposits (Pyrenees, Betics, Montagne Noire, Southern Alps and Graz, and the Balkan Peninsula; Schönlaub and Histon 2000; Sudar et al. 2018).

Recently, Viséan to lower Bashkirian shallow-water carbonates have been discovered in the core of the Picos de Europa province (CZ; Figs. 1, 2a), informally named as the Valdediezma Limestone (Sanz-López et al. 2018). The morphology and development of the platform remained poorly explored to date. Intact Mississippian shallow-water platforms are not preserved in the southern branch of the Variscan belt, where original carbonate platforms were eroded and reworked into younger synorogenic siliciclastic deposits (e.g., Engel et al. 1981; Oliveira et al. 2019). Thus, the

Valdediezma platform constitutes an exceptional record of a shallow-water platform in this part of the Variscan Orogen, an area that was largely dominated by pelagic and hemipelagic sedimentation.

Scant knowledge of Mississippian shallow-water carbonates contrasts with the excellent exposures of the Pennsylvanian carbonate facies and its geometric spatial relations to mapped shallow-water platforms and basinal facies (e.g., Bahamonde et al. 1997, 2007, 2008; Della Porta et al. 2002, 2004; Merino-Tomé et al. 2009, 2014). The rocks of the Mississippian-early Bashkirian Valdediezma platform were misinterpreted as Moscovian platform-top facies (Bahamonde et al. 2007, figs. 8C, 13). Moreover, the Valdediezma Limestone was also confused with the Barcaliente, Valdeteja and most of the Picos de Europa formations in regional maps of the central-eastern part of the Picos de Europa Province (Fig. 2) (Merino-Tomé et al. 2014; and previous maps). Thick amalgamations of rather similar massive pale grey limestones occur in those units, and only the biostratigraphy provided by microfossils allows a subdivision of the stratigraphic succession (e.g., Blanco-Ferrera et al. 2017; Sanz-López et al. 2018).

We describe a new shallow-water carbonate platform set within the context of deeper-water facies which has been overlooked for decades by the vast Pennsylvanian platform of the Cantabrian Mountains. We demonstrate that this platform was the seed for the Pennsylvanian platform developement, a new mechanism not hinted at so far. The aims of this study are: (i) to characterize the lithostratigraphy and sedimentology of the only existing platform laterally interbedded with the deep-water and condensed griotte facies in the southern Variscan front for the Mississippian and basal Pennsylvanian; (ii) to reconstruct and correlate the shallow-water carbonate platform, the platform slope and the transition to the basinal settings using a detailed biostratigraphy; (iii) to discuss the mechanisms for the onset of the shallow-water facies within the dominant pelagic and hemipelagic environments (such mechanism for the rest of the southern Variscan front has been rarely discussed because the shallow-water limestones were mostly reworked in Pennsylvanian synorogenic flysch); (iv) to characterize the regional tectonic factors controlling the demise of the platform and its relationship with the younger Pennsylvanian platform, set within the context of the foreland of the southern branch of the Variscan Belt.

Geological context

The Cantabrian Zone (CZ) is a tectonostratigraphic unit situated in the northwestern part of the Iberian massif (Fig. 1) and consists of a foreland basin system in the southeastern external part of the Variscan Belt. It contains a thick Palaeozoic succession that was deformed by thin-skinned tectonics (folds and thrusts) during the Variscan Orogeny (Pérez-Estaún et al. 1988). Six tectono-stratigraphic provinces have been defined in the CZ (Julivert 1971, 1978): the Narcea thrust sheets, the Folds and Nappes (Somiedo, Esla, Valsurbio, Bodón y Aramo units), the Central Coal Basin (or Asturian Coalfield), the Ponga Nappe, the Picos de Europa and the Pisuerga-Carrión provinces (Fig. 1). The studied area is in the Tejo tectonic unit which is situated in the central-eastern part of the Picos de Europa Province (Fig. 2b). It constitutes part of the northern branch of the Asturian Arc, and its tectonic style has been described as an imbricate system of thrust sheets stacked from the south during the late Moscovian–Gzhelian time interval (Marquínez 1989; Farias and Heredia 1994; Merino-Tomé et al. 2009).

The Tejo unit includes the most extensive outcrops of the Valdediezma Limestone. It is bounded by the Tresviso (or Cabuérniga) Fault to the north and the San Carlos and Saigu faults to the south (Fig. 2b). The San Carlos Fault isa Variscan thrust rotated as a subvertical fault that results in a triangular-shaped outcrop of the Tejo unit. The San Carlos Fault (like the Cabañes Fault to the northeast) has a long movement history and controlled Permian and Mesozoic sedimentation. These faults subsequently experienced reverse displacements during the Alpine Orogeny (Espina 1994). Triassic strata are locally preserved in the footwall of the Tresviso reverse fault (Fig. 2b).

The Tejo unit consists of several tectonic subunits bounded by faults, which, from northwest to the southeast, are the Saigu, Varera, Las Llamas-Bejes, La Hermida and the Mesa Sin Pan subunits (Fig. 2b). The Valdediezma Limestone was only informally described because its lower boundary corresponds to faults in the different tectonic subunits. The top of the Valdediezma Limestone is an erosive surface situated below latest Moscovian–Kasimovian strata of the uppermost part of the Picos de Europa Formation (Fig. 2a). Locally, Kasimovian shales and limestones of the Aliva and the Las Llacerias formations directly overlie the Valdediezma Limestone (and in places, continental Permian and Triassic rocks; Sanz-López et al. 2018). The Valdediezma Limestone is exposed below the Barcaliente Formation only in the Mesa Sin Pan subunit.

Outcrops located to the north of the Tejo unit (Gamonedo-Cabrales thrust unit; Fig. 2b), and south and west (Aliseda-Cabrones-Vegas de Sotres thrust unit, ACVS) are represented by the typical lithostratigraphic succession of upper Tournaisian to Moscovian of the CZ (Fig. 2a). These are the Alba, Barcaliente, Valdeteja and Picos de Europa formations (e.g., Colmenero et al. 2002). Only in outcrops of the ACVS Serpukhovian strata of the Valdediezma Limestone is sandwiched between the Alba and Barcaliente formations (Fig. 2a). Microfossils from the Valdediezma Limestone support the correlation to both these formations (Sanz-López et al. 2018).

Materials and methods

A field survey in the region allowed us to distinguish the main tectonic subunits, from which eleven stratigraphic sections have been measured. These sections are the most representative and contain the entire diversity of recognized facies (Fig. 2b). The sampling interval was not uniform, but varies typically, between 2 to 4 m, but can be up to 10 metre intervals (depending on the observed facies) in sections several hundred metres-thick, containing the thickest and most representative succession of the platform (e.g., Valdediezma valley and Jitu l'Escarandi sections). A sampling interval of a few centimetres was used on condensed carbonate sections, where the entire section is only 10 metres thick (e.g., Vegas de Sotres section). In total, 490 samples were collected in the main sections, as well as some spot samples (about 100) in other studied sections. More than 3000 thin sections (28 x 48 mm) were prepared for microfacies analysis. Classifications by Dunham (1962), Embry and Klovan (1971), Wright (1992) and Rodríguez-Martínez et al. (2010) were used to describe the microfacies. The abundance of grains, cement and matrix was visually estimated using the charts of Baccelle and Bosellini (1965).

Foraminifers were studied in 3000 thin sections for ascertaining biostratigraphy. Additionally, 170 samples of 2–11 kg were collected and processed for conodonts. The detailed biostratigraphy was published in Cózar et al. (2015, 2016, 2018a), Blanco-Ferrera et al. (2017) and Sanz-López et al. (2018). The microfossil analysis allowed a subdivision of the succession largely ranging from Mikhailovian (late Viséan) to a probable Krasnopolyanian (early Bashkirian) age according to Cózar et al. (2018a). Correlations with the regional Russian substages from the Moscow Basin follow the nomenclature used in Davydov et al. (2012, fig. 23.1).

Facies distribution and environmental interpretation

Lithological variations have been grouped in a total of 16 microfacies (Facies F1-F16), which are summarized in Table 1, and displayed in the different tectonic subunits and stratigraphic sections in Figs. 3 to 7.

Saigu subunit

Compared to the other tectonic subunits, the Saigu subunit shows a significant contribution of microbially-induced facies, mainly formed during the upper Viséan (Fig. 3). This subunit is entirely composed of the Valdediezma Limestone, and no other Mississippian aged formations are recognized within the succession. However, the vertical distribution of facies through the succession allows a subdivision into seven intervals, dependent on the predominant microfacies (numbered as I1 to I7 in Fig. 3). In the lower I1 interval of the Valdediezma valley and coinciding with rocks assigned to the Mikhailovian Substage (Viséan), there is a predominance of cementstone (sensu Wright 1992), as well as peloidal cement- and matrix supported facies (sensu Rodríguez-Martínez et al. 2010) (Facies F1 to F3 in Table 1; Fig. 3a), alternating with bioclastic cement-supported limestones (Facies F5; Fig. 3b–c). Rudstones (Facies F15) are composed of micropeloidal pebbles. Mudstone and wackestone textures (Facies F8; Fig. 3f) have negligible abundance. The most common bioclasts are crinoids, followed by fenestellid bryozoans and brachiopods. Other bioclasts are scarce and sparsely distributed. Facies with fenestrae filled with radiaxial fibrous cement (RFC) (e.g., Richter et al. 2011) and blocky cement (BC) (e.g., Flüegel 2004) are common (Fig. 3a–b). Foraminifers and cyanobacteria (mostly *Girvanella* and *Ortonella*) occur sparsely.

At outcrop, it is difficult to recognize morphological differences in the strata due to weathering of the limestone surface. Small domed-shaped morphologies are locally developed that are 8 to 20 m high and laterally extend over less than 100 m (Fig. 4a–b).

Higher up in the succession (interval I2) and during most of the Venevian (Viséan), the prevailing lithofacies are like the previous interval (Facies F1–F3). A single bioclastic cement-supported bed (Facies F5) and rudstone bed (Facies F16) occurs (Fig. 3). Skeletal remnants of fenestellid bryozoans predominate over brachiopods and crinoids. However, foraminifers are relatively common as well as cyanobacteria, Aphralysiacean, problematic Algospongia (*Claracrusta*, *Ungdarella*, *Falsocalcifolium* and *Praedonezella*; see Vachard and Cózar 2010, for the suprageneric classification of the Algospongia documented in this study), as well as the problematic bryopsidal green alga *Saccamminopsis*. The bedding morphology of the limestones is poorly observed, although the size of mounds may be larger than in the underlying interval, because bedding is not easy recognized in many intervals up to 50 m thick.

During the Venevian and most of the Tarussian (Viséan-Serpukhovian), the predominant lithofacies of the interval I3 (Fig. 3) is similar to those at the base of the section, with common cementstone and peloidal lithofacies (Facies F1–F3), alternating with bioclastic cement- and matrix-supported facies (Facies F5–F6; Fig. 3C). Crinoids are abundant, although brachiopods are the predominant skeletal component in some beds. Foraminifers are common, as well as fenestellids and the Algospongia *Praedonezella* as the main skeleton-rigid bioconstructor. Rudstones are only present in the lower Tarussian. Individual dome-shaped morphologies of lithosomes are recognized, but are smaller than at the base of the section (domes less than 10 m thick, with lateral extensions of some tens of metres). Ooidal grainstone facies occur rarely (Facies F14; Fig. 3h).

The interval from the upper part of the Tarussian to the lower part of the Protvian (Serpukhovian; interval I4) is marked by a sharp change in the lithology and components. This change is highlighted by: (i) rare cementstone and peloidal-micropeloidal cement-supported facies (Facies F1-F4), compared to the underlying intervals; (ii) predominance of bioclastic cement- and matrix-supported facies (Facies F5–F6); (iii) rudstones are composed of bioclastic and/or oolitic pebbles (Facies F16); (iv) abundant grainstone beds (Facies F13–14; Fig. 3g–h), including oolitic grainstones; (v) abundant and diverse green algae (e.g., *Eovelebitella*, *Anatolipora*, *Borladella*, *Paraepimastopora*, *Cabrieroporellopsis* and *Atractyliopsis*; see Vachard et al. 2016 for the systematics of this group). In this interval, the cementstone and micropeloidal textures are commonly capped by grainstone facies.

During most of the Protvian (interval I5 in Fig. 3), the facies returned to the previously predominant peloidal-bioclastic carbonate microfacies (Facies F5–F6), with rare mudstone, wackestone (Facies F7and F9) and rudstones (composed of micropeloidal clasts; Facies F15). Individual morphology of lenses that display dome-shaped bodies are recognized in coalesced associations (interval I5 in Fig. 4c). In contrast to the lower part of the section, they are rich in bioclasts, which mostly includes Algospongia *Calcifolium*, *Praedonezella* and *Fasciella*. Dasycladal green algae occur, and foraminifers are relatively abundant. The abundance of *Calcifolium* increases upwards, but only in the uppermost samples does it constitute 20–30% by volume, values typically present in the overlying interval.

The succeeding interval I6 represents most of the Zapaltjubian and it is mainly characterized by: (i) poorly developed microbial facies (bioclastic, as well as peloidal-micropeloidal); (ii) abundant bioclastic packstones and grainstones (Facies F10, F13);

(iii) abundant *Calcifolium* (up to 45% of the facies by volume); and (iv) highly diverse bioclastic content.

The carbonates of the uppermost Zapaltjubian and Voznesenian (Serpukhovian/Bashkirian boundary interval) contain abundant diagenetic chert nodules (interval I7 in Fig. 3). They indicate another distinct change in sedimentation style shown by: (i) rare microbial strata; (ii) a predominance of mudstones to wackestones; (iii) rather diverse bioclastic content ; (iv) the abundance of calcispheres (mostly in the lower half); (v) the lower half is also characterized by the large accumulations of small mounds (boundstones) of *Calcifolium*/*Praedonezella*, which are replaced by *Donezella* in the upper part; (vi), mudstones commonly show lumpy texture, possibly related to cyanobacteria influence (although calcified cyanobacteria filaments are rarely recognized); and (vii) the occurrence of packstone beds are rare.

The upper part of the Valdediezma Formation shows brecciated levels with mud-cracks and pedotubules in limestones near Jitu l'Escarandi, as well as in the Tresviso area. Palaeosoils *sensu stricto* containing clays have not been recognized. Thes brecciated levels occur 20 m below the breccia that separates the Valdediezma Limestone from the Triassic red beds in the Jitu l'Escarandi section. In the Cheese Cave area (Sobra Valley), grainstones of *Penella* with superficial ooidal coatings (interpreted as spores of green algae by Flügel 2004), typical ooidal grainstones, and one coral horizon occur in the uppermost interval (60–80 m thick). This interval was considered as possibly Krasnopolyanian in age (lower Baskhirian) according to Cózar et al. (2018a).

*Interpretation.***—** The lower interval I1 (Mikhailovian) is interpreted to comprise small stacked and amalgamated microbial carbonate mounds forming a complex mound system (Somerville et al. 1996; Fernández et al. 2006; Rodríguez-Martínez et al. 2012). These mounds are only locally interrupted by capping beds in the upper part of the buildups (rudstones), when the bioconstructions grew-up into more turbulent water conditions, above the storm wave base. The occurrence of sparse cyanobacteria suggests at least dysphotic conditions (Lees and Miller 1995; Cózar et al. 2019). Due to the relative abundance of bioclasts, a proximal outer platform setting is interpreted for this interval, like similar interpretations of microbial mounds of equivalent age in southern France (Cózar et al. 2019).

The interval I2 also contains microbial mounds with common cyanobacteria and Algospongia, which suggest at least dysphotic to euphotic conditions on the platform (Lees and Miller 1995). Due to the lowest abundance in bioclasts, as well as the predominance of fenestellids, a facies change to a more distal outer platform setting is suggested, compared with the previous Mikhailovian interval. The occurrence of breccias composed of micropeloidal pebbles is likely the result of currents or storms that reworked the top of the carbonate mounds (Rodríguez-Martínez et al. 2012).

In the interval I3 (upper Venevian-Tarussian), environmental conditions are interpreted as rather similar to those at the base of the succession, in a proximal outer platform setting, which rarely reached storm wave-base (especially in the lower part of the interval). Individual mounds are smaller than in the underlying intervals.

The interval I4 (upper Tarussian-lower Protvian) shows a change in the platform facies, interpreted as very shallow-water depositional environments above the fair-weather wave-base (FWWB), with common grainstone facies capping the growth of mounds. The green algae are as abundant in the mounds (in situ) as in the grainstone beds (transported). Such abundance of green algae in Mississippian microbial facies is only known in the Montagne Noire of France (Cózar et al. 2018b, 2019). The inferred shallow-water conditions, even with some levels reaching the wave-base, suggests a distal inner platform setting. The common packstone and breccia beds are interpreted as storm-related deposits in a shallow-water setting.

The interval I5 (Protvian in age) suggests the microbial mounds developed in an environment of slightly deeper water than in the underlying Tarussian-lower Protvian interval. Although still in rather shallow-water conditions in the proximal outer platform it was rarely affected by storms . Individual morphology of the mounds is still recognizable.

The Zapaltjubian interval I6, is characterized by packstones interpreted as tempestites, but also with common oolitic grainstone beds (incipient bars; Rankey et al. 2006), which suggest frequent intertidal conditions. Hence, these sediments were probablyl deposited in a distal setting of the inner platform. The microbial boundstones did not form domical shapes but instead, occur as stratiform layers among the bioclastic beds (interval I6 in Fig. 4c).

The interval I7 (Zapaltjubian-Voznesenian) shows marked lithologic differences compared to the underlying intervals. Here the carbonates seem to have accumulated in low energy protected areas, between the fair-weather storm-base (FWSB) and the FWWB, somewhat similar to lagoons, although the location of a fringing margin of the platform is unknown. A possibility is that the previous microbial mounds developed palaeorelief allowing areas of protections from storm and tidal currents, but not generating true restricted lagoons, because high bioclastic diversity indicates unrestricted water circulation. Similarly protected areas behind Mississippian microbial mounds and bioclastic shoals are known in basins from southwest Spain (Cózar et al. 2006), as well as in other time periods (e.g., Read 1985; Blomeier and Reijmer 1999; Tucker 2003; Flügel 2004; Bosence 2005). However, this low-energy environment was occasionally influenced by storm episodes, characterized by packstone facies, and locally oolitic bars occur in the Cheese Cave area. The occurrence of mud cracks and pedotubules suggest subaerial exposure of the upper part of the succession, indicating a shallowing trend and emersion of the platform, although the absence of well-developed palaeosols could be due to non-preservation caused by post-Bashkirian erosion.

Las Llamas-Bejes and La Hermida subunits

These successions are exemplified by the Pompedrei Bridge section (in Las Llamas-Bejes subunit; Fig. 5). The carbonates assigned to the Protvian (Serpukhovian) are predominantly packstones (Facies F11 in Table 1; Fig. 5a), and rarely bioclastic grainstones and mudstones (Facies F7, F13). Packstones and grainstones are usually medium- to coarse-grained, showing moderate to good sorting, and a high degree of packing. Parallel and cross-laminations are recognized. Fining-upward sequences, as well as coarsening-upward sequences occur rarely (Fig. 5b). The bioclasts are highly fragmented, with the main bioclasts being crinoid, bryozoans and brachiopods. *Praedonezella* fragments and micritic lithoclasts are relatively common. Grainstones show similar bioclasts and a higher abundance of calcispheres. Interbedded mudstones mostly contain ostracods and crinoid fragments.

The overlying Millaró Member (youngest member of the Alba Formation; Fig. 2a) is more bioclastic than the nodular limestones and shales with ostracods and cephalopods typically described from the CZ. The member is composed of mudstones, packstones and breccias (Facies F7, F11, F16; Fig. 5) interbedded with black siliceous shales and cherts. Limestone facies are predominantly mudstones (Fig. 5c), rarely wackestones, but bioclastic horizons occur. Some beds contain a significant amount of large bioclasts (crinoids, *Calcifolium*, *Praedonezella* and foraminifers in decreasing abundance order), although generally limestones are very fine-grained (Fig. 5d) and also contain typical open marine bioclasts (e.g., radiolarians, ostracods, sponge spicules, thin-shelled molluscs). These bioclastic beds show parallel to wavy lamination with preferred orientation of *Calcifolium*, and are well-sorted with a high degree of fragmentation. Rudstones show varied facies ranging from bioclastic wackestone-packstone to mudstone, rarely micropeloidal.

A 20 m-thick interval of the Barcaliente Formation is recognized above the Millaró Member. It is mostly composed of organic-rich black mudstones containing ostracods, sponge spicules and radiolarian casts. In addition, there are very thin layers (1–3 cm thick) of pale grey limestone, mostly peloidal to bioclastic cementstone and wackestones (Fig. 5e–f) with parallel lamination, with fining-upwards sequences (Fig. 5g). Some rudstone, mudstone-wackestone and microbial facies are recorded in the Pompedrei Bridge section (Facies F6), which probably represents a continuation of the facies recorded in the Millaró Member.

The Barcaliente Formation is overlaid by a substantial thickness of clotted facies of the Valdediezma Limestone deposited during the uppermost Zapaltjubian and the Voznesenian (about 350–400 m in the Sierra de Bejes). Textures are mostly cementstones and cement-supported micropeloidal facies (Fig. 5h), interbedded with rare mudstones. Thick massive stratification dominates and dome-shape mounds were not observed in the field. The younger part of the succession is characterized by more bioclastic clotted limestones, locally developed as non-microbial packstones and wackestones.

Interpretation.— The basal grainstone and packstone deposits developed during the Protvian, are interpreted as turbidites, whereas the rare interbedded mudstones formed the background slope sedimentation (e.g., Reijmer et al. 2012, 2015; Cózar et al. 2017).

In the Millaró Member (described as a condensed pelagic limestone-shale interval in the Cantabrian Zone according to Sanz-López et al. 2004, 2007), the carbonates recorded in the Pompedrei Bridge section are interpreted as turbidites (wackestone and packstones) with background slope sedimentation of mudstones and shales. Rudstones are considered distal debris flows due to the small size of the clasts (Flüegel 2004; Payros and Pujalte 2008; Reijmer et al. 2015). The very distal turbidite sedimentation with more frequent open marine fauna (Reijmer and Everaars, 1991), and the siliciclastic component in the black shales, suggest a distal slope or toe-of-slope environment for the Millaró Member.

A predominance of suspension background sedimentation in a quiet and restricted basin is inferred for the Barcaliente Formation, which was interrupted by very distal turbidites in the CZ (Evers 1967; Hemleben and Reuther 1980). Some authors have suggested restricted circulation and a degree of temporal anoxia on the sea-bottom, based on the laminated limestones, presence of organic matter, and scarce fossil content (Reuther 1977; Sanz-López et al. 2013). Well-oxygenated sea bottom periods must have alternated with poorly oxygenated conditions because bioturbation is present (Hemleben and Reuther 1980). A moderate water depth in the outer continental shelf has been inferred from bioturbation fabrics (Reuther 1977), with common ichnofossils *Scalarituba*, *Muensteria*, rare *Phycosiphon*, *Gyrophylles*, *Neonereites* and the absence of meandering forms, and burrows of suspension feeders.

The overlying Valdediezma Limestone represents a marked change from the deep-water settings of the Barcaliente Formation. Boundstones of microbially-mediated facies are prevalent, although mound morphologies are not recognized. These boundstones contain poorly represented bioclastic facies and seem rather different from the microbial mounds observed in the platform facies of the Saigu subunit. This poverty of bioclasts is interpreted to characterize the deepest part of the outer platform, or possibly development on the uppermost slope (Cózar et al. 2019). In the upper part of the section, capping beds are present, as well as the slightly richer bioclastic content, which are more typically developed on distal outer platform settings.

A similar succession of microbial and bioclastic-microbial limestones, but cut by faults, occurs in the path from the Jitu l'Escarandi to the Casetón de Andara section in the western part of the same tectonic subunit (Fig. 2b).

Mesa Sin Pan subunit

The Tournaisian to upper Viséan part of the Mesa Sin Pan section shows a reduced thickness compared to other parts of the succession and a lower abundance of skeletal grains (Fig. 6a). At the base occurs two metres of reddish mudstone to wackestone with bryozoans and echinoderm fragments, partly as coated grains enriched in ferrous oxides (Facies F12 in Table 1). Conodonts indicate the upper Tournaisian *Scaliognathus anchoralis* Zone with *Gnathodus mirousei*, *G. pseudosemiglaber* and *Vogelgnathus simplicatus*. Above are about 45 m of mudstones and wackestones (Facies F7–F9), breccias and micritic-peloidal cement- supported and matrix-supported beds (Facies F2-F4). Laminated dark grey to black mudstones with radiolarians represent intervals of quiet and deep-water sedimentation. Grey-coloured skeletal wackestones and packstones show fining-upward sequences and parallel lamination. Rudstone beds consist of micropeloidal pebbles and locally show reddish colour associated with stylolites.

Above is an upper Serpukhovian interval composed of limestone with black shales and cherts, suggesting a correlation with the Millaró Member of the other tectonic units. Carbonates in this interval are composed of mudstone to bioclastic packstone beds (see facies in Table 1).

Higher up in the succession, a 100 m-thick interval of Zapultjubian age consists of cementstones and micropeloidal textures, with low bioclastic content, dominated by *Praedonezella*, fenestellid bryozoans and crinoids. It corresponds to thick-and massive bedded limestones with rare rudstone beds.

In the upper part of the succession, the Barcaliente Formation is more than 150 m thick below the Triassic . Lowermost Bashkirian conodonts occur about 130 m above the base of the formation (sample MSP-5 in Fig. 6).

Interpretation.**—** The abundance of beds with skeletal and reworked grains and rare microbial mudstone occurrences (interpreted as small mounds) suggest a toe-of-slope setting for the lower part of the succession.

The upper Serpukhovian mudstone to packstone beds were deposited as turbidites on the slope and the toe-of-slope, where micrite represents the background sedimentation, similar to the better preserved beds of the Millaró Member in other sections.

The second interval of the Valdediezma Limestone (Zapaltjubian age) contains textures and bioclasts which suggest microbial mounds in deep-water conditions, similar to those in the upper part of the Pompedrei Bridge section.

The overlying Barcaliente Formation contains only scarce and distal turbidite beds in a prevailing quiet and deep-water environment.

Varera subunit and ACVS thrust sheet

The Varera tectonic subunit (Fig. 2b) includes a slice of basal Cambrian rocks below the Alba Formation and the Valdediezma Limestone (Argaña section, Fig. 6b). The Alba Formation occurs below the Valdediezma Limestone in the ACVS (southwards of the Tejo unit). It consists of ammonoid-bearing nodular pink to reddish to grey limestone. The nodular to well-stratified lime mudstone to wackestones commonly display bioturbation, ferromanganese crusts over the intraclasts and bioclasts, as well as hardground surfaces. Fossil content is concentrated in bioclastic bands and includes sponge spicules, ostracods, conodonts, radiolarians, ammonoids and more rarely crinoids, molluscs, bryozoans, brachiopods and trilobites. Bioclastic limestones are abundant in the upper five meters of the Canalón Member in the Cueto de los Senderos and Vegas de Sotres sections (Figs. 6c, 7). These beds are commonly 2 to 5 cm thick, and interbedded with mudstone-wackestone to packstones. Elongated bioclasts show a slight preferred orientation and locally cross-lamination to wavy-lamination occur. Those beds do not differ significantly from the overlying Valdediezma Limestone, except for the prevailing pinkish colour of the nodular limestone.

Higher up, the well-bedded Valdediezma Limestone consists predominantly of packstones to wackestones, in beds that are 5 to 20 cm, rarely up to 50 cm thick, often with irregular bases and tops (lithological unit 2 in Figs. 6–7). Rarely, thin pale grey nodular beds are interbedded. Shale partings of millimeter thickness occur rarely. The main feature of the Valdediezma Limestone is the high bioclastic content, with a relative mixture of typical deep-water fossils (sponge spicules, radiolarians) and more typical shallow-water organisms (abundant foraminifers, abundant calcispheres, *Kamaenella*, brachiopods). Th ebioclasts are always fine- to very fine-grained, although the amount of micrite matrix varies significantly, resulting in a range of mudstone to packstone textures (locally grainstones; Facies F12; Fig. 7c–g). Fining-upward cycles occur, but coarsening-upward cycles are more common (less than 1 cm thick, and up to 4–5 cm thick). The mudstones contain sponge spicules and ostracods like those in the Canalón Member (reddish to pink), but with a different colour (pale grey).

The overlying dark grey limestone (lithological unit 3 in Figs. 6–7) consists of intraclastic-bioclastic mudstones to rudstones (Fig. 7h), with chert nodules. Packstone levels show grading. Angular intraclasts are commonly observed within the mudstone and wackestone textures and, rounded grainstone intraclasts occur rarely. Pebbles include bioclastic packstones and grainstones from shallow-water settings (common algospongiids, foraminifers, bryozoans, ostracods, molluscs, as well as rare conodonts, sponge spicules, trilobites and red algae), including silicified macrofossils (solitary and branching rugose corals, brachiopods and crinoids). The diverse foraminiferal assemblages recognized in this unit, with typical taxa of the shallow-water platform is a noteworthy feature (see full list of taxa in Cózar et al. 2016, 2018a).

Interpretation.**—** The typical griotte nodular limestones exposed at the base of the sections have been interpreted as deep-water and condensed sediments that were deposited at a depth of some hundreds of metres (Tucker 1974; Wendt and Aigner 1985). The bioclastic horizons mostly recorded in the uppermost part of the Alba Formation are interpreted as distal turbidites.

Bioclastic beds of the Valdediezma Limestone are mostly interpreted as turbidites deposited in a hemipelagic setting that transported material from the outer part of a shallow-water platform into the basin. This inference is based on the predominant foraminiferal genera recorded in the resedimented material, such as the lasiodiscids, suggesting a calm environment in the outer platform and highly tolerant genera (such as the archaediscids, *Mediocris* and *Tetrataxis*, according to Cózar and Rodríguez 2003). The inverse grading observed in numerous beds, may represent typical turbidites alternating with turbidites reworked by deep-water bottom currents (e.g. Stanley 1988; Rebesco et al. 2014; Shanmugam 2017), suggestive of a distal slope setting, inferred from the size as well as the occurrence of reworking (i.e. contour currents).

The deposition of unit 3 corresponds to a lower slope setting with debris-flow deposits within the turbidite system. Grainstone intraclasts and its fossil content suggest transportation from shallow-water platform facies, whereas intraclasts of mudstone to wackestone seem to have been derived from microbial mounds developed in the upper slope or from early cemented beds on a stepped slope.

Discussion

Reconstruction of the Valdediezma platform

The environments of the Valdediezma platform are reconstructed based on stratigraphic profiles from a northwest to southeast transect across the different tectonic subunits (Figs. 2b, 8). Outer (below the FWSB) to distal inner (above the FWSB and commonly affected by the FWWB) platform facies are preserved in the Saigu subunit, outer platform to slope facies are in the Las Llamas-Bejes and La Hermida subunits, and toe-of-slope and basin facies occurs interbedded in the Las Llamas-Bejes subunit (Millaró Member and Barcaliente Formation). The lower slope to toe-of-slope and basin settings are interpreted for the Mesa Sin Pan section, where the Barcaliente Formation partly interdigitates with the upper part of the Valdediezma Limestone. Although the thrust sheets do not allow continuous lateral facies changes to be recognised, the correlation of the sections suggests a platform margin with an approximate southwest to northeast trend (current geographic coordinates). The transition from the platform into the basin in the southwest is apparently more abrupt compared to that in the southeast, because below the Saigu subunit, the Varera subunit consists of several slices with different stratigraphy and important fault movements related to the San Carlos Fault. The northern margin of the Valdediezma platform is buried below the Gamonedo-Cabrales thrust sheet, and Mesozoic rock cover in its eastward continuation. The shallow-water platform in the Tejo unit extends for some 5 by 28 kilometres. According to the reconstruction of the open Asturian Arc by Pastor-Galan et al. (2011), the original orientation of the core of the Picos de Europa province remained unaltered, and thus, the original orientation of the Valdediezma platform was similar to the current orientation.

Shallow-water sedimentation was initiated in the upper Tournaisian based on the conodont evidence indicating the oldest transported sediments in the Mesa Sin Pan subunit (Fig. 8). There, lower to upper Viséan carbonate breccias are at the toe-of-slope, together with thin microbial boundstone beds. High carbonate production rates during the upper Viséan to lower Serpukhovian (associated with the higher sedimentation rate of microbial mounds), are recognized in the carbonate platform facies of the Saigu subunit (Fig. 8). The microbial mound growth occurred from the outer platform to the upper slope. Boundstones of several metres palaeoheight and similar width occurred on the shallow-water platform, whereas thick and massive-bedded limestones are observed in the outer part of the platform. The thickness and facies of the Valdediezma Limestone in the Saigu and the Las Llamas-Bejes subunits (about 520 m) contrast markedly with the thinness of the condensed sections in the southern toe-of-slope and basinal facies (from 10 to 60 metres). These abrupt changes in the Mississippian successions suggest a steep margin for the platform (Fig. 8), possibly induced by the rapid growth of the microbial boundstones. The rapid sedimentation rate of microbial mounds is a common feature in the younger Pennsylvanian carbonate platform of the CZ and in other platforms known from the geological record, causing high-relief carbonate platforms with step margins (e.g., Bechstädt et al. 1985; Neuweiler 1993; Kenter et al. 2005; Bahamonde et al. 2007; Olivier et al. 2011).

Calciturbidites with bioclasts that were derived from the shallow-water platform formed a lateral wedge, which extended to the southern part of the basin. Progradation of this wedge is recognized from the upper Viséan (Venevian) based on the evidence of interbedded units within the Canalón Member of the eastern part of the ACVS. An increase in the amount of transported sediments is recognised from the lower to the upper Serpukhovian (Tarussian to Protvian). The lateral wedge thins along the toe-of-slope, from a maximum of ca. 140 m in the Argaña, Pompedrei Bridge and Mesa Sin Pan sections (Tejo unit) to less than 10 m at the Vegas de Sotres section in the south (ACVS; Fig. 8). Protvian bioclastic and intraclastic limestones occur in the outer platform to slope transition (Las Llamas-Bejes and La Hermida subunits). Debris flows are scarce but breccias occur in the Protvian of unit 3 at the Vegas de Sotres section. These facts, together with the different thicknesses between the shallow-water and the basinal carbonates, suggest a steep-fronted platform margin

The disappearance of calciturbidites during the upper Serpukhovian in the ACVS coincides with the Millaró Member or a thick interval (20 m thick) in the southern margin of the Valdediezma Limestone (Las Llamas-Bejes and Mesa Sin Pan subunits; Fig. 8). This member was deposited during an extended drowning episode at the top of the Alba Formation in the CZ. It was described as a condensed, pelagic deep-water limestone-shale interval with abundant benthonic and nektonic faunas by Sanz-López et al. (2004, 2007). The Millaró Member includes thin distal deposits with platform-derived bioclasts in the Tejo unit and its occurrence there suggests back-stepping of the platform area with high carbonate production (Fig. 8).

The microbial and skeletal carbonate factory fed sediments to the area of the southern slope of the Valdediezma platform, starting in the upper Serpukhovian (Zapaltjubian in Fig. 8; Las Llamas-Bejes, La Hermida and Mesa Sin Pan subunits). This shallow-water interval is absent in the Barcaliente Formation of the ACVS. Thicknesses (and accumulation rates) are similar for the upper part of the Valdediezma Limestone and the Barcaliente Formation, contrasting with divergent thicknesses of the Alba Formation and the lower part of the Valdediezma Limestone (Fig. 8). This similar thickness in carbonates of the upper Valdediezma Limestone and the Barcaliente Formation coincides with the upper Serpukhovian, high rate of subsidence and deepening trend of the foreland system of the CZ (Sanz-López et al. 2013).

The latest Serpukhovian-early Bashkirian deep-water carbonate sedimentation of the Barcaliente Formation extended from the foreland margin into the foredeep (filled by siliciclastic turbidites) in the westernmost CZ (Sanz-López et al. 2006). It coincides with the deposition of the Barcaliente Formation on the southern margin of the Valdediezma platform (Las Llamas and Mesa Sin Pan subunits in Fig. 8). The Barcaliente Formation shows high accumulation rates in a moderately deep basin with carbonate sediment re-distributed by currents. The accumulation rate on the platform and the basin were similar and subsidence rates are likely similar between both areas. (Fig. 8). The shallow-carbonate platform showed continued growth during sedimentation of the Barcaliente Formation into the early Bashkirian (Krasnopolyanian, Kinderscoutian). Microbial boundstones and skeletal limestones occurred in the outer platform to slope (Las Llamas-Bejes subunit), whereas microbial mounds and bioclastic shoals sheltered low-energy areas on the inner platform (Saigu subunit).

The Valdediezma platform is interpreted as an isolated shallow-water platform (in the sense of Read 1985), or an unattached platform or major offshore bank in the sense of Bosence (2005). This platform developed in a starved basin with prevailing pelagic sedimentation of cephalopod-bearing nodular limestone (Alba Formation) in the western margin of Palaeotethys Ocean during the upper Tournaisian-Serpukhovian (Sanz-López et al. 2018). In the western part of the Palaeotethys Ocean, there was a shallow-water carbonate ramp also known from the late Tournaisian of the Montagne Noire (South France) to the late Serpukhovian (Protvian), although mainly reconstructed from olistoliths and klippes (Vachard et al. 2017; Cózar et al. 2017, 2019). Microbial mound development on these carbonate ramps and siliciclastic platforms was contemporaneous with deep-sea fan sedimentation in the Montagne Noire basin from the late Viséan (Mikhailovian age). This age interval corresponds to the high carbonate production observed in the Valdediezma platform, which persisted from the latest Serpukhovian to the early Bashkirian, when Variscan deformation had exhumed the Montagne Noire ramp. This tectonic event may relate to the late Serpukhovian deepening trend of the Millaró Member in the CZ. The previous Serpukhovian progradational wedge associated with the accumulation of microbial boundstone of the Valdediezma platform, also coincides in time with the Serpukhovian progradational wedge described by Collins et al. (2006) in the Tengiz build-up in the subsurface of the Precaspian Basin (Kazakhstan) also part of the Palaeotethys Ocean. Relationships of the Valdediezma progradational wedge with Variscan tectonics and/or eustacy are yet to be analyzed.

Nucleation of the platform

The substrate of the Valdediezma Limestone seems to be the Cambrian rocks that are tectonically detached in the Varera subunit. Erosion of the sedimentary sequence down into middle Cambrian rocks is the deepest known below the uppermost Devonian-Mississippian unconformity of the CZ. This erosion was previously inferred to be related to the westwards tilt of the passive margin and denudation of the peripheral bulge in the foreland basin (Martínez García 1978; Keller et al. 2007). An alternative is that the initial growth of the Valdediezma platform may have started on a submarine topographic high that induced carbonate sediment accumulation in the Tejo unit. The Picos de Europa Province (where the Valdediezma platform developed) has been recognized as a block displaying submarine relief during the Mississippian (Eichmüller and Seibert 1984). Basin segmentation into uplifted blocks and troughs bounded by extensional faults was interpreted on the basis of facies distributions, the occurrence of breccias, debris flows and slump deposits in the Alba Formation, although actual faults responsible were not identified (Wendt and Aigner 1985). Distribution of chert and shale sedimentation (of the Lavandera Member) associated with troughs, suggests location of submarine relief in areas with carbonate sedimentation (Fig. 9). Thus, the Valdediezma Limestone seems to correspond to an isolated platform developed on a horst structure (e.g. Blomeier and Reijmer 1999). Sedimentary highs and basins (probably horst and graben topography) have been similarly interpreted from Mississippian pelagic carbonate deposits of southern Europe, from the Pyrenees, Catalonian Coastal Ranges and the Southern Alps (Schönlaub and Histon 2000; Sanz-López et al. 2000, Sanz-López 2002; Casas et al. 2019).

Demise of the platform

Hemleben and Reuther (1980) proposed a shallowing trend in the upper part of the Barcaliente Formation, ending in an interval with channel development, in situ brecciation, laminations interpreted as stromatolite colonization of the sea bottom, and pseudomorphs of evaporitic crystals (see also Reuther 1977; González Lastra 1978). This shallowing trend spans the uppermost Serpukhovian-lower Baskhirian interval according to Sanz-López et al. (2013), where carbonate accumulation compensates for the basin subsidence, promoting expansion of carbonate sedimentation over the siliciclastic turbidites previously deposited into the foredeep. The occurrence of evaporites and stromatolites suggests high salinity conditions during an early Bashkirian event, but not necessarily a littoral intertidal zone. Both could have occurred in the deep-sea-water restricted basin of the Barcaliente Formation and was clearly differentiated from the contemporaneous shallow-water Valdediezma platform. The shallowing trend in the Barcaliente Formation ended with the occurrence of an intraformational breccia (Porma Breccia) in most areas of the CZ . Shallowing events in the Voznesenian/Krasnopolyanian age interval of the Valdediezma and Barcaliente successions units seems to be associated with the eastward migration of the foredeep basin depocenter in the CZ. Strong flexure of the active foreland was caused by nearby thrust loading and subsequent filling of the foredeep by Bashkirian to early Moscovian deltaic systems (Marcos and Pulgar 1982); to be followen, by the carbonate platforms of the Valdeteja Formation developed on the adjacent foreland margin (Eichmüller 1985; Bahamonde et al. 2015; Chesnel et al. 2016). The strong flexure of the active foreland and the migration of the forebulge area eastwards, also caused the exhumation of the Valdediezma platform at the distal craton edge, based on the non-deposition (or erosion) of the lower Bashkirian to Moscovian strata. Flexure of the foreland would have generated significant seafloor relief differences between the Valdediezma platform (several hundreds of metres thick) and the basinal carbonates (where the Alba Formation is ca. 10 metres thick, Fig. 10).

Although sedimentation of the Valdediezma Limestone stopped in the early Bashkirian, Pennsylvanian microbial boundstone-dominated carbonates accumulated in the basin adjacent to the Valdediezma platform due to the relief on the palaeo-seafloor. The Bashkirian- Moscovian platforms accumulated some 720 m of thickness and covered more than 12,000 km^2 according to Bahamonde et al. (2007). These authors differentiated a Bashkirian carbonate ramp (Valdeteja Formation) which evolved to a Moscovian-lower Kasimovian flat-topped carbonate platform with steep margins (Picos de Europa Formation). The inner facies of both platforms were located in the Tejo unit where the older Valdediezma platform is now recognized (Fig. 10).

The burial of the Valdediezma Limestone by the uppermost part of the Picos de Europa Formation corresponds to the tectonic subsidence of the Picos de Europa Province starting from the late Myachkovian (latest Moscovian). According to Merino-Tomé et al. (2009) this subsidence was related to the thrusting and southwards emplacement of the Ponga Nappe Province (Figs. 2b, 10).

Conclusions

The Valdediezma Limestone was deposited on an isolated platform located in the distal margin of the Carboniferous Variscan foreland (Picos de Europa province). The onset of this carbonate platform started during the upper Tournaisian on a topographic high differentiated from the deep-water sedimentation of griotte limestone in the starved basin. The oldest skeletal and lithoclastic sediments with rare microbial limestones crop out only locally. A high subsidence rate balanced by high carbonate production in shallow-water settings resulted in the accumulation of some 800 m of platform succession from the upper Viséan to the lower Bashkirian. Differences in the accumulation of carbonates in the platform and the basin, and the studied slope facies, suggest the Mississippian high-relief platform formed pior to the well-documented Pennsylvanian platforms in the CZ. Sediments derived from the shallow-water platform extended southwards as a thin lateral wedge that accumulated at the toe-of-slope and basin from the upper Viséan but mainly during the Serpukhovian. The progradation of this wedge ended in the upper Serpukhovian when drowning was recorded on the platform margin. This drowning coincided with a regional, deepening event in the CZ (coeval with the Millaró Member), which increased the faunal abundance in the deep basin. Higher subsidence and sedimentation rates in the foreland were associated with the migration of the foredeep at the western margin of the CZ and the supply of synorogenic siliciclastics supplied from the active orogenic front. The moderately deep-water carbonate sedimentation of the Barcaliente Formation was restricted to the foreland margin where occasionally restricted bottom circulation favoured a stratified water column, whereas nearby high productivity was maintained inthe water surface. At this time, the shallow-water carbonate material derived from the Valdediezma platform was deposited on its southern margin. Between the uppermost Serpukhovian and the early Bashkirian, the Valdediezma platform retreated, and finally a during the Voznesenian-Krasnopolyanian, a shallowing trend is seen that coincides with that recognized in the basinal Barcaliente Formation. The demise of the Valdediezma platform was caused by its uplift during the migration of the successive foredeep depocenters, and flexure of the forebulge, generating seafloor topographic relief. Pennsylvanian carbonate platforms attached to this relief, which subsequently collapsed and were buried by upper Moscovian shallow-water carbonates.

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Figure Captions

Table 1 Lithofacies of the Valdediezma Limestone.

Fig. 1 Location of the study area and the Valdediezma Limestone (black) within the Cantabrian Zone and the different tectonostratigraphic units or provinces, particularly them the Picos de Europa Province within the study area. (1) Millaró section, (2) Alba Syncline.

Fig. 2a The main lithostratigraphic units from the Famennian (Devonian) to the Moscovian (Carboniferous) in the Picos de Europa Province (Aliseda-Cabrones-Vegas de Sotres and Tejo tectonic units) in comparison with those typical of the Cantabrian Zone. **b** Tectonics subunits distinguished in the Tejo unit and location of the studied stratigraphic sections: (I) Argaña, (II) road to Sotres, el Bosque-Navayu, (III) Valdediezma valley, (IV) Jitu l'Escarandi, (V) Cheese Cave in the Sobra valley, (VI) road from the Jitu l'Escarandi to the Casetón de Andara, (VII) Pompedrei Bridge, (VIII) La Hermida, (IX) Mesa Sin Pan, (X) Cueto de los Senderos, (XI) Vegas de Sotres.

Fig. 3 Stratigraphic log of the Valdediezma Formation at the Valdediezma-Jitu l'Escarandi section (Saigu subunit) on the left side showing the recognized facies (1 to 16 as in Table 1). Abbreviations: mc microbial, m mudstone and shales, m-w mudstone-wackestone, w-p wackestone packstone, g grainstone, r rudstone and floatstone. On the right side, thin-section photos of the main microfacies (scale bar in the pictures = 2 mm; way-up is to the photo top). **a** Micropeloidal to peloidal (upper part) cement-supported texture (Facies F2). In the middle, a large fenestral cavity with RFC and poorly developed blocky cement. *Terebella*-like tube (t), faecal pellets (p), crinoids (c) and ostracods are observed, Pc4946. **b** Bioclastic cement-supported texture (Facies F5) rich in fenestellids bryozoans (f), brachiopods (b) and crinoids (c), Pc4285. **c** Bioclastic matrix-supported passing into bioclastic cement-supported texture (Facies F5 and F6). Contact between both textures is gradual (particularly rich in foraminifers) and it is oblique the upper top of the bed, Pc4975. **d** Mound-intermound facies alternation, with peloidal matrix-supported textures (p) (Facies F3) veneered by a cyanobacterial crust (cy). Above, a bioclastic grainstone (g) (Facies F13) is filling the palaeorelief of the microbial facies, with common oncoids (o), passing into the upper part to micropeloidal textures (m) with brachiopods (b) and incrusting foraminifers (*Pseudolituotuba gravata*, pg), Pc4976. **e** Poorly sorted and fragmented wackestone (Facies F9) containing molluscs with micritic rims around the bioclasts, Pc4960. **f** Bioturbated mudstone-wackestone (Facies F8) rich in calcispheres, foraminifers and ostracods, Pc4957. **g** *Calcifolium* grainstone (Facies F13), Pc4953. **h** Ooids and cortoids in grainstone (Facies F14) in the intermound facies. Foraminifera and dasycladales are common, Pc4971.

Fig. 4a Two microbial mounds (base and top highlighted with dotted lines) in the lower part of the Valdediezma Limestone close to the trail between the Jitu l'Escarandi and Bejes (Valdediezma valley). **b** Lower part of the Valdediezma Limestone (interval I1), where one buildup is highlighted. The base of the picture corresponds to sample Pc 4948, and the top of the hill corresponds to sample Pc 5967 (Fig. 3). **c** Upper part of the Valdediezma section, at Jitu l’Escarandi with laterally amalgamated mounds (interval I5, corresponds to samples Pc 5073 to Pc 5935), solid line at the base corresponds to a fault; bioclastic facies and microbial mounds in interval I6 (equivalent to samples Pc 4951 to Pc 4957), most of the bioclastic facies does not crop out apart from the road section, and most of the observed limestones in this interval correspond to microbial mounds. Microbial mounds are almost absent in the interval I7 (upper part of the sections in Fig. 3).

Fig. 5 Stratigraphic log of the Pompedrei Bridge section (Las Llamas-Bejes subunit) on the left side, showing the recognized facies (1 to 16 as in Table 1). Abbreviations as in Fig. 3. On the right side, thin-section photos of the main facies (scale bar = 1 mm; way-up to the top of the picture). Dark arrows are the samples for foraminifers and sedimentology. **a** Medium-grained well sorted packstone (Facies F11), Valdediezma Limestone, Pc5108. **b** Microsequences of wackestone to packstone (Facies F12) Valdediezma Limestone, Pc5105. **c** Typical bioturbated mudstones to wackestone (Facies F8) of the Millaró Member, Pc5009. **d** Bioclastic-intraclastic packstone intercalated (Facies F11) in the Millaró Member, note that foraminifers and *Praedonezella* (most of the pale grey small clast in the matrix) are common, Pc5118. **e** Cement-supported micropeloidal limestone (Facies F2) with common small stromatactis cavities with a thin rim of radiaxial cement and blocky spar at the base of the Barcaliente Formation, Pc5119. **f** Bioclastic packstone-wackestone (Facies F10) layer with crinoids and *Calcifolium* (c) within the lower part of the Barcaliente Formation, Pc5120. **g** Laminated micrites (Facies F7) with spicules in the lower part, typical of the Barcaliente Formation, and an upper layer (Facies F8) displaying a finning-upward sequence (with spicules, ostracods and foraminifers), Pc5121. **h** Recrystallized cementstone (Facies F1) with ghosts of algae and bioclasts with micrite coatings, Valdediezma Limestone, Pc5123.

Fig. 6a Stratigraphic section of the Mesa Sin Pan section (Mesa Sin Pan subunit). Dark arrows indicate the position of foraminifers and sedimentology samples, white arrows mark position of conodont samples. **b** Stratigraphic section of the Argaña section containing the Alba and Valdediezma formations (Varera subunit). **c** Stratigraphic logs of the Alba Formation and the interbedded Valdediezma Limestone in the Cueto de los Senderos section, in the Aliseda-Cabrones-Vegas de Sotres unit. Abbreviations: BAS. Bashkirian, C Canalón Member, G Gorgera Member, Mill. Millaró Member, Prot. Protvian. S. Steshevian, Taru. Tarussian, Vozne. Voznesenian.

Fig. 7 Stratigraphic log of the Vegas de Sotres section (Aliseda-Cabrones-Vegas de Sotres unit) on left side, showing the recognized microfacies (F7 to F16 as in Table 1). Abbreviations: mc microbial, m mudstone and shales, m-w mudstone-wackestone, w-p wackestone-packstone, g grainstone, r rudstone, floatstone and Bar Barcaliente. Note that the same facies are in pink and grey colours. On the right side, thin section photographs of the main microfacies (scale bar = 2 mm; way-up to the top of the picture). **a** Radiolarian mudstone to wackestone (right), ferromanganese concentrations in stylolites (Facies F7), Canalón Member, VSF-101. **b** Bioturbated wackestones with ostracods and sponge spicules, ostracods mark a poorly defined low-angle cross-lamination (Facies F8), Canalón Member, VSF-103. **c** Wackestone to packstone in coarsening-upward sequence (Facies F12), Valdediezma Limestone, VSF-14g. **d** Mudstone (m) at the base with bioclastic wackestone (w)-packstone (p) coarsening-upward (Facies F12). The upper wackestone is separated by another erosive surface, Valdediezma Limestone, lower part of VSF-18 (see also F). **e** Microsequence passing from wackestone to grainstone (Facies F12), Valdediezma Limestone, VSF-7. **f** Upper part of the sequence in D, with a grainstone (Facies F12) showing a distinct erosive surface separating it from a packstone containing micritc intraclasts. Valdediezma Limestone, VSF-18. **g** Packstone passing into wackestone in a fining-upward microsequence (Facies F12), Valdediezma Limestone, VSF-4e. **h** Rudstone (Facies F16) composed of intraclasts of grainstone (g), packstone (p) to mudstone with radiolarians (m) in a wackestone matrix with many small intraclasts, Valdediezma Limestone, VSC-6A.

Fig. 8 Correlation proposed for the different sections studied in the Tejo unit between the upper Tournaisian and the lower Bashkirian (location of sections in Fig. 2), and two simplified sections from the western Cantabrian Zone (location of sections in Fig. 1). The upper Tournaisian to middle Viséan is not observed in the Valdediezma-Jitu l'Escarandi-Cheese Cave. Absolute ages based on Davydov et al. (2012). Compare the stratigraphic thickness below and above the black correlation line in the upper Serpukhovian. They accumulated during a time interval some eleven times longer below (Viséan-Serpukhovian, from 346.7 to 324.5 Ma) than above (Serpukhovian-early Bashkirian, from 324.5 to 322.5 Ma).

Fig. 9a Distribution of the Gorgera and Lavandera members of the Alba Formation indicating sedimentary highs (shown as numbers) and troughs in the lower-middle Viséan of the Cantabrian Mountains. (I) lacking or thin Lavandera Member, or pelagic platform, (II) Lavandera Member occurs, (III) Gorgera Member lacking in the Palentine nappes, originally rooted southwards (arrow), (IV) Valdediezma Limestone. **b** Cross-section with the interpreted model of the subdivided basin without scale.

Fig. 10a Schematic map of the north branch of the Ponga Nappe (Ponga-Cuera) and the Picos de Europa provinces modified from Bahamonde et al. (2007, 2008) showing the current geographic extent of the depositional zones for the carbonate platform of the Valdeteja and Picos de Europa formations. The Valdediezma Limestone is located in the core of the internal area of the Picos de Europa province. The direction and sense for the progradation of the Pennsylvanian carbonate and Valdediezma platforms is indicated (white arrows). **b** The correlation diagram shows the temporal relation of the Valdediezma Limestone and the differential sedimentation and subsidence with respect to the Alba and Barcaliente formations (absolute ages according to Davydov et al., 2012, are indicating lower sedimentation rate for the older rocks in the external area). The uplift and erosion of the Valdediezma platform is indicated by a sedimentary hiatus (vertical lines and arrows). The burial of the Valdediezma platform by strata of the uppermost part of the Picos de Europa Formation was due to the extended subsidence of the Picos de Europa province (Gamonedo-Cabrales, Central and Frontal units) as consequence of the emplacement of the frontal thrust sheets of the Ponga Nappe Province (Sierra del Cuera).