



Facies belts of a Carboniferous carbonate platform (San Antolín-La Huelga section, NE Cantabrian Zone, Northern Spain)

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Abstract: The Carboniferous carbonate rocks cropping out in the NE of the Cantabrian Zone formed part of a microbial boundstone-dominated carbonate platform characterized by high-relief margins and steep depositional slopes. Although the most continuous and best-preserved cross-sections of this carbonate platform, showing its seismic-scale depositional profile, have been intensely studied (Sierra del Cuera and Las Llacierias), other are poorly documented from a sedimentological point of view. This paper describes the San Antolín-La Huelga section, where the excellent exposures and the well-preserved depositional fabrics make it a reference section for the characterization of the lithofacies belts forming this particular depositional system.

Keywords: Carboniferous, Cantabrian Mountains, Carbonate platform, microbial carbonates, carbonate slopes.

Resumen: Las calizas carboníferas del NE de la Zona Cantábrica formaron una plataforma de taludes fuertemente inclinados y márgenes elevados sobre el fondo marino, dominada por carbonatos microbiales. Aunque las secciones más completas de la misma, que muestran a escala sísmica su perfil sedimentario, han sido ampliamente estudiadas (Sierra del Cuera y las Llacierias), otras son, sedimentológicamente, poco conocidas. Este trabajo describe la sección de San Antolín-la Huelga, donde el óptimo grado de conservación de las texturas sedimentarias la convierte en una sección de referencia en la caracterización de los cinturones de facies que forman este particular sistema sedimentario.

Palabras clave: Carbonífero, Zona Cantábrica, plataforma carbonatada, carbonatos microbiales, talud carbonatado.

As a consequence of evolution and extinction events affecting the marine life (such as the Devonian Frasnian-Famennian extinction event), carbonate platforms have undergone significant changes in type

and spatial distribution of lithofacies, geometry and responses to variations in environmental conditions. Therefore, depositional models based on modern carbonate platforms, with margins built by corals and

coralline red algae, and/or by oolitic sand shoals (Tucker and Wright, 1990), cannot be straightforwardly applied to fossil platforms. That is the case of the Upper Palaeozoic platforms (including the example here presented of the Carboniferous), which were dominated by microbial carbonates, and do not have equivalent analogues in the recent (Kenter et al., 2005).

The definition of microbial carbonates (Burne and Moore, 1987) is applied to carbonate deposits mediated by microbial mats trapping and binding sediments and/or by precipitation of calcium carbonate minerals induced by micro-organisms, biofilms and reactive organic substrates such as sponges. This mode of carbonate accumulation has significantly contributed to the construction of kilometre-scale systems, particularly during periods of crisis of large skeletal metazoans following extinction events and when physico-chemical conditions of seawater were favourable for the biologically induced precipitation (Webb, 1996).

Significant examples of high-rising microbial-dominated platforms developed between the Late Devonian extinction and the spread of scleractinian corals in the Late Triassic (cf. Della Porta et al., 2003) are: the Famennian of the Canning Basin in Australia (Playford et al., 1989), the Permian Capitan Reef Complex in New Mexico (Bebout and Kerans, 1993; Saller et al., 1999) and the Triassic Dolomites in Northern Italy (Bosellini, 1984; Keim and Schlager, 2001). The mid-Late Carboniferous interval, particularly the Serpukhovian and Bashkirian time, was interpreted as a period of scarce shallow-water calcimicrobial-microbialite reef growth (Riding, 1992). However, microbial frameworks associated with skeletal organisms developed on high-relief platform margins and slopes in Northern Spain, Kazakhstan (Cook et al., 1994), Russia (Antoshkina, 1998), Japan (Nakazawa, 2001) and in the subsurface of the Pricaspian Basin (Weber et al., 2003). The boundstone growth potential of these platforms was at least ten times greater than average values for other ancient carbonate systems and the progradation rates (ranging 400-1000 m/My) were similar to the highest values deduced for the Holocene Bahamian progradational platform margin (Kenter et al., 2005). The progradation of the microbial-boundstone dominated steep slope of Carboniferous platforms is primarily controlled by boundstone growth rates rather than by highstand shedding from the platform top, as it is the case of many modern carbonate systems. Furthermore, boundstone growth in the Carboniferous examples is largely independent from

light and controlled by the physico-chemical characteristics of seawater (Della Porta et al., 2003; Kenter et al., 2005).

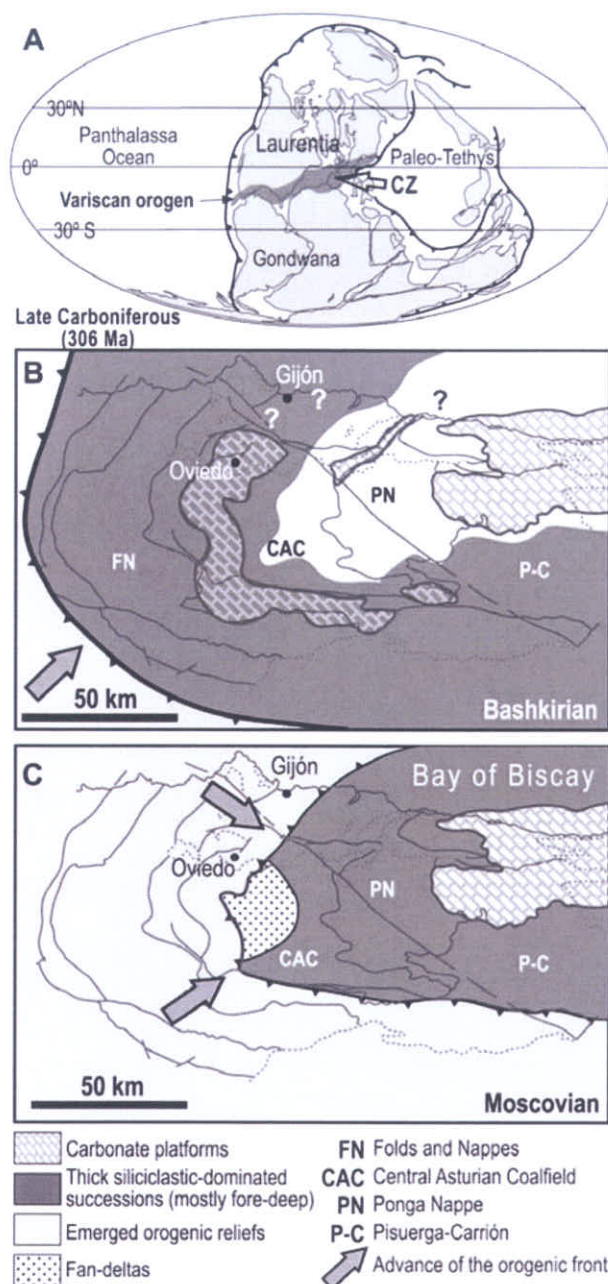


Figure 1: (A) Synthetic paleogeographic map of Pangea during Late Carboniferous time showing the location of the Variscan Foreland basin of the Cantabrian Zone (CZ) and the Variscan orogen (dark grey area) (modified after Golonka et al., 1994); (B) Synthetic paleogeographic maps of the Cantabrian Zone during the Bashkirian and Moscovian times. The maps are based on the present-day geometry and, thus, the significant tectonic shortening in E-W and N-S direction resulting from the Variscan thrusting is not considered.

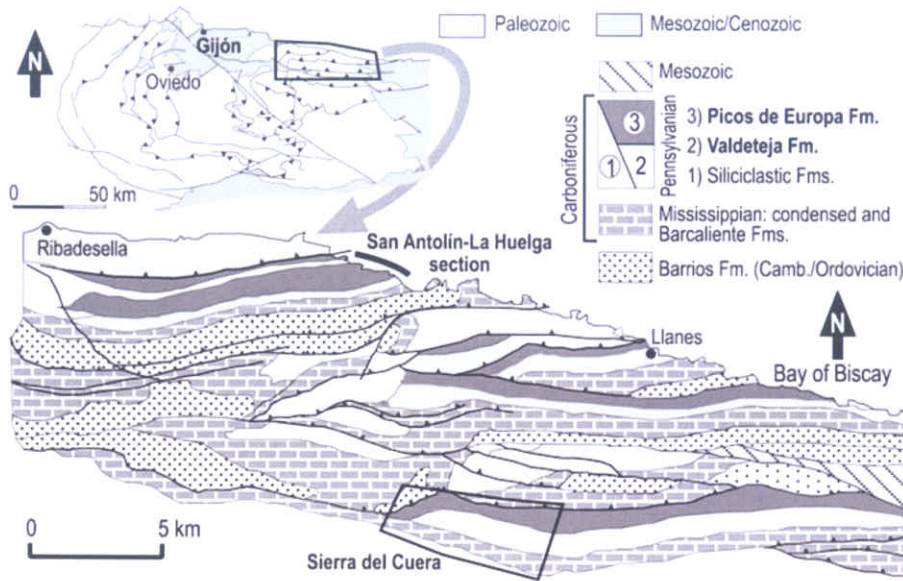


Figure 2: Schematic geological map of the NE portion of the Ponga Nappe Province with location of studied section and Sierra del Cuera outcrops (modified after Marquinez, 1989).

The continuous Carboniferous carbonate outcrops in the eastern portion of the Cantabrian Zone, showing a full transition from inner platform setting to deep-water marine basin, were extensively studied, mostly in the western sector of the Sierra del Cuera (Bahamonde et al., 1997a, 2004; Della Porta et al., 2002a, 2002b, 2003, 2004, 2005; Immenhauser et al., 2002, 2003; Della Porta, 2003; Kenter et al., 2003, 2005; Verwer et al., 2004; Van der Kooij et al., 2007; Martínez-Chacón and Bahamonde, 2008; Van der Kooij et al., in press), and in the Picos de Europa Province (Bahamonde et al., 1997b, 2000, 2007). These investigations have provided a depositional model of lithofacies distribution and evolution of the carbonate system in a foreland basin setting. The detailed biostratigraphy of these carbonate successions (i.e., Navarro et al., 1986; Villa, 1995; Van Ginkel and Villa, 1999) has been crucial to these investigations, including the study of the San Antolín-La Huelva section.

The main aim of this paper is to characterize the lithofacies associations of the carbonate platform cropping out in the San Antolín-La Huelva section, providing a field guide to interpretation of the Carboniferous carbonate rocks of this area (NE coast of Asturias) and contributing to the overall knowledge of this particular carbonate system.

Geological background and depositional context

The Carboniferous marine foreland basin of the Cantabrian Zone was located at equatorial latitudes in the western coast of the Paleotethys Ocean

and eastern sector of the Variscan orogen (Fig. 1A). In the distal and low-subsiding part of the basin (eastern zone) a wide and thick (> 12,000 km² wide and ~1500 m thick, Bahamonde et al., 2007) carbonate platform developed for 12.4 Ma (following the time scale of Gradstein et al., 2004). In contrast to most carbonate systems developing in marine foreland basins that are characterized by a ramp depositional profile (Read, 1985; Al-Tawil et al., 2003; Bosence, 2005), the Asturian platform reached a high-relief flat-topped geometry (Bahamonde et al., 1997; Kenter et al., 2003) displaying comparable accumulation rates to the highest value recorded in modern carbonate systems (Della Porta et al., 2003). This high productivity has been attributed to optimal environmental conditions for the microbial-induced carbonate precipitation, such as high temperatures at tropical latitudes within the starved and oxygen depleted basins allowing the accumulation of organic matter and increasing saturation with respect to carbonates (Della Porta, 2003).

The Asturian carbonate platform prograded towards the orogen into a starved marine basin, which was gradually filled and narrowed due to the sediment input from the orogen and to the forward advance of the deformation (Figs. 1B, 1C). During the last stages of the Variscan orogeny (late Pennsylvanian), first the northern domain (Ponga-Cuera area), and then the southern domain of the Asturian carbonate system (the Picos de Europa Province), were incorporated into the orogenic wedge and displaced by a set of E-W-oriented thrust sheets verging southwards (Merino-Tomé et al., 2009).

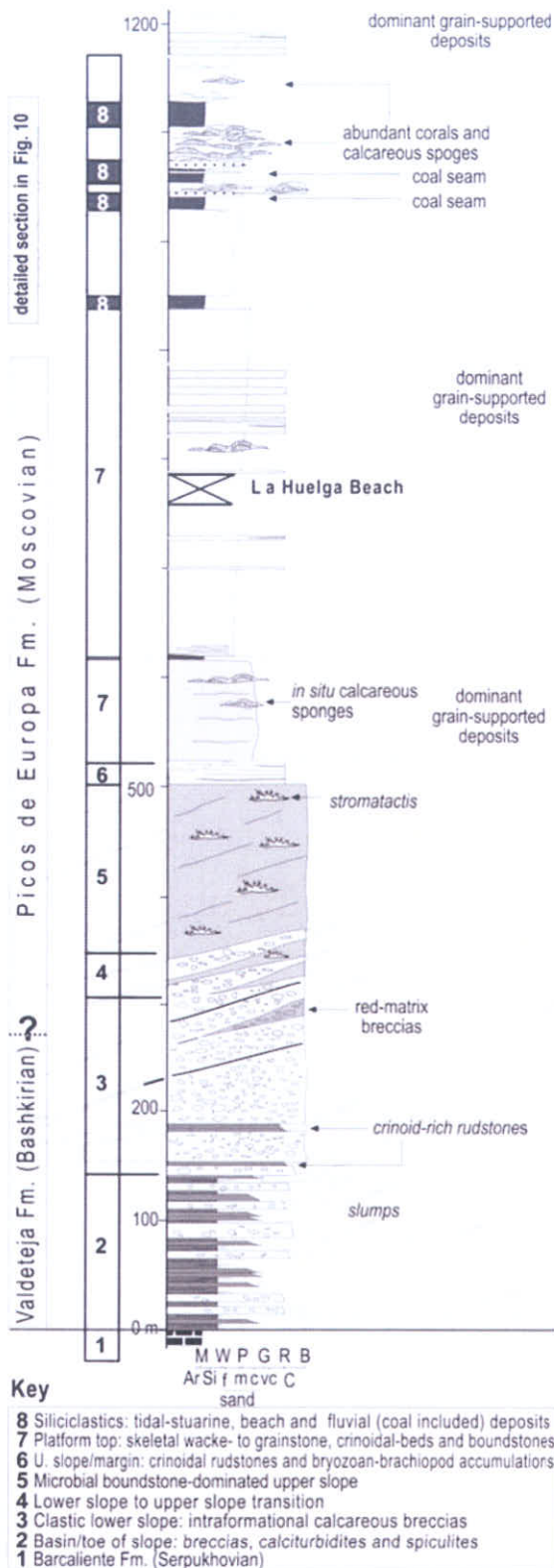


Figure 3: Measured San Antolín-La Huelga section, showing main lithofacies associations and inferred boundary between Valdeteja (Bashkirian) and Picos de Europa (Moscovian) Formations.

Methods

Lithofacies and depositional fabrics were studied and defined in the field and through petrographic analysis of ~100 thin sections and binocular microscopy observation of ~30 polished slabs. Polished slab of decimeter size samples were particularly useful to distinguish between *in-situ* microbial boundstone and detrital boundstone-derived breccias. Field observations focused on fresh-cut surfaces and weathered surfaces that were polished applying HCl (10% concentrated).

Stratigraphy

The studied section is located in the NE sector of the Ponga Nappe (Fig. 2), where the carbonate platform succession overlies the Barcaliente Formation (Serpukhovian) and extends from the base of the Bashkirian to the upper Moscovian (lower Myachkovskian; Villa, 1995). The succession reaches a thickness of 1250 m and is truncated by a thrust (Fig. 3). Navarro et al. (1986) proposed to define this succession as “Calizas del Cuera”. Nevertheless, in this study the terminology applied in the Picos de Europa Province of Valdeteja and Picos de Europa Formations will be maintained, because the successions are similar in age, lithologies and facies. Navarro et al. (1986) introduced the term of “Caliza del Cuera” due to the difficulty of separating the two formations because their boundary is not marked by an evident stratigraphic discontinuity. This difficulty in distinguishing the two lithostratigraphic units occurs in the inner part of the carbonate platform, both in the Cuera area and in the Picos de Europa Province (cf. Bahamonde et al., 2007).

Lithofacies belts

From the base to the top of the San Antolín-La Huelga succession, three facies associations have been identified (Fig. 4). They represent the transition from facies belts of basin/toe-of-slope, slope and platform-top and are analogues to those described in the Sierra del Cuera outcrops (Fig. 5). More detailed descriptions and interpretations of the Sierra del Cuera facies belts are contained in Bahamonde et al. (2000) and Della Porta et al. (2002b, 2003).

Basin/toe of slope

The basin/toe-of-slope deposits form a well-stratified, ~150 m thick, alternation of graded limestone beds, spiculites and calcareous breccias (Figs. 6A, 6B).

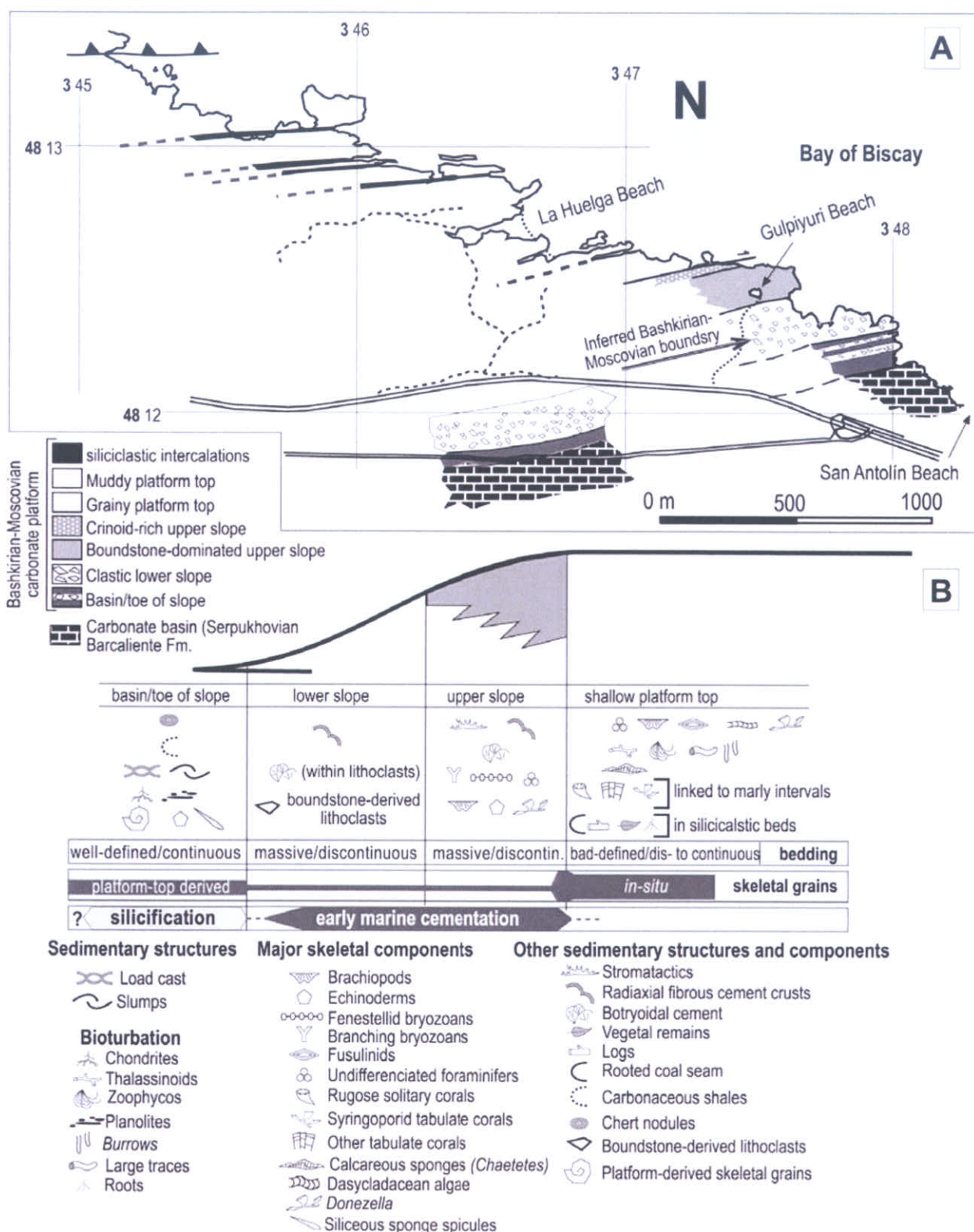


Figure 4: (A) Geological sketch of San Antolín-La Huelga section, showing different lithofacies belts. The position of the Bashkirian-Moscovian boundary is tentatively indicated. (B) Depositional profile of the carbonate platform with main characteristic stratigraphic features and components of the lithofacies associations.

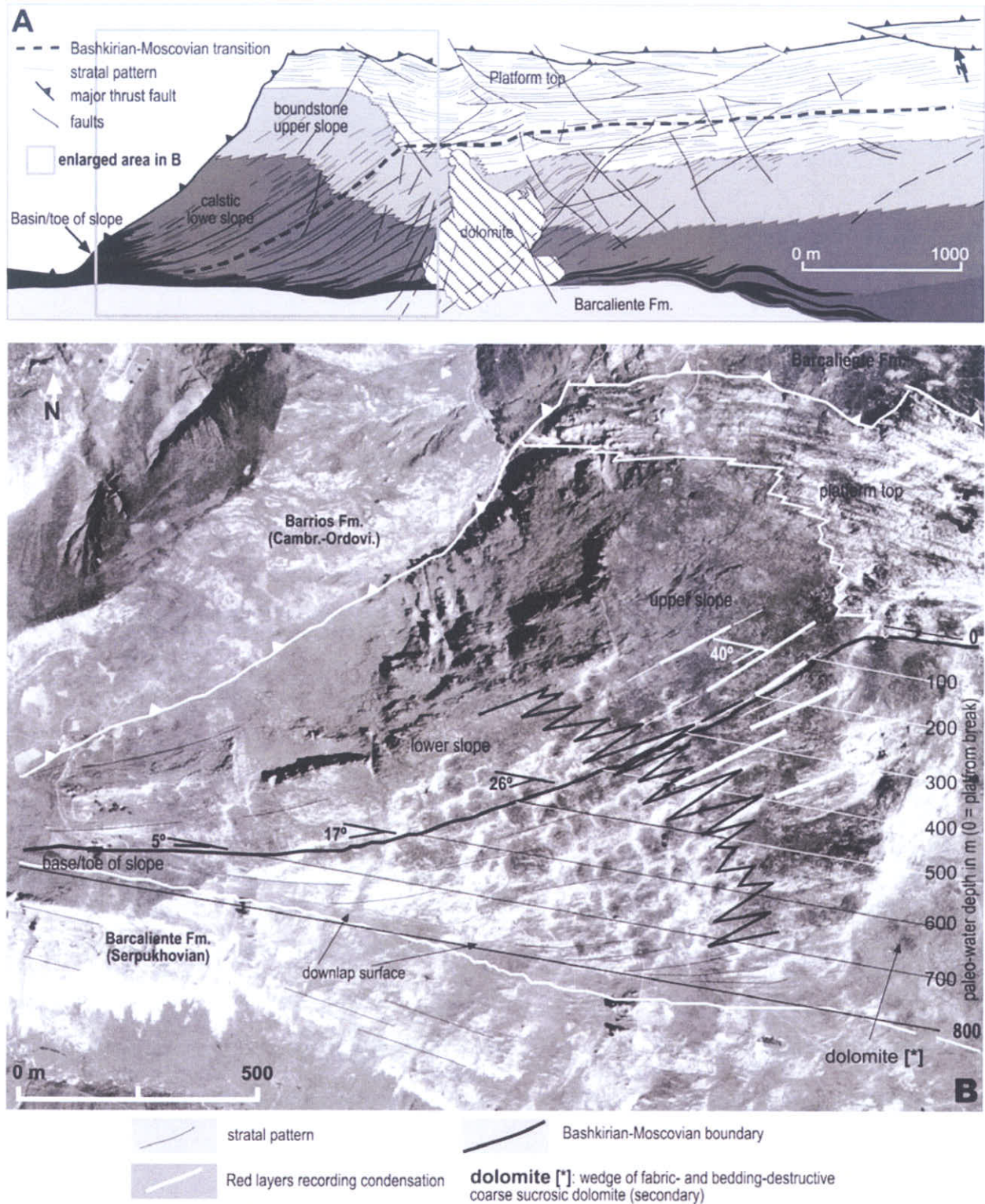


Figure 5: (A) Stratigraphic domains in the carbonate platform margin at the Sierra del Cuera cross section (modified after Della Porta et al., 2002a), used as reference for the interpretation of the studied section; (B) High-altitude aerial photograph of the marked area in A, showing the boundaries between lithofacies belts, real slope inclination and paleo-water depth following a Bashkirian-Moscovian boundary correlation line (assuming 0 m at the platform break) (modified after Bahamonde et al., 2004). The thrust sheet at the top cuts the platform succession at mid-Moscovian (lower Podolskian) strata (Villa, 1995).

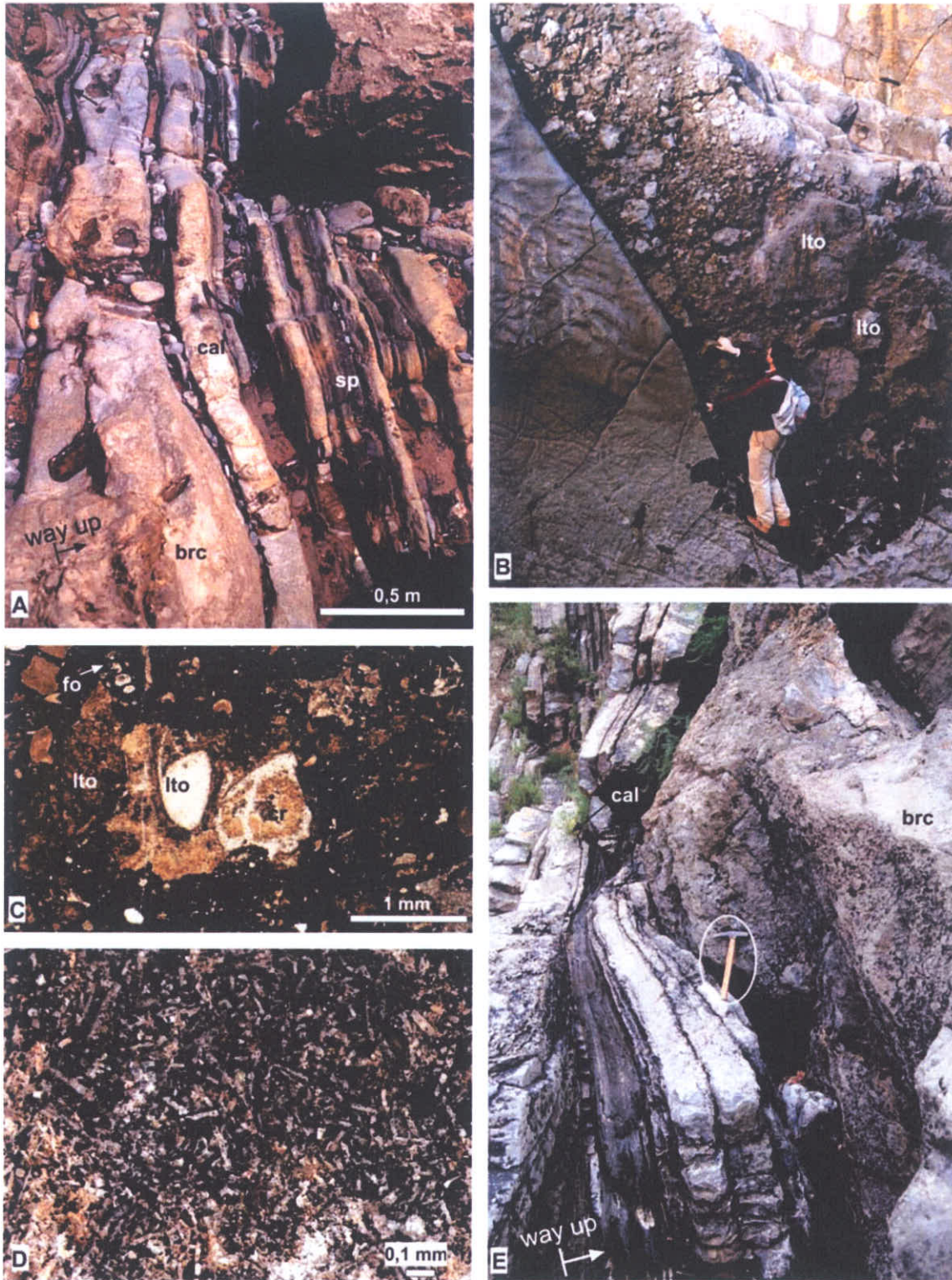


Figure 6: Basin/toe-of-slope deposits. (A) Toe-of-slope alternations: (brc) breccia bed, (cal) calciturbidite, (sp) siliceous spiculite. Black arrows indicate deformation due to differential compaction; (B) Poorly-sorted breccias (lto: lithoclast); (C) Photomicrograph of a skeletal and intraclastic packstone (calciturbidite): (lto) lithoclast, (fo) foraminifer, (cr) echinoderm fragment; (D) Photomicrograph from a binocular lens of the bedding surface of a spiculite (attacked with 10% HCl); (E) Close-up of load/differential compaction deformation affecting spiculites and calciturbidites (cal) at the base of a mega-breccia bed (brc).

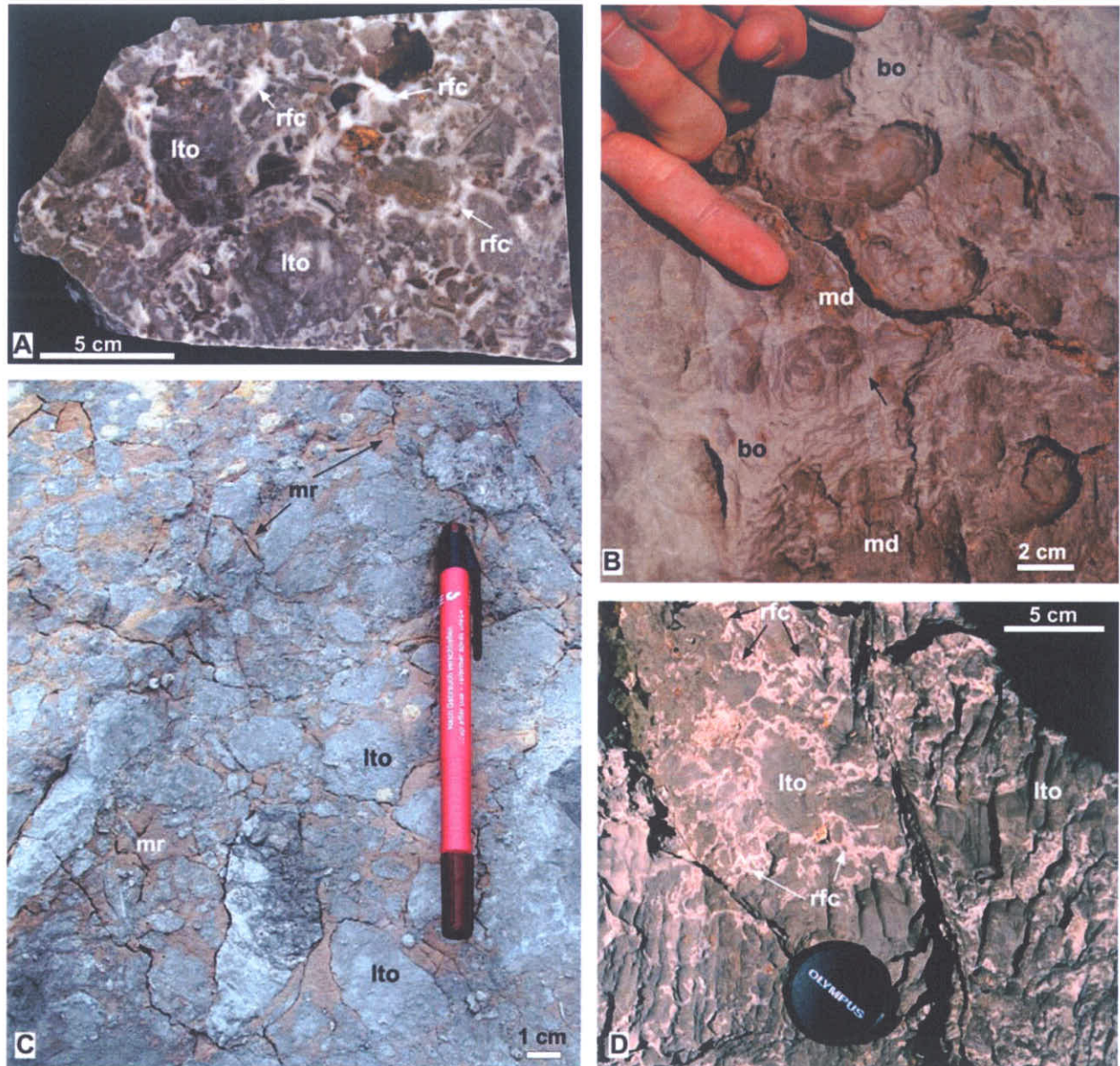


Figure 7: Lower-slope breccias. (A) Polished slab of clast-supported breccia consisting of micritic (boundstone) lithoclasts (lto) surrounded by isopachous layers of marine radial fibrous cement (rfc); (B) Outcrop photograph of microbial boundstone texture within lithoclast: (md) dense micrite, (bo) botryoidal cement (white areas); (C) Outcrop photograph of a breccia with red-micrite matrix (mr) derived from erosion of condensed upper-slope deposits. (lto, lithoclast); (D) Outcrop photograph of a matrix-free breccia showing sub-angular lithoclasts (lto) surrounded by isopachous rims of early marine cement (rfc).

Limestones form 5–25 cm thick beds of grain- to packstones (locally rudstones) (Fig. 6C) composed of reworked, platform-derived skeletal grains and slope-derived intraclasts (sand- to granule-size). These beds often show a crude inverse and/or normal gradation. Some beds are dominated by crinoid fragments. Spiculites are accumulations of monaxon siliceous sponge spicules (Fig. 6D) with a lime-mud matrix and a dark marly appearance (in spite of a very low argillaceous content), forming centimetre to decimetre

intervals (Fig. 6E) and thin laminae among limestone beds. Spiculites including other skeletal grains (thin-walled bivalves and crinoids) and dark limestones with abundant spicules are also present. Clast-supported breccias made of micritic, boundstone-derived clasts are intercalated among the deposits at the toe-of-slope described above. Due to the scarce or absent matrix, clasts show sutured contacts and range in size from a few millimetres to ~1 m in diameter. Internal organization of the breccia units is not

observed and thickness of the beds (10 dm to 2 m) increases toward the top of the succession. Locally, two thin and discontinuous intervals of carbonaceous shales including carbonate rock fragments have been recognized. Slumps, truncated beds, load-cast structures resulting from differential compaction (Figs. 6A, 6E) and chert are common. Bioturbation (*Chondrites* and *Planolites*) is concentrated at the spiculitic bedding surfaces.

Basinal deposits mostly consist of spiculites and shales containing some fine-grained limestone beds. The toe-of-slope facies also include common calciturbidites, boulder and breccia tongues from the lower slope, which seem to pinch out on the basin floor (Bahamonde et al., 2004). Spiculites, which overlapped the lower slope deposits, are typical deep-water basinal sediments (Wilson, 1975; Yurewicz, 1977) accumulated from suspension of spicules realised from degrading siliceous sponge bodies. Similar deposits to grain- to packstone and rudstone beds were interpreted as proximal calciturbidites resulting from storm-triggered, low- and high-density turbidity currents (Reijmer et al., 1991; Harris, 1994). Crinoid beds would derive from the reworking and resedimentation during storm events of crinoidal bars developed below effective fair-weather wave base in the outer platform (Della Porta et al., 2004). Preservation of silica at the toe of slope is indicative of water masses with low alkalinity and temperature. In contrast, the dissolution of biogenic silica on the slope is attributed to high values of alkalinity and temperature, associated with high rates of carbonate precipitation (Arp et al., 2003). The terrestrial origin of the carbonaceous material forming the two matrix-rich (carbonaceous) breccia intervals may suggest accumulation from debris-flows linked to failure of subaerially exposed margin/outer-platform areas triggered by seismic activity elsewhere in the basin. Alternatively, carbonaceous material could be transported by currents from interior parts of the platform.

Depositional slope

Calciturbidites and spiculites decrease and disappear toward the top of the toe of slope, where the succession loses the well-bedded character and gets massive. This stratigraphic interval represents the slope depositional setting. The ~350 m thick slope interval is subdivided into a lower part dominated by breccia (lower slope) and an upper part dominated by boundstones (upper slope) with a transitional zone where both lithologies coexist and alternate (Fig. 3).

The *lower slope* consists of tens of meters thick accumulations of clast-supported and poorly-sorted calcareous breccias separated by thin (decimeter thick) and discontinuous crinoid-rich rudstone beds. Most of the sub-angular breccia clasts are derived from the upper slope boundstone and show an upward fining trend on the upper slope. Primary interparticle porosity is filled by isopachous rims of radial fibrous cement (Figs. 7A, 7D). Early marine cementation was more abundant along the upper slope (in a way-up direction) decreasing towards the toe of slope, where early marine cementation is absent (see Fig. 4B). Lithoclasts composed of botryoidal cements and dense micrite crusts (microbial) are abundant in the lower half of the lower slope (Fig. 7B). One identified red-matrix (red-stained micrite with scarce fossils) breccia (Fig. 7C) bed occurs in the upper part of the lower slope interval.

The *upper slope* consists dominantly of massive boundstones (see Fig. 4B) with irregular, large (several centimeter to decimeter) voids partially filled by multiple isopachous rims of radial fibrous calcites (stromatactoid cavities) and by burial blocky spar in the remaining pore space (Fig. 8A). In thin section, the lime mud shows clotted textures with small (<0.25 mm) and diffuse-margin peloids, cemented by fine-grained equant microspar (peloidal micrite of Pickard, 1996) (Fig. 8B). Subordinately, depositional fabrics consisting of unidentified biomolds (calcisponges and/or algae, Della Porta et al., 2003) encrusted by dark micrite (dense or showing accretionary laminae), which support large cavities occluded by botryoidal cement (~0.5 cm semi-spheres of aragonite in origin, Fig. 8E). Locally *Donezella* colonies, calcimicrobes (*Renalcis*, *Ortonella* and *Girvanella*), encrusting foraminifers (*Tuberitina* and calcitornellids), bryozoans (fenestellids and branching fistuliporids) and echinoderms are common (see Della Porta et al., 2002a, 2003). The uppermost 12-15 m of the upper slope facies belt consists of 20 cm thick rudstone beds made mostly of crinoid ossicles, which alternate with 5-30 cm thick intervals of in-situ accumulation of fenestellid bryozoans and whole brachiopod shells, including radial fibrous cements in primary voids (Figs. 8C, 8D), and patches of reddish micrite.

Due to the common matrix-free fabric of the breccias and the boundstone textures of the most clasts, discrimination between genuine depositional breccias and in situ microbial cement boundstones is locally difficult.

Peloidal micrite fabrics and micritic crusts forming growth-cavities are interpreted as *in-situ* precipitates with mediation of micro-organisms (Neuweiler et al., 1999; Riding, 2000). The formation of stromatactics has been extensively debated, but a biological origin is likely. They supposedly developed due to corrosion of semi-rigid carbonates following the change in pH derived from the organic compounds resulting from the degradation of soft-body organisms (Tsien, 1985), such as sponges (Bourque and Boulvain, 1993). Marine cement nucleating from the cavity walls is an evidence for the early hardening of the lime mud. It emerges that a significant amount of the sediment forming this carbonate system would be a by-

product of bacterial metabolic activity during decaying of siliceous sponge tissues (cf. Della Porta, 2003). Carbonate precipitation induced by cyanobacteria during photosynthesis and heterotrophic bacteria, living in symbiosis with siliceous sponges, were passively responsible (with the contribution of bryozoans, echinoderms, foraminifers and algae) of the accumulation of carbonate successions in the Upper Paleozoic (Wood, 1999). The crinoids-rich beds alternating with well-cemented *in-situ* accumulations of bryozoans and brachiopods, including patches of reddish micrite, show certain similarities to those red layers recording condensation in the upper slope of the Sierra del Cuera (cf. Della Porta et al., 2003).

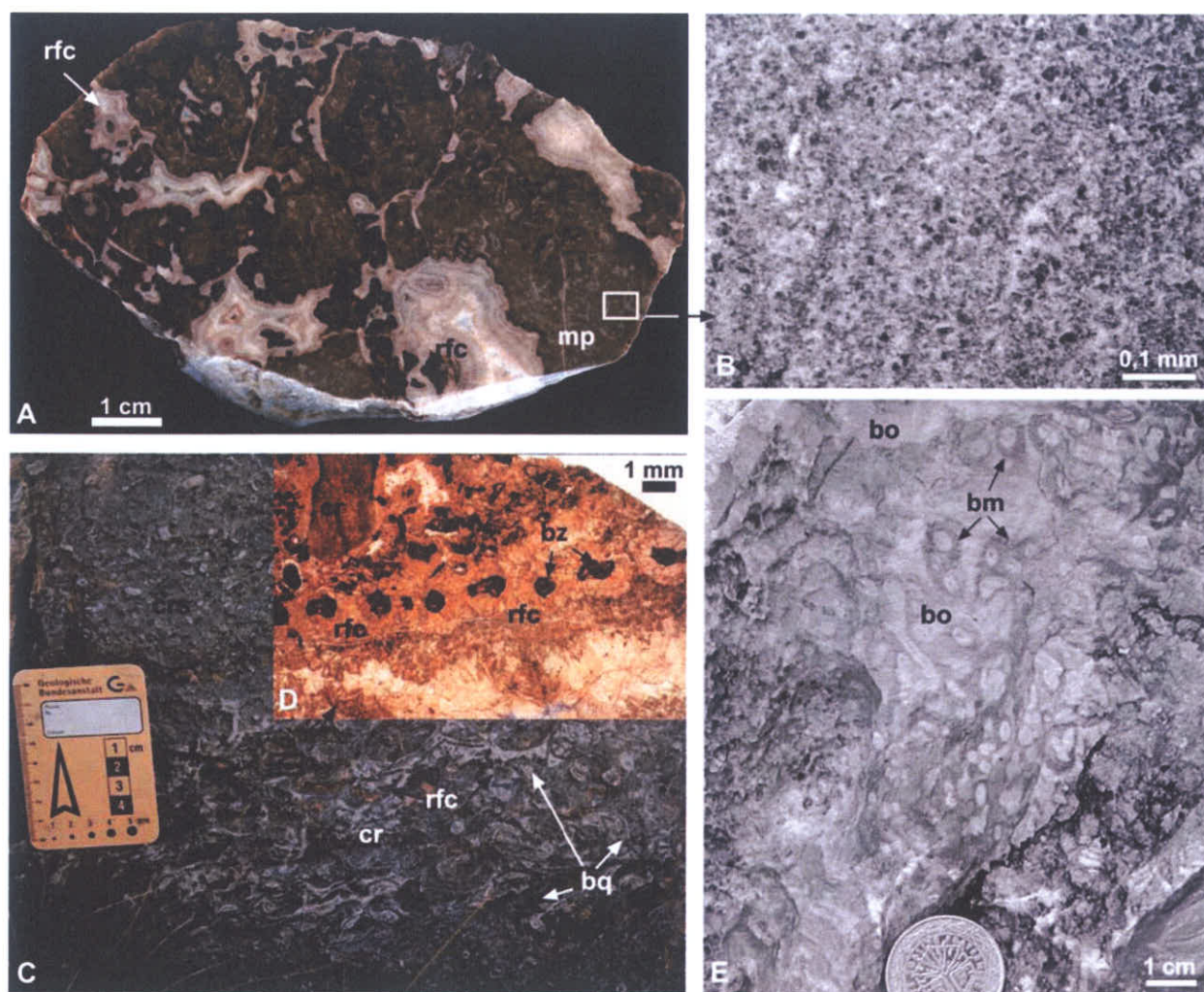


Figure 8: Upper-slope microbial boundstones. (A) Polished slab of the most abundant boundstone fabric in the San Antolín-La Huelga section, made of clotted micrite (mp) and large irregular voids (stromatactoid voids) filled by multiple early marine cement rims (rfc); (B) Detail of the previous facies showing the typical clotted micrite texture (photomicrograph); (C) Outcrop photograph of a crinoid-rich rudstone (cr, crinoids) and a few centimetre-thick interval of *in-situ* brachiopods (bq) and fenestellid bryozoans surrounded by marine cement rims (rfc); (D) Photomicrograph of the area marked in C, showing a section of a fenestellid frond (br) with early marine cement (rfc). Crinoid fragment (cr); (E) Outcrop photograph of a boundstone fabric showing unidentified biomolds (bm) encrusted by dense micrite rims and abundant botryoidal cement (bo, white areas).

Matrix-free fabrics suggest resedimentation from rock-fall and avalanching (Kenter, 1990; Drzewiecki and Simo, 2002) caused by over-steepening of the upper slope as a result of high sediment productivity (Kenter, 1990; Harris, 1994). The early hardening of the microbial micrites (Monty, 1995), favouring the brecciation of the boundstones at the upper slope, and the low potential of the shallow platform to produce and export lime mud (Della Porta et al., 2003) explain the paucity of fine-grained carbonate matrix of the breccias. Favourable conditions for brecciation are linked to relative sea-level rises rather than being associated with erosion at the margin and platform-top during relative sea-level falls (Bahamonde et al., 2004; Della Porta et al. 2004). When red-stained micrite layers with a weak early lithification (recording breaks in boundstone construction at upper slope during relative sea level rises, Della Porta et al., 2003) were involved in erosion processes, cohesive debris-flows developed. These matrix-rich flows were "frozen" downslope depositing the red-matrix breccias. The gradual decrease of flank inclination toward the basin favoured the deposition of crinoid-rich rudstones in the lower part of the slope from non-cohesive granular flows (cf. Kenter, 1990).

The transition from bioconstructed upper slope to detrital lower slope was located at 250-350 m of paleo-water depth (assuming 0 m at the platform break) in the Sierra del Cuera cross section (Della Porta et al., 2003; Kenter et al., 2003; Bahamonde et al. 2004), and at 200-250 m in the Las Llacierias section (NW of the Picos de Europa Province, Bahamonde et al., 2000).

The pervasive marine cementation on most of the slope resulted from the pumping of seawater through the primary porosity in the superficial sediment cover. The origin of the early marine cementation (one of the key processes in slope stabilization and preservation) is well documented in shallow and well-agitated environments, but it is generally reduced in deep depositional settings. Van der Kooij et al. (in press) have proposed the existence of active upwelling currents over the platform flanks as the main mechanism to trigger the seawater circulation in several hundreds of meter depths.

Shallow platform

Platform-top deposits form the thickest stratal domain (~650 m) and consist of alternations of nodular and bioturbated skeletal wackestone and packstone (Fig. 9A), skeletal pack- to grainstones rich

in foraminifers and dasycladacean algae, crinoidal pack- to rudstones including bryozoan fragments, and micritic boundstone with sparse algal colonies. Field features differentiating platform-top deposits from slope are: well-stratified character of platform strata versus the massive upper slope (Fig. 9A), abundant and diverse skeletal grains (occasionally with micrite envelopes) and predominant blocky spar cement and syntaxial rims around echinoderms (lacking early marine cement). These features contrast with the massive character, the low content of skeletal grains and the abundance of early marine cement of the upper slope (see Fig. 4B). Platform-top sediments contain a high diversity of marine biota: echinoderms (crinoids and echinoids), foraminifers (fusulinids, textularids, *Tuberitina*, *Bradyina*, *Endothyra*, *Tetrataxis*, Fig. 9B), bryozoans (fenestellids and branching fistuliporids), green algae beresellids and red algae ungdarellids, chaetetid sponges, and brachiopods; minor components included solitary rugose corals, algae as *Fasciella*, *Epimastopora*, *Donezella* and *Archaeolithophyllum*, gastropods, calcispheres, bivalves, ostracods and trilobites. Non-skeletal grains include peloids, aggregates, faecal pellets and rare ooids and oncoids (Della Porta et al., 2002b, 2005). There is a transition from nodular skeletal wackestone (Fig. 9B) and skeletal-grain supported limestones that locally consist of monospecific accumulations of green algae (mostly *Beresella*) and subordinatedly diverse foraminifers (Fig. 9E). Both are bioturbated with dark patches of grainstone texture (burrows, see Fig. 9C). At the top of grain-supported beds, domical colonies of *Chaetetes* sponges are preserved in life position. The micrite-rich boundstones are made of both homogeneous and clotted micrites and bioclasts (> 15%) with *Donezella* and phylloid algae being the most common organisms (see Della Porta et al., 2002b). In the upper part of the succession (Podolskian, according to Villa, 1995; Westphalian D, according to García-Bartolomé et al., 2003), the occurrence of three intercalations, each of them several metre- to decametre thick, consisting of siliciclastic sediments, including argillaceous shallow-water and estuarine deposits, sandy fluvial channels, beaches (Fig. 9D) and coal seams, is conspicuous (Fig. 10). In between siliciclastics, carbonates include marly interbeds and a very rich association of macrofauna with tabulates (syringoporids and others) and rugose (solitary and colonial) corals, *Chaetetes*, brachiopods and bryozoans (cf. Rodríguez and Ramírez, 1987). Locally, these coral accumulations developed metre-scale depositional relief and progradational growth style. Additionally to the common burrows, large horizontal traces and *Zoophycos* (Fig. 9F) and *Thalassinoids* ichnofossils have been recognized (see Fig. 4B).

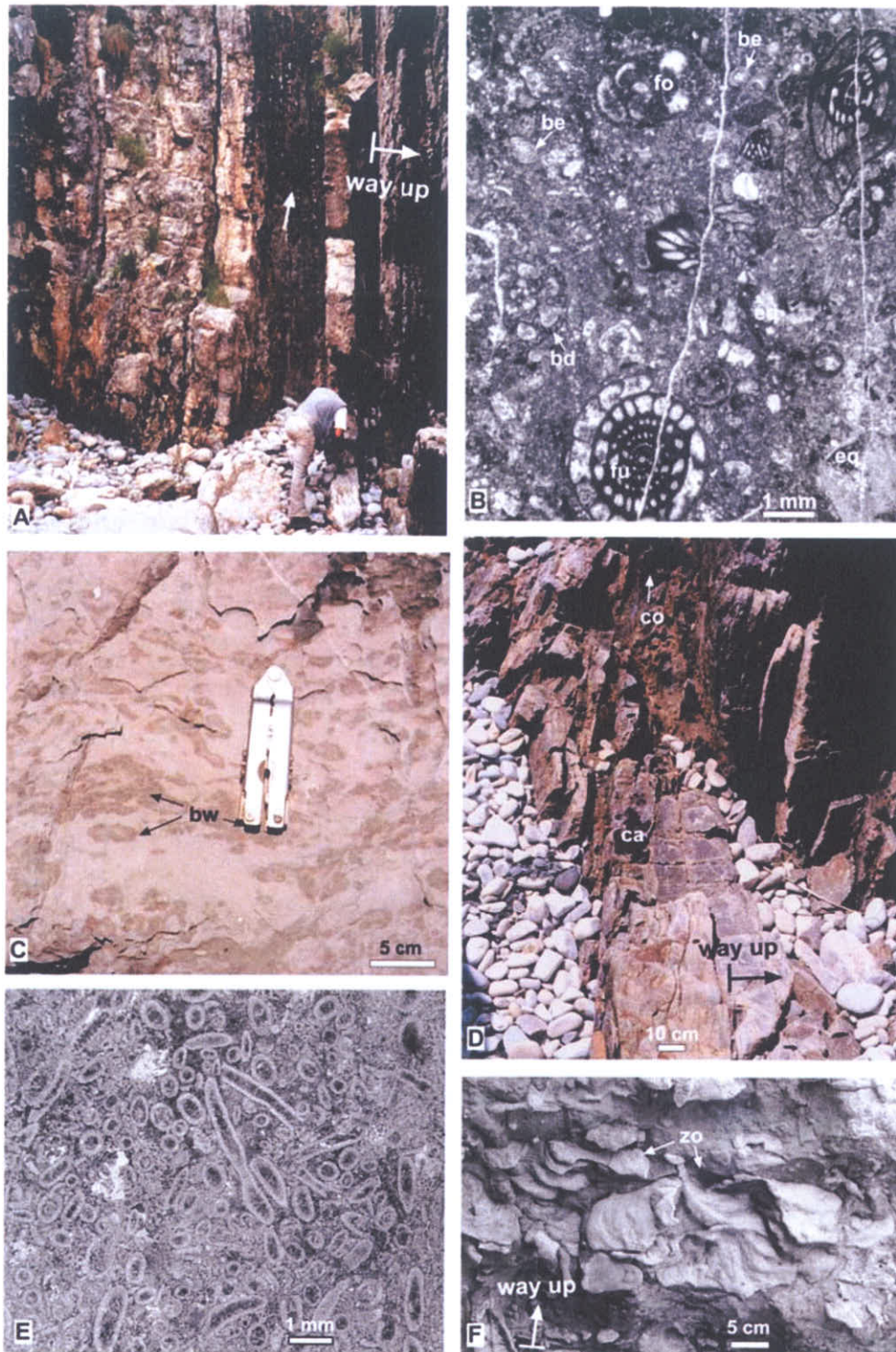


Figure 9: Platform-top deposits. (A) Outcrop photograph of nodular skeletal wackestone with marly partings at the top of the first argillaceous intercalation (white arrow). (Encircled person for scale); (B) Photomicrograph of a biomicrite including diverse marine biota: (fu) fusulinid, (cr) echinoderm, (fo) undifferentiated foraminifer, (bd) *Bradyina*, beresellid algae (be); (C) Outcrop photograph of bioturbated skeletal packstone. Dark dots with a grainstone texture represent burrows (bw); (D) Outcrop photograph of a fluvial channel-fill sandstone (ca) and a coal seam (co), concerning to a siliciclastic intercalation at the upper part of the section (Podolskian); (E) Photomicrograph taken through a binocular lens of a green beresellid-algal (*Beresella*) bafflestone; (F) Close-up of marly intervals with intense bioturbation by *Zoophycos*, at the uppermost part of the section.

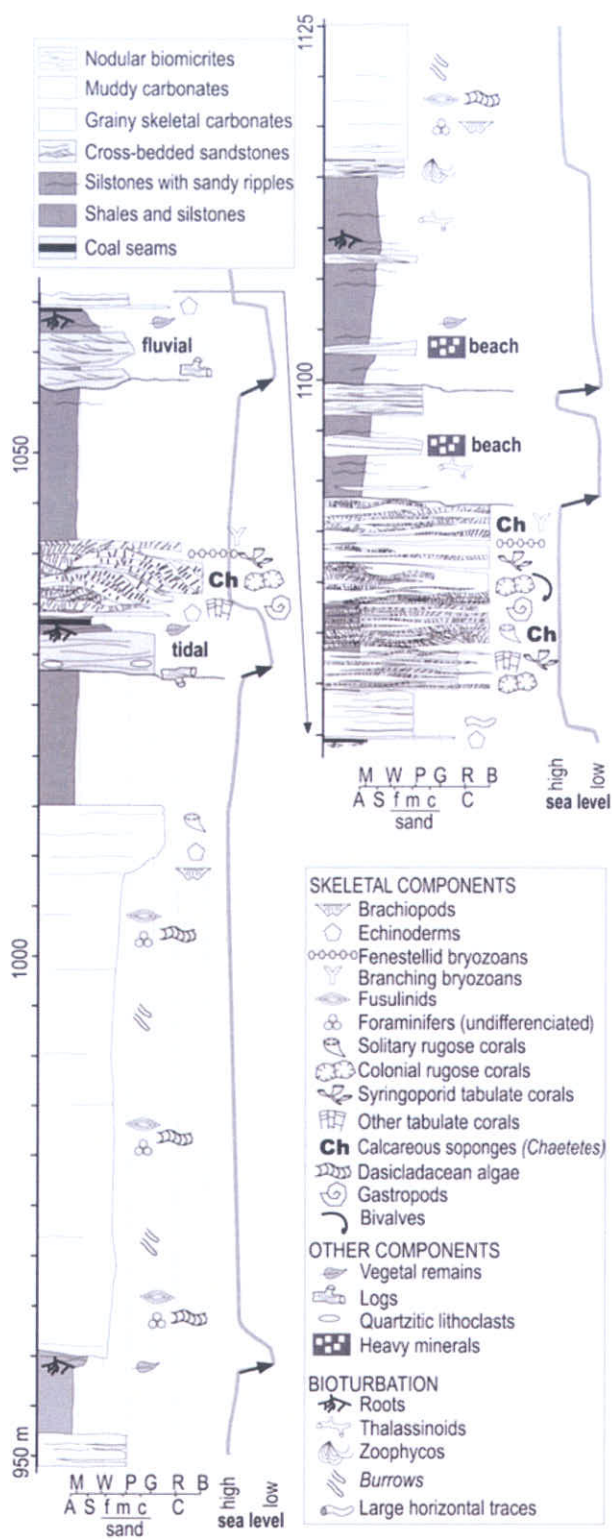


Figure 10: Stratigraphic columns of siliciclastic intercalations (Podolskian) (see Fig. 4 for location). Sea-level fluctuation curves have been constructed using relative water depth interpreted from the depositional facies. Distribution of corals is based on Rodríguez and Ramírez (1987).

In the Sierra del Cuera cross section, the platform interior facies belt displays well-defined shallowing-upward cycles, which have been documented in detail by Della Porta et al. (2002b) in inner platform settings. However, this facies belt has not been studied in detail in the San Antolín-La Huelga section, and consequently a cycle stacking pattern is not provided here.

In general terms, micrite-rich boundstones would record subtidal conditions, below effective fair-weather wave base, and grain-supported sediments would represent shallower conditions. *Chaetetes* colonies in life position at the top of skeletal pack- and grainstones are interpreted as shallow deposits, presumably above wave base (Connolly et al., 1989). Beresellid algae form low-relief accumulations in protected lagoon settings (Mamet, 1991), whereas their association with *Chaetetes* colonies would record normal, open-marine conditions (Della Porta et al., 2002b). Crinoids and bryozoans would have formed submarine meadows in deeper conditions (subtidal, below fair-weather wave base), which are reworked during storm events giving rise to sandy (grainstones) accumulations on platform top (Madi et al., 1996).

The abundance of crinoid-rich accumulations and the lack of subaerial exposure surfaces in the lower Moscovian platform succession, despite the well-documented high-amplitude glacio-eustasy during Late Carboniferous, suggest high rates of tectonic subsidence. Similarly, Bahamonde et al. (1997) and Della Porta et al. (2004) concluded that increase tectonic subsidence rate during the Moscovian might have prevented long time subaerial exposure and favoured an aggradational growth style in the Sierra del Cuera outcrops (Kenter et al., 2003). On the contrary, the Podolskian siliciclastic intercalations, including transitional and continental deposits, would record subaerial exposures of platform top, once the adjacent basin was filled up (at least in the N sector) and the subsidence rates had decreased in the course of the Moscovian (cf. platform evolution in Kenter et al., 2003). Carbonate cycles bounded by prominent paleokarsts of similar Moscovian age were described in other sectors of the Ponga Nappe Province (Escalada Formation in the Beleño section, Bahamonde and Colmenero, 1993) reinforcing the proposed hypothesis.

The abundant macrofauna forming limestones between marly intervals, shales and sandstones may be related to the increase of nutrients (meso- to eutrophic conditions) linked to the siliciclastic input

coming from the orogen. Similar findings from the Las Llacerias Formation (Kasimovian) in the Picos de Europa Province have been interpreted as triggered by increased nutrient levels by Merino-Tomé et al. (in press). Notwithstanding that Holocene eutrophic oceanic conditions are not favourable for the growth of hermatipic corals (Hallock and Schlager, 1986), in the Moscovian brachiopods, bryozoans, rugose corals, some types of gastropods and calcareous desmospoges, might have thrived under high levels of nutrients (Wood, 1993).

Discussion

The vertical transition from basin/toe-of-slope and slope to platform-top facies belts in the San Antolín-La Huelga section is characteristic of the external zone of this carbonate platform (see Bahamonde et al., 2007), where an active progradational growth took place. The parallel bedding relationship between the three defined stratal domains is interpreted as a consequence of the W-E orientation of the thrust sheets being perpendicular to the northwards direction of

progradation of the carbonate margin succession exposed in the San Antolín-La Huelga section (Fig. 11). This contrasts with the oblique-exponential clinofolds (oblique stratal patterns) displayed in several seismic-scale cross sections of the western border of the carbonate system, where progradation and thrust orientations are parallel. Measurements on slump axes in the toe-of slope strata, confirm a paleo-slope towards the north in the San Antolín-la Huelga section.

Location of the Bashkirian-Moscovian boundary

Because the paucity of bio-stratigraphic markers (mainly fusulinids) in the massive slope lithofacies (both in boundstone and breccias), the Bashkirian-Moscovian boundary was not located in previous papers dealing with this section (Navarro et al., 1986; Villa, 1995). However, the stratigraphic features described in this paper could provide information on the location of the Bashkirian-Moscovian boundary. In the Sierra del Cuera cross section, boundstone textures containing encrusting micritic cruts and abundant

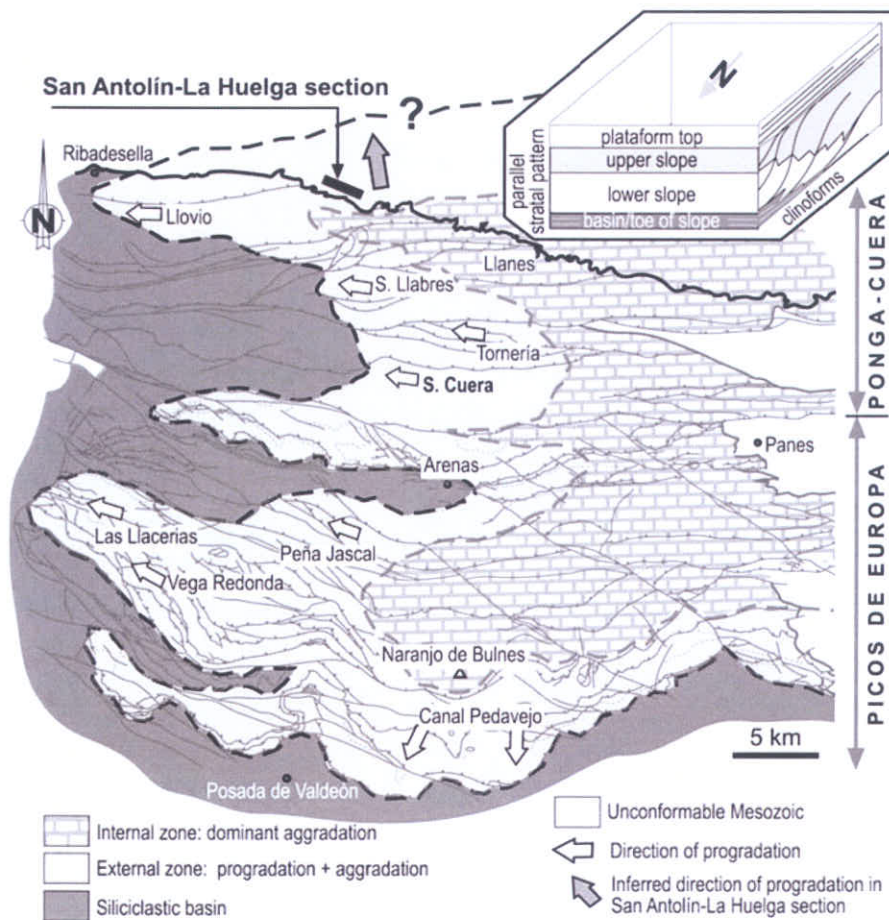


Figure 11: Synthetic paleogeographic map of the Carboniferous carbonate platform (Ponga-Cuera Unit and the Picos de Europa Province) differentiating two domains of the carbonate system (inner platform in the east and outer platform, margin and slope in the west) and showing the extent of the internal (predominant vertical growth) and external (vertical and horizontal growth) zones, and the boundary with the siliciclastic adjacent basin (based on Bahamonde et al., 2007). Map is based on the present-day geometry of the Cantabrian Zone and, thus, tectonic shortening in N-S direction was not considered. Direction of progradation in western and southern platform borders are recorded in 2-D kilometre-scale cross sections (Bahamonde et al., 1997; 2007); and northwards progradation deduced from data provided in this study. Block diagram in the upper-right corner explains parallel bedding relationship between three stratal domains exposed in the San Antolín-La Huelga section.

botryoidal cement (*boundstone* type B of Della Porta et al., 2003) are dominant in the Bashkirian flanks and scarce in the Moscovian upper slope. Because in the San Antolín-La Huelga section, the lithoclasts derived from this type of boundstone are very abundant in the first half of the lower slope (and rare at the upper half), it is inferred that the Bashkirian to Moscovian transition could be located in an intermediate position of the lower slope facies belt (Fig. 4A).

Summary

The Carboniferous succession of the San Antolín-La Huelga section records the northwards margin progradation of a high-relief, microbial-dominated carbonate platform, including (from base to top) the basin/toe-of-slope, slope and platform-top lithofacies belts. Because the direction of progradation was perpendicular to the thrusts orientation, the stratal domains display an apparent parallel bedding relationship.

A well-bedded alternation of spiculites (accumulations of siliceous sponge spicules with a micrite matrix), calciturbidites (graded skeletal and intraclastic grain- to packstones and rudstones) and clast-supported calcareous breccias form the basin/toe-of-slope facies association. Load cast and differential-compaction structures, slumps and chert nodules are common.

The platform slope consists of massive breccia beds (lower slope) and micritic boundstone accumulations (upper slope). Boundstones are made of clotted or peloidal micrite, dense and dark micrite crusts, which are interpreted as microbial-mediated precipitates,

and contemporaneous marine cements (radial fibrous and botryoidal). The clast-supported texture of the breccias (almost matrix-free fabric) suggests avalanches and gravitational rock falls from the upper slope as the main mechanism of transport. The massive character, the paucity of skeletal grains and a pervasive marine cementation (in boundstones and boundstone-derived clasts and surrounding the clasts) are the main features of the slope facies association.

Platform-top deposits form a thick and well-bedded interval with abundant and diverse marine biota and absence of early marine cement. They consist of nodular and bioturbated skeletal wackestones, packstones and grainstones with abundant foraminifers and green algae, crinoid-rich rudstones and micritic boundstones with scattered colonies of algae (*Donezella* and phylloids). The siliciclastic intercalations at the upper part of the section (Podolskian) include coastal and fluvial deposits and record the fill-up of the adjacent basin and the subaerial exposure of the platform top.

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