Geology of the 'Sénia stone' from Ulldecona, Catalonia (Aptian, Maestrat Basin, Iberian Chain) and its implications for regional stratigraphy

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ABSTRACT

The municipality of the town of Ulldecona (Catalonia) is notable for extensive quarrying activities, which exploit limestone, popularly named Stone from Ulldecona, for ornamental and building purposes. The Stone from Ulldecona, commercially known as Sénia stone, is one of the most important ornamental and building stones quarried in Catalonia, and is used worldwide in all kinds of public and private buildings. Little is known about the geological nature of this stratigraphic interval of commercial value. Therefore, this study explores the geology of the Stone from Ulldecona in open pit quarries and natural outcrops. The Stone from Ulldecona consists of limestones of upper lower Aptian age, including wackestone, packstone and grainstone textures containing peloids, miliolids, *Palorbitolina lenticularis*, *Orbitolinopsis simplex*, *Paracoskinolina maynci*, *Lithocodium aggregatum*, *Choffatella decipiens*, *Salpingoporella muehlbergi*, *Chondrodonta*, *Toucasia carinata*, *Polyconites* sp. and *Mathesia darderi*. These platform carbonates rich in orbitolinids and rudists belong to the Villarroya de los Pinares Formation of the Maestrat Basin. Locally, the limestones are highly bioturbated and/or dolomitized. Dolomitic limestones, calcitic dolostones and dolostones are stratabound tabular geobodies with thicknesses of up to 60 metres. Dolomitic limestones and calcitic dolostones corresponding to initial and intermediate stages of dolomitization mainly exhibit isolated euhedral dolomite crystals or idiotopic mosaics. Dolostones (advanced dolomitization stages) are sucrose, exhibit vacuolar and cave porosities, and are characterized by idiotopic and hypidiotopic mosaics, which indicate temperatures lower than 50-60ºC during dolomitization. Dolomite textures are mainly fabric-destructive and pervasive, but locally retentive and/or selective fabrics also occur. The limestones of the Villarroya de los Pinares Formation, the underlying marls of the Forcall Formation and the overlying marls and platform carbonates of the Benassal Formation examined can be arranged into two high-rank, low-frequency transgressive-regressive sequences. Similar coeval long-term transgressive-regressive trends have been reported from other

basins, indicating that eustatism largely controlled accommodation of the Aptian succession studied in Ulldecona.

Keywords
carbonate platform, sequence stratigraphy, dolomitization, quarrying, Maestrat Basin, Aptian

1. Introduction

The Stone from Ulldecona, commercialized as 'Sénia stone', is a limestone rock extracted from the Godall Range (Fig. 1), in the environs of the town of Ulldecona in southern Catalonia (NE Spain). In the area, the Stone from Ulldecona is cut in seven quarries by five different companies. Four local factories manufacture different products from it (Ajuntament d'Ulldecona, 2005). The Stone from Ulldecona is used as building/ornamental stone for both inner and outer parts in public and private construction, as well as for sculpture. Different commercial varieties exist based on the distinct colours and textures exhibited by this stone: Ulldecona, Ulldecona Cream, Sénia Jalo, Sénia Cream and Imperial (Martín et al., 2001; Navarro Torta, 2006). The hardness and versatility of the Stone from Ulldecona are of great value to engineers and architects, and it is produced and manufactured in different finishes such as cut, polished, flamed, ancient, sandy, bush hammered and honed (Ajuntament d'Ulldecona, 2005). It is probably the most important building and ornamental stone extracted in Catalonia.

Remarkable constructions in Barcelona where the Stone from Ulldecona was used include Casa Milà, also known as "La Pedrera" (Figs. 2A-B), and the Sagrada Família Temple (Figs. 2C-D), both edifices designed by the architect Antoni Gaudí, and World Heritage Sites designated by the United Nations Educational, Scientific and Cultural Organisation (UNESCO). Also in Barcelona, the shopping and entertainment centres Illa Diagonal (Fig. 2E) and Diagonal Mar are paved (Fig. 2F) and exterior wall cladded, respectively, with stone from Ulldecona (Ajuntament d'Ulldecona, 2005).

In Madrid, the Stone from Ulldecona was utilized for example in the Prado Museum to renew the floors of several rooms, as well as for interior and exterior wall cladding in the building of the Spanish Olympic Committee (Figs. 3A-B). In the nearby city of Alcalá de Henares, designated as Human Heritage by UNESCO, the Stone from Ulldecona paves the renewed floors of the Magisterial Cathedral (Figs. 3C-D).

Furthermore, the Stone from Ulldecona was employed as wall cladding and/or pavement in notable constructions around the world such as the Olympic Stadium of Sevilla (Spain), the Northern Beach Promenade of Peníscola (Spain), the Ca Na Xica Hotel in Eivissa (Spain), the Puerta de Toledo in Ciudad Real (Spain), the Midsummer Place Shopping Centre in Central Milton Keynes (United Kingdom), the Tramway of Montpellier (France), the Swiss

Bank Corporation in Basel and the Nestlé Headquarters in Vevey (Switzerland), the Mondrian building and Les Jardins de la Couronne in Brussels (Belgium), the Amsterdam Arena Stadium (The Netherlands), the Rivierenstede building in Groningen (The Netherlands), the Supreme Education Council Headquarters in Doha (Qatar) and the Al Ain University of Science and Technology in Abu Dhabi (United Arab Emirates). In the United States of America, the Stone from Ulldecona paves floors and/or clads walls of the Helen and Martin Kimmel Center for University Life in Manhattan-New York, the Ritz Hotel in Aspen, the Park Regency in Atlanta, the Hilton Hotel and the cathedral of Los Angeles and the Miami Tower and the Four Seasons Hotel in Miami (Ajuntament d'Ulldecona, 2005).

Published studies of the Stone from Ulldecona are scarce and mainly restricted to the examination of the physical and mechanical properties of the rock and its pathologies (Torta Navarro, 2002, 2006; Fernández Burriel, 2009; Fernández et al., 2009). Only the explanatory notes of the Geological Map 1:50.000 of Spain by Leyva et al. (1972) and the works by Fernández Burriel (2009) and Fernández et al. (2009) provide brief remarks on the geology and age of the Stone from Ulldecona. Leyva et al. (1972) give an Aptian (Lower Cretaceous) age to the marine limestone rocks quarried in the municipality of Ulldecona (*Comarca* of El Montsià). However, the analysis of the Aptian sedimentary record by these authors was not carried out in the area of Ulldecona but around 25 km to the W-SW, in the surroundings of the town of Xert (*Comarca* of El Baix Maestrat; Fig. 1B). Fernández Burriel (2009) and Fernández et al. (2009) characterize the Stone from Ulldecona as a limestone rock of Cretaceous age exhibiting wackestone, packstone, grainstone and dolosparite textures and containing skeletal components such as orbitolinids, miliolids and rudists.

The present work characterizes the petrology, sedimentology, diagenesis, stratigraphy and palaeontology of the Aptian platform carbonates extracted as Stone from Ulldecona, and investigates their exact age and distribution in the southern part of the Godall Range, also known as the Grossa Range. Moreover, the studied carbonate platform, which paves floors and clads walls around the world, is placed in regional and global contexts, and compared to coeval carbonate systems of the Tethys. The paper may be of relevance to those studying Cretaceous carbonate depositional systems, but also to those engaged in geological heritage, quarrying and construction activities.

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2. Geological setting

The carbonate sedimentary succession studied gives rise to the Godall Range, which is located in the north-eastern part of the Maestrat Basin, in the eastern Iberian Chain (Fig. 1A). The Iberian Chain was formed by the Late Eocene-Early Miocene inversion of a rift system affecting the eastern Iberian Plate that resulted from two rifting cycles of Late Jurassic and Early Cretaceous ages (Nebot and Guimerà, 2018). The Late Jurassic rifting cycle was related to the opening of the North Atlantic, whereas the Early Cretaceous cycle corresponded to extensive intraplate deformation linked to the opening of the Bay of Biscay (Salas and Casas, 1993). These two rifting stages controlled the development of six major areas of preferential sedimentation or sedimentary basins in the north-eastern Iberia: i) Cantabrian, ii) Cameros, iii) Maestrat, iv) South-Iberian, v) Garraf, and vi) Columbrets (offshore) (Fig. 1A; Salas et al., 2001).

The syn-rift structure of the Maestrat Basin was formed by two systems of extensional listric faults generating a double roll-over geometry (Salas et al., 1995; Nebot and Guimerà, 2016). A northern system was formed by WNW-oriented normal listric faults dipping southwards (i.e., Herbers and Turmell faults; Fig. 1B), whereas a south-western system was oriented NW-SE and dipped towards the NE. This structure compartmentalised the Maestrat Basin into seven sub-basins: Aliaga, Galve, Oliete, Penyagolosa, Salzadella, El Perelló and Morella (Salas and Guimerà, 1996) (Fig. 1B). The Godall Range is located in the eastern sector of the Morella Sub-basin, which was the half-graben corresponding to the northern part of the Maestrat Basin (Fig. 1B).

In the Maestrat Basin, during the Late Jurassic-Early Cretaceous time period, sedimentation occurred in shallow-marine carbonate settings, which was interrupted by inputs of coastal siliciclastics and continental sedimentation during the latest Jurassic (Purbeck Facies), the Barremian (Weald Facies and freshwater carbonates) and the Albian (Utrillas Facies). The thickness of the Upper Jurassic-Lower Cretaceous syn-rift succession is superior to 4 km in depocentral areas.

In the Morella Sub-basin, the Aptian lithostratigraphic units overlie the upper Barremian succession, which includes the shallow-marine carbonates and marls rich in oysters of the Artoles Formation, the continental red clays and sandstones containing dinosaur remains of the Morella Formation, the coastal mixed carbonate-siliciclastic deposits of the Cervera del Maestrat Formation, and the marine sandstones, sandy limestones, marls and limestones rich in *Palorbitolina lenticularis* of the Xert Formation (Fig. 4) (Bover-Arnal et al., 2016). From older to younger, the Aptian units correspond to the basinal marls, marly-limestones and limestones with *Palorbitolina lenticularis* and ammonoids of the Forcall Formation, the platform carbonates with rudists and corals of the

Villarroya de los Pinares Formation, and the marls and limestones with rudists, corals and *Mesorbitolina texana* of the Benassal Formation (Fig. 4) (Canérot et al., 1982; Salas, 1987; Salas et al., 1995; Bover-Arnal et al., 2014, 2016). The Aptian succession is overlain by the sandstones and clays of the Utrillas Facies (Fig. 4) (Canérot et al., 1982), which are Albian in age (Garcia et al., 2014; Bover-Arnal et al., 2016) and include the Escucha and Utrillas formations. In the Godall Range, the Utrillas Facies is locally capped by the Cenomanian marine limestones and dolostones of the Mosqueruela Formation (Figs. 5-6) (Canérot et al., 1982).

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3. Materials and methods

The Early Cretaceous carbonate sedimentary succession of the southern part of the Godall Range (Grossa Range) was investigated by means of field and laboratory work. Fieldwork involved the generation of an original 1:25,000 scale geological map of the area (Fig. 5), the logging and sampling of a representative stratigraphic section (Figs. 7-8), lithofacies description, macrofossil identification and taxonomic determinations of rudist bivalves, mapping of lithofacies architecture on panoramic photomosaics of the quarries, and random sampling within the quarries. The geological scheme was created over a 1:25,000 scale topographic base of Catalonia by the Institut Cartogràfic i Geològic de Catalunya (sheet 62-41; available at http://www.icgc.cat).

The laboratory work included the production of three geological cross-sections (Fig. 6) to recognize the general structural framework and stratigraphic relationships of the study area, as well as the analysis of microfacies and determination of microfossils on 64 thin sections produced from the samples collected in the field. The carbonate rocks examined were classified following Dunham (1962) and Embry and Klovan (1971). The taxonomic determinations of rudists, orbitolinids and of other benthic foraminifera, which were used to determine the age of the rocks investigated, follow the biostratigraphic analyses by Masse (2003), Skelton (2003), Bover-Arnal et al. (2010, 2016), Skelton et al. (2010), Schroeder et al. (2010), Cherchi and Schroeder (2013), Skelton and Gili (2012) and Steuber et al. (2016). The transgressive-regressive sequence-stratigraphic arrangement of the sedimentary record studied follows the nomenclature proposed by Catuneanu et al. (2011).

4. Geological scheme and cross-sections

In this chapter, a geological scheme of the southern part of the Godall Range is presented (Fig. 5). Due to a requisition by a funding agency of this study, the original geological scheme was simplified and only six cartographic units are characterized. From base (older) to top (younger), these stratigraphic units correspond to the Forcall Formation (lower Aptian), the Villarroya de los Pinares Formation (upper lower Aptian), the Benassal Formation (uppermost lower Aptian-upper Aptian), the Escucha Formation (Albian), the Mosqueruela Formation (Cenomanian) and undifferentiated Quaternary deposits.

Three representative schematic geological cross-sections of the Grossa Range (Fig. 6) were produced from the geological map. The location of the cross-sections can be seen in Figure 5. The A-A' cross-section is a SE-NW-oriented profile that displays the stratigraphic relationships between the Forcall, Villarroya de los Pinares and Benassal formations (Fig. 6). The B-B' cross-section is also oriented in a SE-NW direction and cuts the highest peak in the area, Lo Molló (Fig. 6). The C-C' cross-section follows a NE-SW direction and crosses the Grossa Range from the site of Mas del Dengo to Les Tosses (Fig. 6).

An anticline and a syncline with SW-NE orientation characterize the structure of the area studied (Fig. 5). These regional folds exhibit the same SW-NE direction as the Godall Range (Fig. 5). With the exception of the strata close to the axial planes of the folds, the dips of the sedimentary record analysed are mainly gentle between 3 and 20 degrees, with a marked component to the NW (Figs. 5-6).

The Villarroya de los Pinares Formation is the main outcropping lithostratigraphic unit in the southern part of the Godall Range (Figs. 5-6). The building/ornamental stone industries, which quarry the lower part of the Villarroya de los Pinares Formation, are essentially located in the SE edge of the Godall Range, following the overall SW-NE structural trend (Fig. 5). The Forcall Formation, which stratigraphically underlies the Villarroya de los Pinares Formation (Fig. 4), crops out locally around the intersection between the axial plane of the anticline fold mapped and the road TV-3313, in the NE part of the study area. Strata belonging to the Benassal Formation, which stratigraphically overlies the Villarroya de los Pinares Formation (Fig. 4), is also locally preserved in the NE part of the Grossa Range, in the Mas del Dengo site (Figs. 5-6). In addition, in the most western edge of the area investigated, in Les Tosses hillock, Albian and Cenomanian deposits, which respectively correspond to the Utrillas Facies and the Mosqueruela Formation, unconformably overlie the Aptian succession.

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5. Stratigraphic log

The representative stratigraphic column of the Grossa Range (Figs. 7-8) was mainly measured along the TV-3313 road that goes from Ulldecona to the town of Godall (Fig. 5). This road cuts the most complete section that has been recognized in the area, including the upper part of the Forcall Formation (25 m-thick), the whole of the Villarroya de los Pinares Formation (296 m-thick) and the basal part of the Benassal Formation (3 m-thick). These lithostratigraphic units correspond to the three marine formations of the Aptian of the Maestrat Basin (see Fig. 4 for the chronostratigraphy of the Early Cretaceous of the Maestrat Basin). The upper part of the Villarroya de los Pinares Formation, and the preserved deposits of the Benassal Formation have been measured on the hill of Mas del Dengo, adjacent to the TV-3313 road, as shown in Figure 5.

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6. Facies succession and fossil content

The sedimentary succession examined begins with the marls of the Forcall Formation (Figs. 7, 9A). These marls crop out locally in the axial part of an antiform structure that crosses the area studied from the NE to the SW (see Fig. 5). Macrofossils were not found within the marls. At the upper part of the Forcall Formation, two limestone layers with wackestone and packstone textures contain miliolids, the bivalve *Chondrodonta* and other skeletal components (Fig. 7).

Above, the platform carbonates of the Villarroya de los Pinares Formation exhibit an initial section made up of marly-limestones and limestones rich in orbitolinids (between 25 and 38 m of the succession) (Figs. 7, 9B). Then, between 38 and 135 m, the succession consists basically of limestones with wackestone (Fig. 9C), packstone (Fig. 9D) and grainstone (Fig. 9E) textures rich in miliolids, orbitolinids, textularids, other benthic foraminifers, dasycladacean algae, oysters, nerineid gastropods, other gastropods, echinoderms and peloids. Packstone, floatstone and rudstone textures containing *Chondrodonta* and rudist bivalves in life position are locally present. Interbedded dolostones, calcitic dolostones, dolomitic limestones, as well as intensively bioturbated levels, also occur (Figs. 7, 9F). From 135 to 155 m, the succession is formed by packstone, grainstone and floatstone limestones characterized by the presence of abundant rudists and *Chondrodonta* (Figs. 7, 10A). Locally, colonies of scleractinian corals were recognized (Fig. 10B).

The stratigraphic interval quarried as an ornamental/building stone in the Grossa Range corresponds to the succession between 38 and 155 m (Figs. 7, 10C). The wackestone (Fig. 9C), packstone (Fig. 9D) and grainstone (Fig. 9E) textures dominated by peloids, miliolids and dasycladaceans are the most prized microfacies as an ornamental and building rock in the quarries of the Grossa Range as they exhibit a gray or homogeneous cream tone without visible skeletal components. The bioturbated levels or beds including bivalves such as rudists and *Chondrodonta* are not as commercially attractive, but are marketed as well. When skeletal components are visible, the rock is considered unsightly. Bioturbated levels (Fig. 9F), apart from being considered unattractive, are less consistent, break more easily, and it is not possible to give a homogenous polish to the rock. A recent penetrative karst system (Fig. 10D) developed in the limestones of the lower part of the Villarroya de los Pinares Formation is also problematic for the quarrying industry of the area.

Above 155 m, the succession is intensively dolomitized until 215 m (Fig. 7). From 215 to 322 m, the Villarroya de los Pinares Formation is made up of floatstone to rudstone limestones dominated by rudists (Figs. 7). Accordingly, in the Grossa Range, the Villarroya de los Pinares Formation can be subdivided into three units; a lower and an upper limestone-dominated units, which are separated by a middle dolostone interval (Fig. 7). The stratigraphic interval of mining interest from which the building and ornamental stone from Ulldecona is extracted corresponds to the limestones and dolomitic limestones of the lower part of the Villarroya de los Pinares Formation (Fig. 7).

The fossil content recognized within the Villarroya de los Pinares Formation, which gives rise to the Grossa Range, includes *Palorbitolina lenticularis* (Blumenbach) (Fig. 11A), *Orbitolinopsis simplex* (Henson) (Fig. 11B), *Paracoskinolina maynci* (Chevalier) (Fig. 11C), *Choffatella decipiens* Schlumberger (Fig. 11D), *Lithocodium aggregatum* Elliott (Fig. 11E), *Salpingoporella muehlbergi* (Lorenz) (Fig. 11F), *Chondrodonta* Stanton (Fig. 10A), *Toucasia carinata* (Matheron) (Fig. 12A), *Mathesia darderi* (Astre) (Fig. 12B) and *Polyconites* sp. (Figs. 12C-D). The *Polyconites* sp. surveyed are characterized by exhibiting a modest size (between 2 and 4 cm in height), a relatively thick aragonite wall and a flattened left valve (Fig. 12D).

At 322 m, a 2 m-thick interval of basinal marls, which correspond to the base of the Benassal Formation (Fig. 13A), cover a hardground exhibiting borings of lithophagid bivalves and iron mineralizations (Figs. 13B-C). This hardground is located at the top of a rudist-bearing limestone bed belonging to the Villarroya de los Pinares Formation (Fig. 7). Above the marls, limestones with orbitolinids and bouquets of polyconitid rudists occur (Figs. 7, 13D).

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7. Dolomites and dolomitization

The Villarroya de los Pinares Formation in the Grossa Range consists of an alternation of marls, marly-limestones, limestones, dolomitic limestones, calcitic dolostones and dolostones. The stratigraphic interval with dolomites is mainly located in the middle part of the formation, between 155 and 216 m in the section measured on the TV-3313 road that goes from Ulldecona to Godall (Figs. 5, 7).

The dolomite levels are stratabound tabular geobodies, with thicknesses that vary from a few decimetres to tens of metres (up to 61 m in the type section displayed in Figure 7). This latter stratigraphic interval of between approximately 40 and 60 meters (Fig. 14A) is a continuous level throughout the Grossa Range. The dolomite interval caps the stratigraphic succession extracted as an ornamental/building stone in active (e.g., Ebre, Sant Joan and Godall) and abandoned (e.g., El Xertolí) quarries in the municipality of Ulldecona (Fig. 14A), and is well exposed along the TV-3313 road that goes from Ulldecona to Godall (Figs. 5, 7).

The dolomite level of the middle part of the Villarroya de los Pinares Formation (Fig. 7) also presents the highest degree of dolomitization recognized within the Grossa Range. Dolostones are sucrose, beige, and exhibit vacuolar (Fig. 14B) and cave (Fig. 14C) porosities. At the base of this dolostone level, ghosts of skeletal components such as orbitolinids and rudists can be recognized. These dolostones are not extracted as ornamental/building rocks in the quarries of the area, but must be removed by the companies to reach the underlying limestone that is of economic interest (Fig. 14A).

Decimetric to metric stratabound tabular levels of dolomitic limestones and calcitic dolostones are recurrent within the Villarroya de los Pinares Formation (Fig. 14D) below the thick and widespread dolostone reference level (Figs. 7, 14A). These decimetric and metric dolomitic levels of the lower middle part of the Villarroya de los Pinares Formation are darker than the limestone with miliolids, peloids, rudists and *Chondrodonta* extracted as an ornamental/building rock, and are therefore easily recognizable inside the quarries of the area studied (Fig. 14D). When these stratabound decimetric to metric levels of dolomitic limestones and calcitic dolostones are cross-cut by fractures, the circulation of calcite-rich meteoric waters calcitize the dolomitic hostrock, and the darker colour exhibited by the dolomitic limestones and calcitic dolostones diffuses around the fracture (Fig. 10D).

The dolomitic limestones, calcitic dolostones and dolostones found in the succession studied are of secondary origin, and formed by replacement during diagenesis (burial). The rocks investigated show different degrees of dolomitization; initial stages (Fig. 15A), intermediate stages (Fig. 15B) and advanced stages (Figs. 15C-D). Initial and intermediate stages of dolomitization mainly show idiotopic mosaics with euhedric crystals (rhomboids), and a destructive and pervasive fabric. Locally, retentive (i.e., ghosts and mouldic porosity of orbitolinids and rudists) and/or selective (mainly micritic matrix-selective dolomitization) fabrics have also been observed. Advanced dolomitization stages show a destructive and pervasive fabric with idiotopic (Fig. 15C) and hypidiotopic (Fig. 15D) mosaics exhibiting euhedral and subhedral crystals.

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8. Discussion

8.1. Age of the succession

In the Grossa Range, the Villarroya de los Pinares Formation, which includes the stratigraphic interval commercialized as an ornamental/building rock by the quarries located in the municipality of Ulldecona, contains *Palorbitolina lenticularis* (Figs. 9B, 11A) and *Orbitolinopsis simplex* (Figs. 9D, 11B). *Palorbitolina lenticularis* has a stratigraphic distribution from the upper Barremian to the lower Aptian (Schroeder et al., 2010; Cherchi and Schroeder, 2013), whereas *Orbitolinopsis simplex* ranges from the upper lower Aptian to the upper Aptian (Masse, 2003; Schlagintweit et al., 2016). Accordingly, the age of the Villarroya de los Pinares Formation is upper lower Aptian. In this regard, the occurrence of *Paracoskinolina maynci* (Fig. 11C), *Choffatella decipiens* (Fig. 11D), *Lithocodium aggregatum* (Fig. 11E), *Salpingoporella muehlbergi* (Fig. 11F), *Chondrodonta* (Fig. 10A), *Toucasia carinata* (Fig. 12A), *Polyconites* sp. (Fig. 12D) and *Mathesia darderi* (Fig. 12B) is also in accordance with an upper lower Aptian (Bedoulian) age (e.g., Arnaud et al., 1998; Bernaus et al., 2003; Skelton, 2003; Bover-Arnal et al., 2010, 2011, 2015, 2016; Skelton et al., 2010; Schlagintweit and Bover-Arnal, 2012; Skelton and Gili, 2012; Schlagintweit et al., 2010, 2013, 2016; Granier et al., 2013; Gili et al., 2016; Steuber et al., 2016;

Posenato et al., 2018). In addition, the observed *Polyconites* rudists exhibit a relatively thick aragonite wall (Fig. 12D), a flattened left valve, and a modest size, typical characteristics of specimens of late Early Aptian age (*Dufrenoyia furcata* ammonoid zone; see Fig. 4) (Skelton et al., 2010; Pascual-Cebrian, 2014; Pascual-Cebrian et al., 2016) and hence, most likely to be *Polyconites hadriani* Skelton et al. (Skelton et al., 2010).

On the other hand, age-diagnostic fossils were not found within the Forcall Formation, which crops out locally in a TV-3313 road cut intersecting the axial part of a major antiform structure (see Figs. 5-7, 9A). In all the sub-basins of the Maestrat Basin, including the Morella Sub-basin where the area studied is found (Fig. 1B), the age of the Forcall Formation has been determined by means of ammonites as lower Aptian (Weisser, 1959; Canérot et al., 1982; Salas, 1987; Salas et al., 2001; Vennin and Aurell, 2001; Moreno-Bedmar et al., 2009, 2010, 2014; Bover-Arnal et al., 2010, 2015, 2016; Ossó et al., 2018). More precisely, the boundary between the Barremian and the Aptian is located within the lower, non-basal part of the Forcall Formation (Moreno-Bedmar and Garcia, 2011; Garcia et al., 2014; Bover-Arnal et al., 2016; see Fig. 4). Accordingly, a lower Aptian age for the Forcall Formation in the area of Ulldecona is assumed.

The age of the Benassal Formation has not been possible to determine in the Grossa Range, either. The lower part of this formation is preserved at Mas del Dengo (Figs. 5-7). In the Maestrat Basin, the boundary between the early and the late Aptian is stratigraphically located in the lower, non-basal part of the first marl interval of the Benassal Formation (Bover-Arnal et al., 2014, 2016; see Fig. 4). In the Morella and Galve sub-basins, the lower, non-basal part of this first marly horizon of the Benassal Formation contains ammonites of the *Dufrenoyia furcata* Zone (uppermost lower Aptian) (Moreno-Bedmar et al., 2012a; Bover-Arnal et al., 2014, 2016; Garcia et al., 2014). According to this chronostratigraphic framework (Fig. 4), the boundary between the early and late Aptian in the Grossa Range is also assigned to the lower, non-basal part of the first marl interval of the Benassal Formation (Figs. 7, 13A).

The Escucha and Mosqueruela formations mapped in Les Tosses area (Figs. 5-6), are ascribed respectively to the lower Albian according to Moreno-Bedmar et al. (2008), Garcia et al. (2014) and Bover-Arnal et al. (2016), and to the Cenomanian in accordance with Canérot et al. (1982).

8.2. Changes in accommodation and platform evolution

Stratal terminations or stacking patterns were not recognized along the succession studied and thus it was not possible to characterize systems tracts. Accordingly, the changes in accommodation that controlled sedimentation during the Aptian in this eastern part of the Maestrat Basin (Fig. 1B) are discussed herein by means of a transgressive-regressive analysis (*sensu* Johnson and Murphy, 1984). The transgressive-regressive sequence stratigraphic approach is based on the identification of maximum-regressive and maximum-flooding surfaces, which mark large-scale changes of facies trends from shallowing- to deepening-upwards, and from deepening- to shallowing-upwards, respectively (e.g., Catuneanu et al., 2011).

The marls of the Forcall Formation have been mainly interpreted throughout the Maestrat Basin as transgressive deposits (Malchus et al., 1995; Vennin and Aurell, 2001; Bover-Arnal et al., 2009, 2010, 2014, 2015, 2016; Embry et al., 2010). In this respect, this marly unit contains relatively deep-water biota such as ammonoids and nautiloids (Weisser, 1959; Martínez and Grauges, 2006; Moreno-Bedmar et al., 2009, 2010; Grauges et al., 2010; Garcia et al., 2014; Lehmann et al., 2017), and is regionally overlain by shallower-water platform carbonates rich in rudists and corals (e.g., Malchus et al., 1995; Bover-Arnal et al., 2010, 2016) that belong to the Villarroya de los Pinares Formation (Salas, 1987; Canérot et al., 1982; Fig. 4).

In the area studied, the Villarroya de los Pinares Formation begins with an alternation of marls and limestones with wackestone, packstone and grainstone textures mainly containing peloids, orbitolinids, miliolids, *Chondrodonta* and oysters. Upwards in the succession, this lithostratigraphic unit progressively evolves into floatstones and rudstones dominated by rudists (Fig. 7). Aptian rudist-bearing limestones indicate platform-top environments (e.g., Skelton and Gili, 2012; Bover-Arnal et al., 2015; Gili et al., 2016). Therefore, the lithofacies evolution recorded by the Villarroya de los Pinares Formation in Ulldecona marks a long-term progressive shallowing-upwards trend from distal platform-slope to more proximal platform-top settings, which is in accordance with a regressive context (Fig. 7).

The maximum flooding surface bounding the transgressive marls of the Forcall Formation from the overlying regressive deposits is interpreted to correspond to the base of the first limestone level logged at metre 21, in the uppermost part of the Forcall Formation (Fig. 7). This limestone bed is made up of a packstone texture containing relatively shallow-water biota such as miliolids and *Chondrodonta*, and is interpreted to represent the first shedding arrival in the basin of platform top carbonate from a carbonate prograding system. In seismic sequence stratigraphy, the maximum flooding surface is placed at the first downlapping clinoform recorded above transgressive deposits (e.g., Catuneanu et al., 2011).

At 322 m (Fig. 7), at the top of a rudist-dominated limestone layer, a hardground exhibiting borings of lithophagous bivalves and iron mineralizations occurs (Figs. 13B-C). Physical signs of subaerial exposure such as karst features were not observed in this latter stratigraphic surface. The hardground is overlain by a 2 m-thick basinal marl interval, which belongs to the base of the Benassal Formation (Fig. 13A), and thus marks the drowning of the Villarroya de los Pinares Formation carbonate platform (Figs. 7, 13B-C). Accordingly, this hardground surface is interpreted as a maximum regressive surface which bounds regressive platform carbonates of the Villarroya de los Pinares Formation from transgressive marls of the Benassal Formation (Fig. 7).

Above the marl interval, the presence of limestones with mesorbitolinids and *Polyconites* rudists in life position (Fig. 13D) indicates a renewed carbonate platform growth and thus, a marine regressive context (Fig. 7). These platform carbonates, which have been preserved locally from recent erosion (Figs. 5-6), still belong to the lower part of the Benassal Formation (Fig. 4; see Bover-Arnal et al., 2016). The maximum flooding surface between the transgressive marls and the regressive carbonates of the Benassal Formation was placed at the base of the first limestone layer above the marls (*ca*. 324 m; Fig. 7) following the same criterion explained above.

Accordingly, two low-frequency (high-rank; *sensu* Catuneanu et al., 2011) transgressive-regressive sequences were characterized along the Aptian succession of the Grossa Range. These sequences are of lower Aptian and uppermost lower-lower upper Aptian age, respectively. The transgressive units correspond to marls, whereas the regressive deposits are platform carbonates dominated by rudist bivalves.

8.3. Regional and global significance of interpretations

The transgressive marls of the Forcall Formation identified in the Grossa Range (Figs. 5-7, 9A) can be regionally traced throughout the Maestrat Basin (Fig. 4; Canérot et al., 1982; Salas, 1987; Salas et al., 2001; Moreno-Bedmar et al., 2009, 2010; Garcia et al., 2014; Bover-Arnal et al., 2016). These marls, which frequently alternate with marly-limestones and limestones, have been interpreted as basinal deposits, and are commonly rich in *Palorbitolina lenticularis*, ammonoids, nautiloids and sponge spicules (e.g., Weisser, 1959; Canérot et al., 1982; Salas, 1987; Vennin and Aurell, 2001; Martínez and Grauges, 2006; Moreno-Bedmar et al., 2009, 2010; Grauges et al., 2010; Embry et al., 2010; Garcia et al., 2014; Bover-Arnal et al., 2016; Lehmann et al., 2017). Along the same lines, coeval relatively deep-water lithostratigraphic units are found in other basins of the Iberian Chain (Fig. 1A). For example, the Margues de Vallcarca Unit in the Garraf Basin (Fig. 1A; Moreno-Bedmar et al., 2016) or the lower and middle parts of the Malacara Member in the South Iberian Basin (Fig. 1A; Mas, 1981).

In the Maestrat Basin, the deposition of the marls of the Forcall Formation constitutes the acme of a large-scale transgression that commenced with the deposition of the marine sandstones, sandy-limestones and limestones with *Palorbitolina lenticularis* of the underlying Xert Formation during the Late Barremian (Fig. 4; Bover-Arnal et al., 2010, 2016). This high-rank transgressive trend led to the oceanic anoxic event 1a (OAE1a), which is recorded within the Forcall Formation (*Deshayesites forbesi* ammonoid zone) in the Maestrat Basin

(Moreno-Bedmar et al., 2009; Bover-Arnal et al., 2010, 2011, 2016; Embry et al., 2010; Cors et al., 2015).

High-rank transgressive trends of Early Aptian age characterized by the deposition of basin marls were also recorded in nearby basins such as the Organyà Basin in the southern Pyrenees (Bernaus et al., 2003; Sanchez-Hernandez et al., 2014), the Prebetic Domain in southeast Iberia (Vilas et al., 1995; Castro et al., 2008; Moreno-Bedmar et al. 2012b), the Basque-Cantabrian Basin in northern Iberia (García-Mondéjar et al., 2009; Schlagintweit et al., 2016; Fernández-Mendiola et al., 2017), and the Southeast France Basin (Masse and Fenerci-Masse, 2011; Pictet et al., 2015). Along the same lines, coeval large-scale transgressions have been reported from other parts of the Tethys (Föllmi et al., 1994; Sahagian et al., 1996; Hardenbol et al., 1998; Pittet et al., 2002; Wissler et al., 2003; Husinec and Jelaska 2006; Husinec et al., 2012; Hfaiedh et al., 2013; Suarez-Gonzalez et al., 2013; Wilmsen et al., 2015; Zorina et al., 2016), as well as from other basins worldwide (Cooper, 1977; Haq, 2016).

The regressive platform carbonates of the Villarroya de los Pinares Formation studied are also widespread in the Maestrat Basin (Fig. 4; Canérot et al., 1982; Salas, 1987). Throughout the Maestrat Basin, besides rudists and *Chondrodonta*, this formation also includes abundant corals, orbitolinids and miliolids (Salas, 1987; Malchus et al., 1995; Vennin and Aurell, 2000; Bover-Arnal et al., 2010, 2012, 2014). The Villarroya de los Pinares Formation cropping out in the Grossa Range is coeval with the platform carbonates of the same formation that form the nearby hillock called La Mola de Xert (Fig. 1B; Salas, 1987; Malchus et al., 1995), which is located 25 km to the W-SW, in the environs of the town of Xert (*Comarca* of El Baix Maestrat). (The town of Xert and La Mola de Xert should not be confused with the Xert Formation of Barremian age (Fig. 4; see Bover-Arnal et al., 2016)). The two successions characterized by the presence of rudists and *Chondrodonta* were probably part of the same carbonate platform system. The limestones of the Villarroya de los Pinares Formation of La Mola de Xert have been also traditionally exploited as an ornamental stone, which is commercially known as Crema Jaspe. The succession exploited in La Mola de Xert is correlatable with the rudist-dominated upper part of the Villarroya de los Pinares Formation in Ulldecona (Fig. 7). On the other hand, the rock extracted in Ulldecona, which belongs to the lower part of the Villarroya de los Pinares Formation (Fig. 7), correlates with deeper-water micritic limestones containing sponge spicules, *Dufrenoyia furcata* and orbitolinids in La Mola de Xert (see Salas, 1987; Malchus et al., 1995). Accordingly, the Aptian succession of La Mola de Xert represents more distal depositional environments than the succession studied in the Grossa Range. Similar to the Grossa Range, the Villarroya de los Pinares Formation of La Mola de Xert has been interpreted as a long-term regressive (highstand) succession (Malchus et al., 1995).

In the central part of the Morella sub-basin (Fig. 1B), in the surroundings of the city of Morella (*Comarca* of Els Ports), the Villarroya de los Pinares Formation includes forced regressive, lowstand normal regressive and highstand normal regressive deposits (Bover-Arnal et al., 2014). In this area, the highstand platform was thicker than 80 metres, whereas the lowstand platform and the forced regressive wedge were *ca*. 10 and 5 m thick, respectively (Bover-Arnal et al., 2014). On the other hand, in a platform-to-basin transition found in the Galve sub-basin (western Maestrat Basin; Fig. 1B), the Villarroya de los Pinares Formation exhibits downlapping slope geometries over and into the marls of the Forcall Formation, and it is stacked in an aggrading-retrograding pattern, which indicates a highstand normal regressive unit (Bover-Arnal et al., 2009, 2012; Gili et al., 2016). The thickness of this highstand platform where it is wholly preserved is around 50 metres (Bover-Arnal et al., 2010). Thinner isolated highstand platforms (*ca*. 15 m thick) and thicker highstand platform carbonate successions (*ca*. 90 m thick) belonging to the Villarroya de los Pinares Formation also occur in the Galve sub-basin (Bover-Arnal et al., 2010, 2015). In this western marginal part of the Maestrat Basin, there are also sedimentary bodies belonging to the Villarroya de los Pinares Formation, which are interpreted as forced regressive, lowstand normal regressive and transgressive deposits (Bover-Arnal et al., 2009, 2010, 2015). Interpreted lowstand and forced regressive units belonging to the Villarroya de los Pinares Formation in the Galve sub-basin are up to 32 and 5 m thick, respectively (Bover-Arnal et al. 2009; Skelton et al., 2010). Finally, the highstand platforms cropping out in the Galve sub-basin were subaerially exposed and incised during the late Early Aptian (Peropadre et al., 2007; Bover-Arnal et al., 2009, 2010, 2015).

On the other hand, in Ulldecona, signs of subaerial exposure at the top of the Villarroya de los Pinares Formation were not observed, thus this stratigraphic surface was interpreted as a maximum regressive surface (Figs. 7, 13B-C). However, it could also be that the signs of emersion were masked or removed by the latest Early Aptian transgression depositing the marls of the Benassal Formation (Figs. 7, 13A-C). The relatively thick succession exhibited by the Villarroya de los Pinares Formation in the Grossa Range (*ca*. 300 m thick) and the strong aggrading component of its upper part (Fig. 7), which is typical of inner platform settings, suggests that it was developed during a highstand normal regressive stage of sea level.

Sedimentary records of uppermost lower Aptian regressive platform carbonates are extensive in coeval basins of the Tethys and the Atlantic extension of it (e.g., Röhl and Ogg, 1998; Bosellini et al., 1999; Lehmann et al., 2000; van Buchem et al., 2010; Hfaiedh et al., 2013; Schlagintweit et al., 2016). In the Arabian Plate for example, the uppermost lower Aptian regressive limestones characterized by the presence of rudists belong to the Shu'aiba Formation and are also of economic importance but as hydrocarbon reservoirs (van Buchem et al., 2010; Yose et al., 2010). Furthermore, as reported from the

Galve sub-basin (Fig. 1B; Bover-Arnal et al., 2009, 2010, 2015), carbonate platforms from different Tethyan locations were also subaerially exposed around the boundary between the early and the late Aptian (e.g., Arnaud and Arnaud-Vanneau, 1989; Bernaus et al., 2003; Hillgärtner et al., 2003; Bachmann and Hirsch, 2006; Husinec and Jelaska, 2006; Yilmaz and Altiner, 2006; Burla et al., 2008; Husinec et al., 2012; Rameil et al., 2012; Fernández-Mendiola et al., 2013; Ruberti et al., 2013).

This widespread late early Aptian low-frequency regression has been linked to a glacio-eustatic event in some studies (e.g., Bover-Arnal et al., 2009; Husinec et al., 2012; Rameil et al., 2012; Maurer et al., 2013), and thus to a late early Aptian cooling episode (Solé de Porta and Salas, 1994; Hochuli et al., 1999; Steuber et al., 2005; Bover-Arnal et al., 2010; Skelton and Gili, 2012; Bottini et al., 2015; Cors et al., 2015; Bonin et al., 2016; Pascual-Cebrian et al., 2016). However, other water sequestration mechanisms such aquifer-eustasy or changes in the container capacity of the oceans (Immenhauser, 2005; Cloetingh and Haq, 2015; Sames et al., 2016; Wendler and Wendler, 2016; Wendler et al., 2016) could have also partly governed these high-rank sea-level changes identified in Ulldecona.

Along the same lines, the marine transgression and regression that led respectively to the deposition of the marls of the Forcall Formation and the platform carbonates of the Villarroya de los Pinares Formation in the Grossa Range during the early Aptian are correlatable with the Tethyan and global short-term sea-level events Ap3 of Hardenbol et al. (1998) and KAp1 of Haq (2016). Accordingly, the early Aptian high-rank transgressive-regressive sea-level trend characterized in the Grossa Range (Fig. 7) was in large part a eustatic event.

Nonetheless, in the Maestrat Basin, the record of the lower Aptian transgressive marly deposits of the Forcall Formation is slightly diachronous (Fig. 4; Bover-Arnal et al., 2016). In the Morella and Galve sub-basins (Fig. 1B), the Forcall Formation spans the four early Aptian ammonoid zones, namely *Deshayesites oglanlensis*, *Deshayesites forbesi*, *Deshayesites deshayesi* and *Dufrenoyia furcata* (Garcia et al., 2014; Bover-Arnal et al., 2016), whereas in the Oliete sub-basin (Fig. 1B), it only spans the *Deshayesites forbesi* Zone (Moreno-Bedmar et al., 2010; Garcia et al., 2014). Along the same lines, the regressive platform carbonates of the Villarroya de los Pinares Formation are of upper lower Aptian age (intra *Dufrenoyia furcata* Zone) in the Morella Sub-basin and the central Galve Sub-basin (Bover-Arnal et al., 2010, 2014, 2016), whereas in the eastern part of the Galve Sub-basin it spans the *Deshayesites dehayesi* and *Dufrenoyia furcata* zones (Bover-Arnal et al., 2010, 2016). These facts highlight that antecedent topography and local to regional tectonics played a part in controlling accommodation in the Maestrat Basin during the early Aptian global transgressive-regressive trend.

In the Grossa Range, the carbonate platform of the Villarroya de los Pinares Formation was drowned during the latest early Aptian and buried under transgressive marls of the base of the Benassal Formation (Figs. 7, 13A-C). Drowning of carbonte platforms during the latest early Aptian or at the early/late Aptian boundary has been reported from within the Maestrat Basin (Bover-Arnal et al., 2010, 2014, 2016), but also from geographically distant locations such as Central Iran (Wilmsen et al., 2013), south-eastern France (Masse and Fenerci-Masse, 2011), Mexico (Moreno-Bedmar et al., 2012a) or Venezuela (Jacquin et al., 1993).

Above the transgressive marls of the lowermost Benassal Formation (Figs. 7, 13A), a carbonate platform with mesorbitolinids and rudists belonging to the lower part of the same formation flourished during an early late Aptian regression (Figs. 7, 13D). This low-frequency transgressive-regressive sea-level trend recorded by the lower part of the Benassal Formation and preserved in Ulldecona is correlatable with the Tethyan and global short-term sea-level events Ap4 of Hardenbol et al. (1998) and KAp2 of Haq (2016). Consequently, this additional high-rank transgressive-regressive sequence of latest early-early late Aptian age (Fig. 7) is interpreted to have been largely controlled by eustasy as well.

Concerning the dolomitized levels studied in Ulldecona (Figs. 7, 14-15), massive dolomitization of the lower Aptian Villarroya de los Pinares Formation mainly occurs in eastern parts of the Maestrat Basin including the sub-basins of Morella, El Perelló, La Salzedella and Penyagolosa (Fig. 1B) (see Salas, 1987; Nadal, 2001). In addition, throughout the Maestrat Basin, minor saddle dolomite is also frequently found pore filling in large skeletal components such as rudist shells and corals of the Villarroya de los Pinares Formation (Bover-Arnal et al., 2010, 2014). Nevertheless, lower Aptian volumetrically large, replacive dolostones are poorly studied in the Maestrat Basin (Salas, 1987; Nadal, 2001). One of these rare studies is that from El Coll del Vidre section (Fig. 1B; Penyagolosa sub-basin), nearby the town of Vistabella del Maestrat (*Comarca* of l'Alcalatén), where Nadal (2001) reported the occurrence of massive dolostones exhibiting a destructive and pervasive fabric with an idiotopic-hypidiotopic mosaic, as well as widespread saddle dolomite, replacing lower Aptian limestones. The geometry of this dolomitized geobody belonging to the Villarroya de los Pinares Formation, however, is not recognizable according to Nadal (2001).

On the other hand, more attention has been paid to dolomitization of upper Aptian limestones of the Benassal Formation (Nadal, 2011; Martín-Martín et al., 2013, 2015, 2017; Corbella et al., 2014; Gomez-Rivas et al., 2014). In the Orpesa Range (Fig. 1B; Penyagolosa sub-basin), to the northeast of the city of Benicàssim (*Comarca* of La Plana Alta), dolostones belonging to the Benassal Formation form seismic-scale stratabound tabular geobodies, which are associated with fault zones and Mississipi Valley Type deposits. Dolostones from the Orpesa Range are mainly characterized by replacive dolomites with non-planar textures and saddle dolomite (Martín-Martín et al., 2013, 2015; Gomez-Rivas et al., 2014). Accordingly, dolomitization in this area has been interpreted as a hydrothermal process (above 80ºC), which would have occurred during the Late Cretaceous post-rift stage of the Maestrat Basin (Martín-Martín et al., 2013, 2015; Gomez-Rivas et al., 2014). Given the absence of xenotopic mosaics, saddle dolomite or Mississipi Valley Type ore deposits in the samples from Ulldecona examined (Fig. 15), the dolomitized interval studied (Figs. 5, 7, 14) would correspond to a lower-temperature, and perhaps to different, dolomitization event than the one described in Benicàssim. In this respect, idiotopic and hypidiotopic mosaic textures such as the ones observed in Ulldecona (Fig. 15) are commonly linked to temperatures below 50-60°C during dolomitization (Sibley and Gregg, 1987). Furthermore, in the Grossa Range it is currently unknown whether or not the dolomitization event characterized was controlled by faults.

9. Conclusions

The ornamental and building Stone from Ulldecona, commercially known as 'Sénia stone', corresponds to the Villarroya de los Pinares Formation of the Maestrat Basin. The Stone from Ulldecona is mainly constituted by limestones, locally bioturbated, with wackestone, packstone and grainstone textures rich in peloids, miliolids, orbitolinids, dasycladaceans and bivalves. Given the occurrence of *Orbitolinopsis simplex* together with *Palorbitolina lenticularis*, the Stone from Ulldecona is lower Aptian in age. Furthermore, the *Polyconites* rudists observed exhibit a relatively thick aragonite wall, a flattened left valve, and a modest size, which are indicative features of specimens of late early Aptian age (*Dufrenoyia furcata* ammonoid zone).

The platform carbonates of the Villarroya de los Pinares Formation characterized in Ulldecona developed on the northern margin of the Tethys Ocean in a eustatic regressive context, which post-dated the late Barremian-early Aptian global transgressive trend that led to the OAE 1a. The analysed regressive limestones and the underlying transgressive marls of the Forcall Formation, which crop out locally in the axial zone of an antiform structure, are interpreted as a large-scale (high-rank, low-frequency) transgressive-regressive sequence. An overlying long-term transgressive-regressive sequence of latest early-late Aptian age belonging to the Benassal Formation is locally preserved in the area examined. This second sequence is also of global significance and made up of transgressive marls, and regressive platform carbonates containing orbitolinids and rudists.

The middle part of the Villarroya de los Pinares Formation studied was affected by dolomitization during diagenesis. The decimetre- to tens of metres-thick dolomitized levels are stratabound, thus indicating a facies control on dolomitization. Dolomitic limestones, calcitic dolostones and dolostones occur. Dolostones, which are not extracted as ornamental or building rocks in the quarries of the area, are sucrose and exhibit vacuolar and cave porosities. Initial and intermediate stages of dolomitization mainly show idiotopic mosaics, and a destructive and pervasive fabric. Locally, retentive and/or selective fabrics also occur. Advanced dolomitization stages show a destructive and pervasive fabric with idiotopic and hypidiotopic mosaics, which have been commonly associated with temperatures below 50-60°C during dolomitization.

Lower Aptian limestones with rudists and orbitolinids are well-known sedimentary records from many basins worldwide and commercially important hydrocarbon reservoirs in the Arabian Peninsula (i.e., Shu'aiba Formation). This study, however, also draws attention to the potential as an ornamental/building stone of these platform carbonates formed along the margins of the Tethys during a late early Aptian global regression.

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Figure captions:

FIGURE 1 A) Geographical location of the Maestrat, South Iberian and Garraf basins in the eastern Iberian Chain (E Iberian Peninsula). B) Simplified palaeogeographic and structural map of the Maestrat Basin during the Late Jurassic-Early Cretaceous rifting cycle and situation of the Godall Range in the eastern Morella Sub-basin. Mo: Morella Sub-basin, Pe: El Perelló Sub-basin, Sa: La Salzedella Sub-basin, Ga: Galve Sub-basin, Ol: Oliete Sub-basin, Al: Aliaga Sub-basin, Pg: Penyagolosa Sub-basin. Modified after Salas et al. (2001).

FIGURE 2 Examples of representative constructions in Barcelona where the Stone from Ulldecona has been used. The Casa Milà (“La Pedrera”) (A) exhibits honed finished pavements made up of Stone from Ulldecona in its inner courtyards (B). In the Sagrada Família Temple (C), polished Stone from Ulldecona was employed to pave the floor of the sacristy (D). The shopping and entertainment centre Illa Diagonal (E) is paved with polished and honed (F) finished Stone from Ulldecona.

FIGURE 3 Examples of use of the Stone from Ulldecona in well-known buildings in Madrid and Alcalá de Henares. In Madrid, the exterior (A) and interior (B) walls of the Spanish Olympic Committee headquarters are cladded with sandy and honed finished Stone from Ulldecona, respectively. The Magisterial Cathedral of Alcalá de Henares (C) is paved with polished and honed finished Stone from Ulldecona (D).

FIGURE 4 Chrono-stratigraphic chart for the Late Barremian-Early Albian of the Maestrat Basin including the major transgressive-regressive sequences identified in the basin, Sr-derived numerical ages for the different lithostratigraphic units, stratigraphic position of the Oceanic Anoxic Event 1a (OAE1a) and relevant ammonoid, orbitolinid and rudist occurrences. Different species and related stratigraphic ranges are distinguished by using distinct colours. Numerical ages, geo-magnetic polarity intervals and ammonoid zones are taken from Gradstein et al. (2004). The ammonite zones identified by Moreno-Bedmar et al. (2009, 2010, 2012a) and Garcia et al. (2014) are dashed in grey. The global transgressive-regressive sequence-stratigraphic framework of European basins is taken from Hardenbol et al. (1998). Modified after Bover-Arnal et al. (2016).

FIGURE 5 Geological scheme of the southern part of the Godall Range (Grossa Range) with the six cartographic units characterized (key is inset). The geological cross-sections (A-A', B-B' and C-C') and the stratigraphic section logged are displayed in figure 6 and 7, respectively. The underlying topographic map was cropped from the 1:25,000 scale topographic base of Catalonia by the *Institut Cartogràfic i Geològic de Catalunya* (sheet 62-41; available at http://www.icgc.cat).

FIGURE 6 Simplified geological cross-sections (A-A', B-B' and C-C') showing the general structural framework and stratigraphic relationships of the southern part of the Godall Range (Grossa Range). The location of cross-sections is indicated in Figure 5.

FIGURE 7 Representative stratigraphic log of the Grossa Range that includes ages, lithostratigraphic units, lithologies, textures, dominant skeletal components, sedimentological characteristics, a sequence-stratigraphy analysis and the stratigraphic position of the interval quarried as an ornamental and building stone. This log commences on the TV-3313 road that goes from Ulldecona to Godall, with the marl deposits of Forcall Formation (lower Aptian), which is the oldest lithostratigraphic unit recognized in the area, and finishes in the Mas del Dengo, on a hill adjacent to the road where the basal part of the Benassal Formation crops out (uppermost lower Aptian-upper Aptian). The location of the stratigraphic column measured in the Grossa Range is indicated in Figure 5. The legend of the log is found in Figure 8.

FIGURE 8 Key to Figure 7.

FIGURE 9 Representative lithofacies of the lower Aptian of the Grossa Range. A) Marls of the Forcall Formation cropping out in the axial part of an antiform structure cut by the TV-3313 road. B) Close-up view of *Palorbitolina lenticularis* specimens found at the base of the Villarroya de los Pinares Formation on the TV-3313 road. Scale bar = 2 cm. C) Wackestone with fragments of the dasycladale *Salpingoporella muehlbergi* and gastropods of the Villarroya de los Pinares Formation quarried as an ornamental and building stone in the Grossa Range. Scale bar = 0.5 mm. D) Packstone with miliolids, *Orbitolinopsis simplex* and fragments of *Salpingoporella muehlbergi* of the Villarroya de los Pinares Formation extracted as an ornamental/building stone in the Grossa Range. Scale bar = 0.5 mm. E) Peloidal grainstone with miliolids and other foraminifera of the Villarroya de los Pinares Formation quarried as an ornamental and building stone in the Grossa Range. Scale bar = 0.5 mm. F) Detail of a bioturbated layer extracted as an ornamental stone.

FIGURE 10 Sedimentary features of the lower part of the Villarroya de los Pinares Formation in the Grossa Range. A) Stratigraphic level of the lower part of the Villarroya de los Pinares Formation quarried as an ornamental/building stone in the southern part of the Godall Range characterized by the presence of *Chondrodonta* and rudist bivalves. B) Close-up view of a scleractinian coral colony. C) Panoramic view of the lower part of the Villarroya de los Pinares Formation quarried as an ornamental/building stone nearby the town of Ulldecona. D) Outcrop view within a quarry of a recent karst partially filled with a speleothem. Note also how around the fractures and karst affecting the dolomitic limestone to calcitic dolostone bed of the upper part of the image, there is a marked change from dark to a lighter gray colour due to calcitization. Scale bar = 1 m.

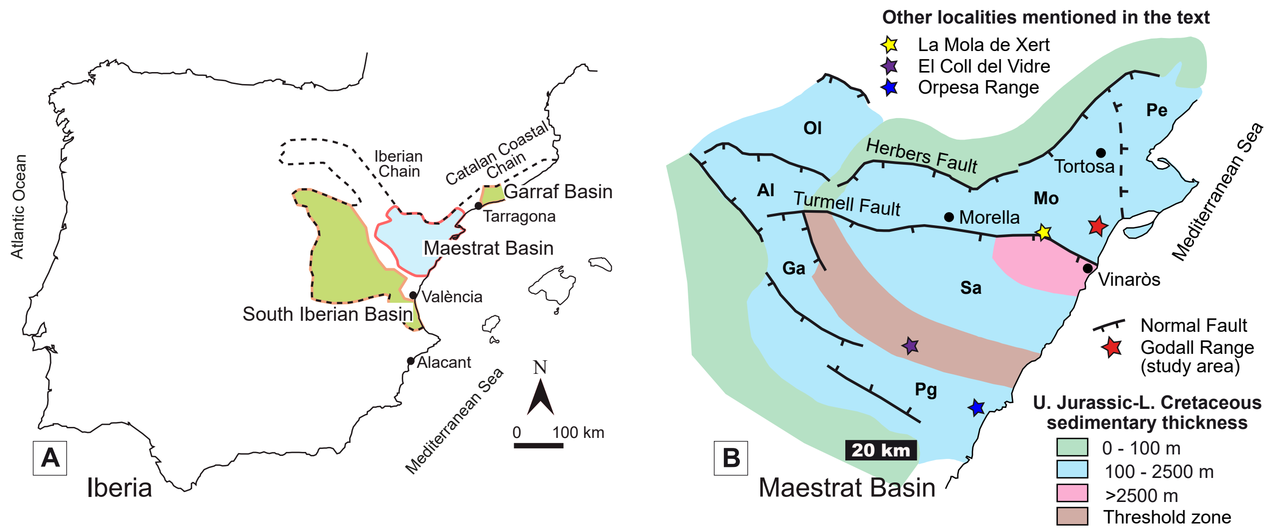
FIGURE 11 Characteristic microfossils of the Villarroya de los Pinares Formation from the Grossa Range. A) The orbitolinid *Palorbitolina lenticularis*. Scale bar = 0.5 mm. B) The orbitolinid *Orbitolinopsis simplex*. Scale bar = 0.5 mm. C) The orbitolinid *Paracoskinolina maynci*. Scale bar = 0.25 mm. D) The benthic foraminifer *Choffatella decipiens*. Scale bar = 0.5 mm. E) The microproblematicum *Lithocodium aggregatum*. Scale bar = 0.5 mm. F) The dasycladale *Salpingoporella muehlbergi*. Scale bar = 0.25 mm.

FIGURE 12 Rudist bivalves characteristic of the upper lower Aptian of the Grossa Range. A) *Toucasia carinata* from the Villarroya de los Pinares Formation. Camera cap = 5.8 cm. B) *Mathesia darderi* from the Villarroya de los Pinares Formation. C) *Polyconites*-bearing limestone from the upper part of the Villarroya de los Pinares Formation cropping out in a TV-3313 road cut. D) Specimens of *Polyconites* sp., most likely *Polyconites hadriani*, from the upper part of the Villarroya de los Pinares Formation. Scale bar = 2 cm.

FIGURE 13 Facies and sedimentology of the top of the Villarroya de los Pinares Formation (upper lower Aptian) and the Benassal Formation (uppermost lower Aptian-lower upper Aptian) of the Grossa Range. A) Outcrop of the transgressive marls of the base of the Benassal Formation in the Mas del Dengo. Hammer length = 32 cm. B) Hardground located at the top of the Villarroya de los Pinares Formation that marks the drowning of the rudist-dominated lower Aptian carbonate platform in Mas del Dengo. Hammer length = 32 cm. C) Detail of the hardground shown in Fig. 13B. Note the presence of borings of lithophagid bivalves and of iron stains. D) Closely-packed cluster of *Polyconites* from the upper Aptian Benassal Formation at Mas del Dengo site. Camera cap = 5.8 cm.

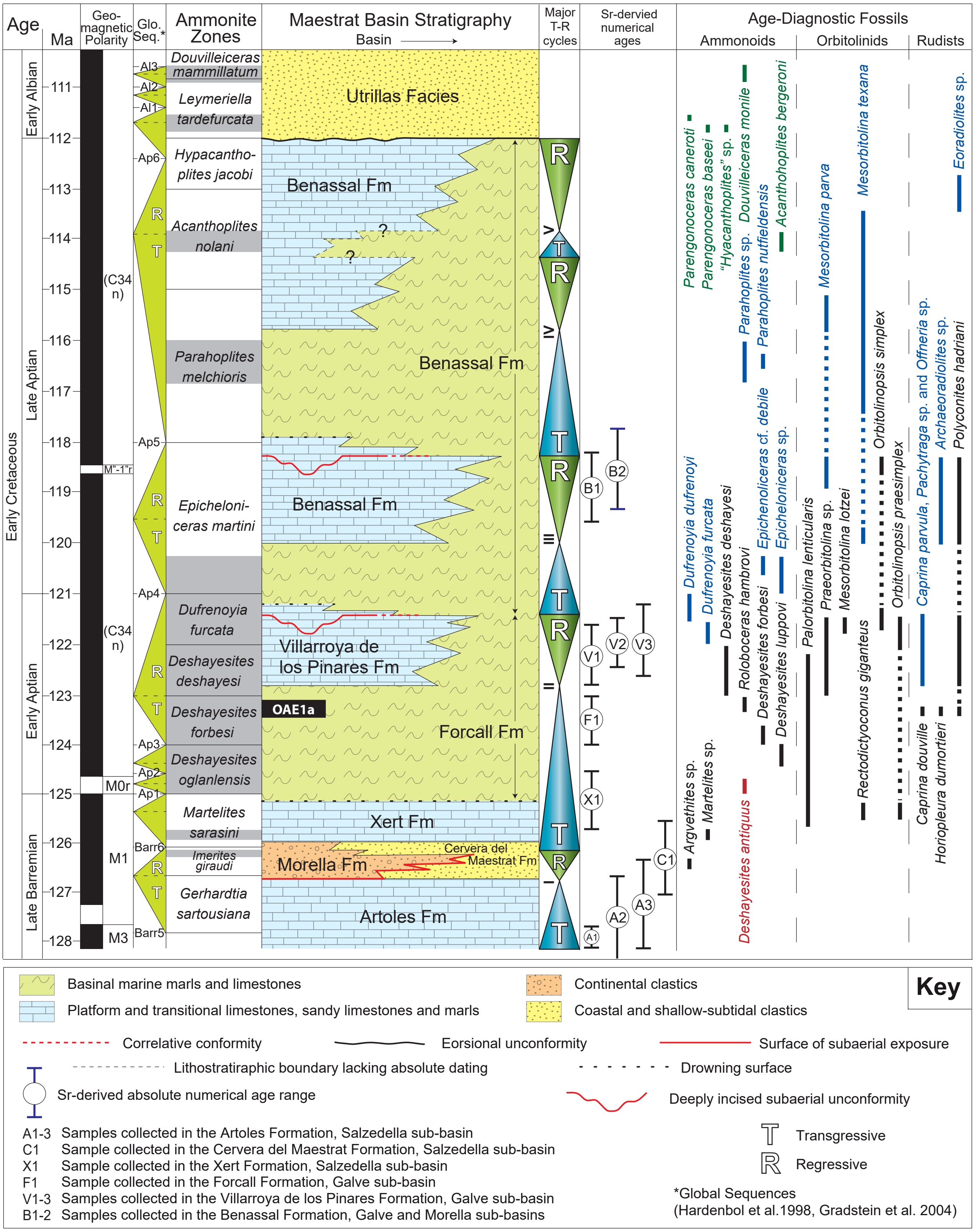
FIGURE 14 Dolomitization of the lower Aptian platform carbonates of the Villarroya de los Pinares Formation in the Grossa Range. A) Laterally continuous and thick (*ca*. 40 m thick) stratabound level of dolostones capping the succession commercialized as an ornamental/building stone in the quarries of Ulldecona. B) Detail of vacuolar porosity observed in the Sant Joan quarry. Camera cap = 5.8 cm. C) Detail of cave porosity photographied in the Sant Joan quarry. Scale bar = 1 m. D) Decimetric stratabound levels of dolomitic limestone to calcitic dolostone (red arrows) that appear in the lower part of the Villarroya de los Pinares Formation in the Sant Joan quarry.

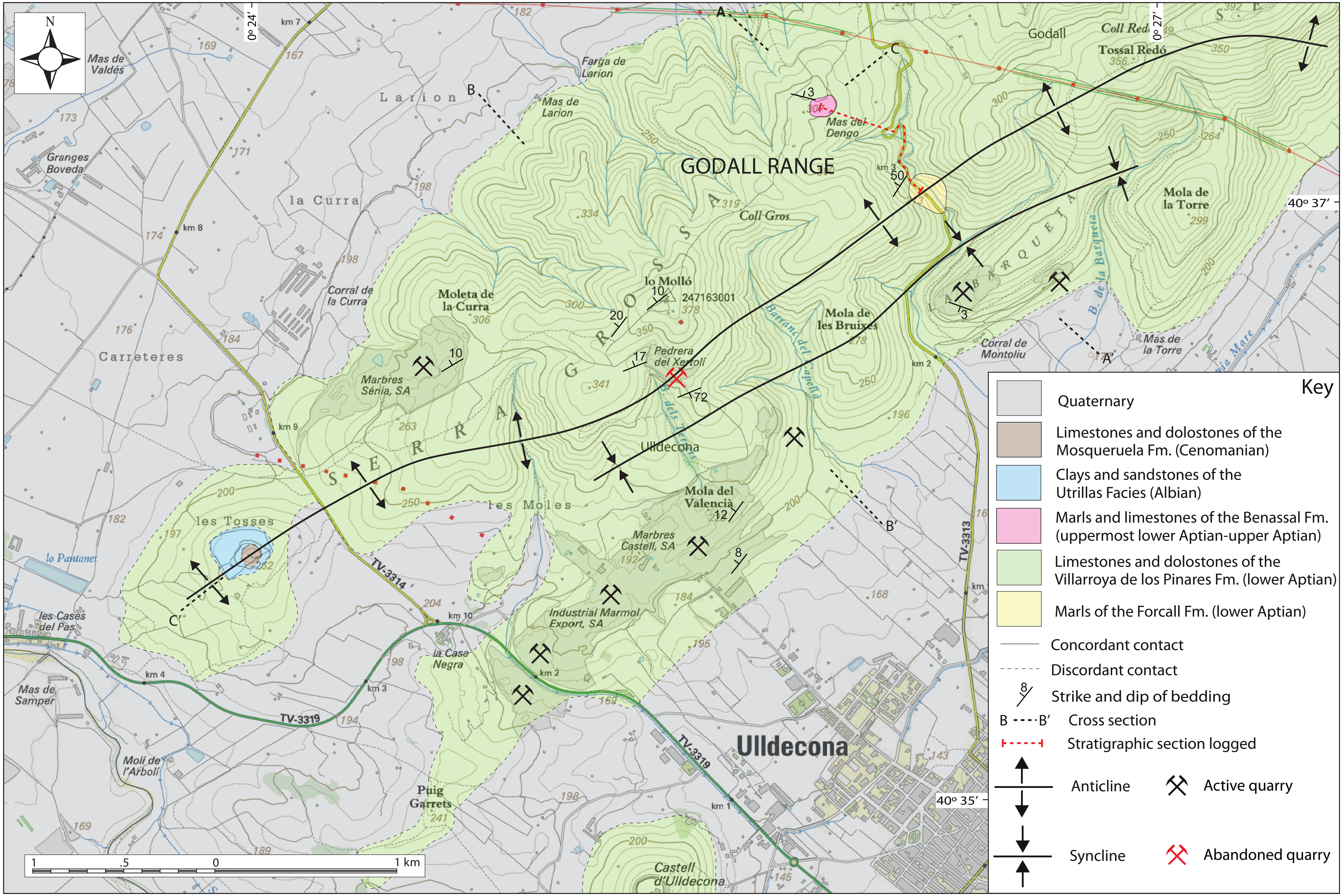
FIGURE 15 Dolomitization of the lower Aptian platform carbonates of the Villarroya de los Pinares Formation in the Grossa Range. A) Initial dolomitization stage of a packstone-grainstone texture with peloids and orbitolinids. B) Intermediate dolomitization stage of a wackestone-packstone texture with miliolids and peloids. C) Idiotopic mosaic texture in an advanced stage of dolomitization. D) Hypidiotopic mosaic texture in an advanced stage of dolomitization. Scale bars = 0.5 mm.


Atlantic Ocean
Iberian Chain
Catalan Coastal Chain
Garraf Basin
Tarragona
Maestrat Basin
València
South Iberian Basin
Alacant
Mediterranean Sea
N
0 100 km
A
Iberia
Other localities mentioned in the text
La Mola de Xert
El Coll del Vidre
Orpesa Range
Ol
Herbers Fault
Pe
Tortosa
Al
Turmell Fault
Morella
Mo
Mediterranean Sea
Ga
Sa
Vinaròs
Normal Fault
Godall Range (study area)
Pg
U. Jurassic-L. Cretaceous sedimentary thickness
20 km
B
Maestrat Basin
0 - 100 m
100 - 2500 m
>2500 m
Threshold zone

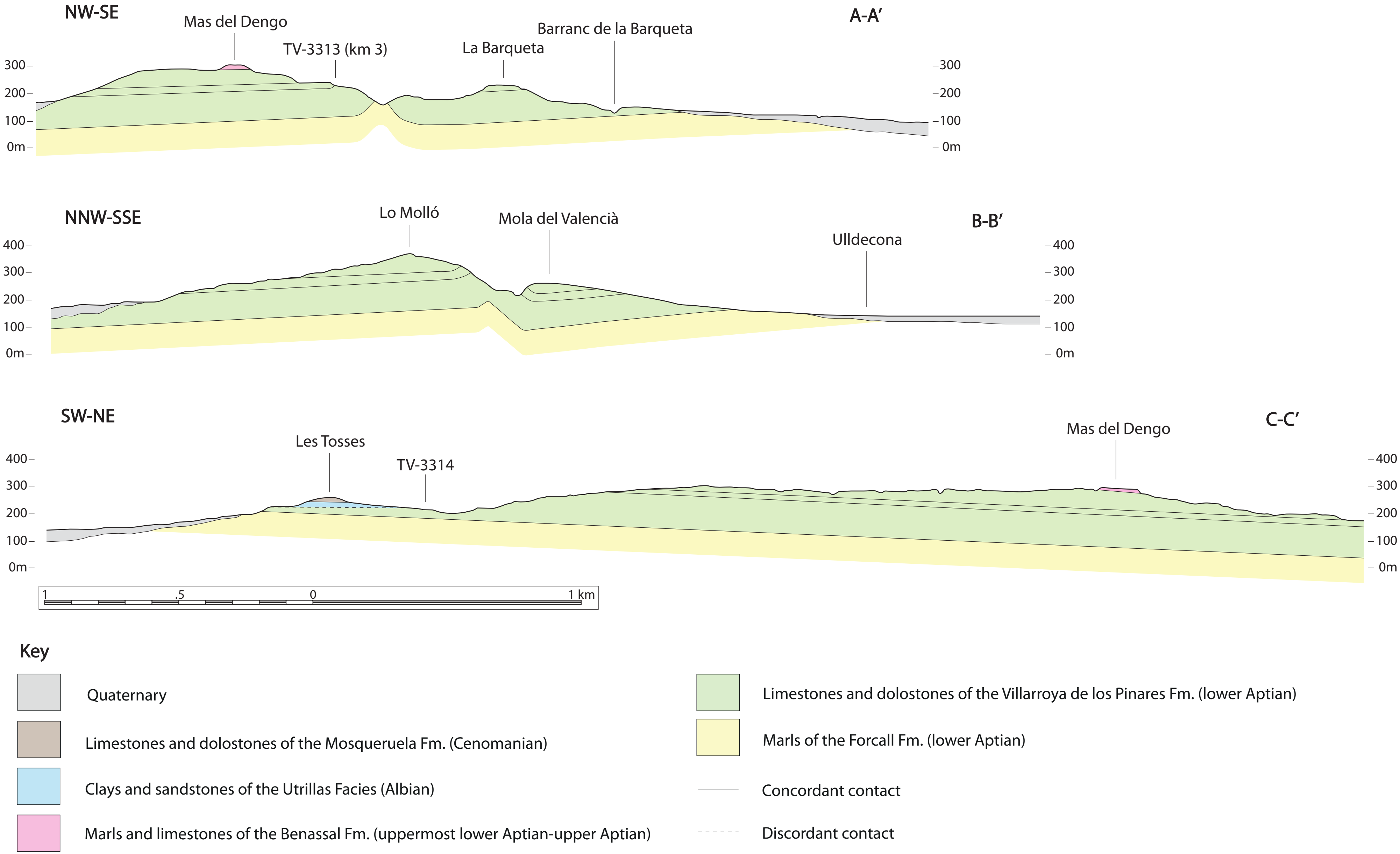

A
B
CAUTION
WET FLOOR
C
D
E
ferrer
TRAM
F

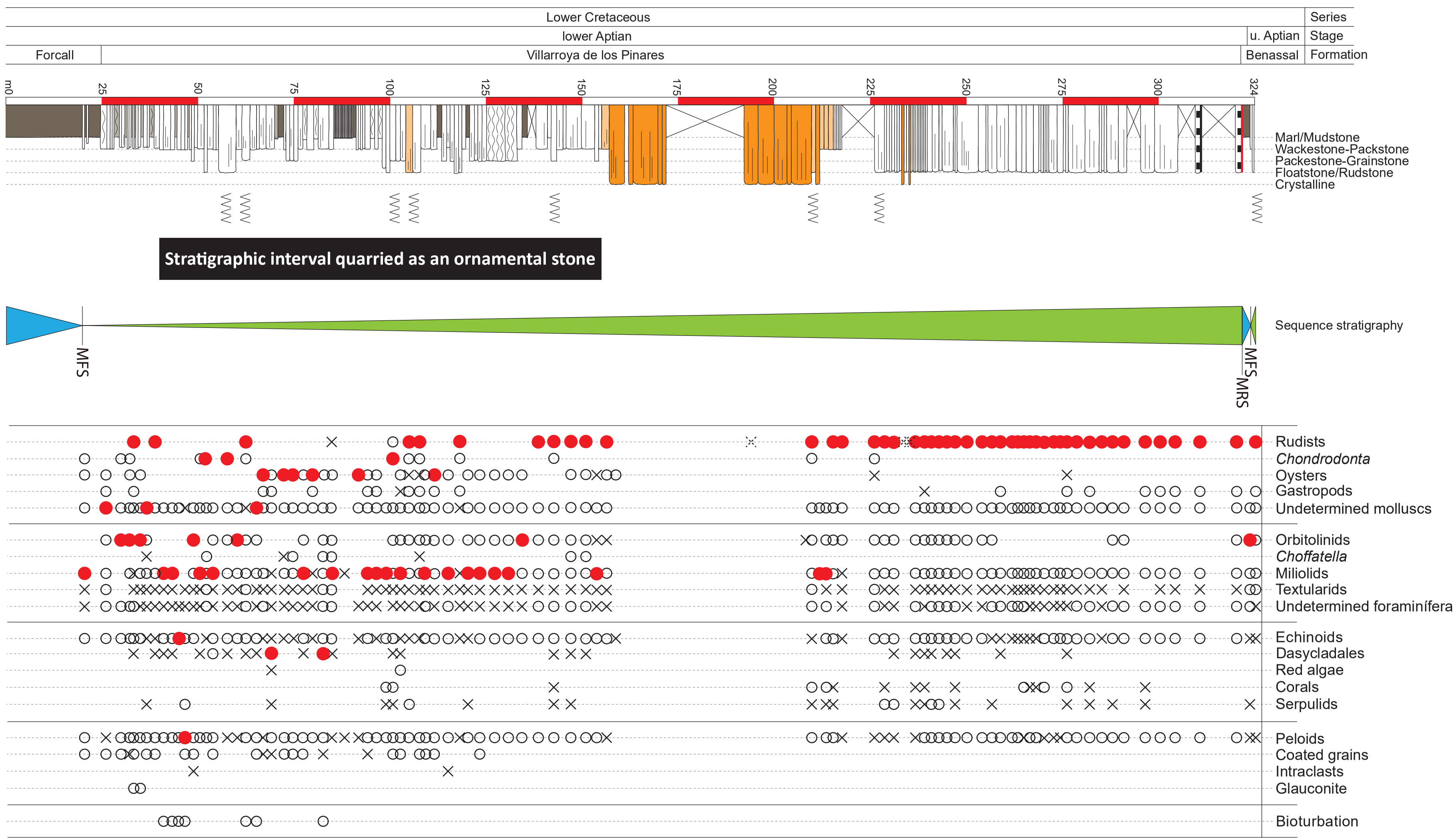

A
B
C
D


Age
Ma
Geo-magnetic Polarity
Glo. Seq.*
Ammonite Zones
Maestrat Basin Stratigraphy
Basin
Major T-R cycles
Sr-dervied numerical ages
Age-Diagnostic Fossils
Ammonoids
Orbitolinids
Rudists
Early Cretaceous
Early Albian
Late Aptian
Early Aptian
Late Barremian
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
(C34 n)
M"-1"r
(C34 n)
M0r
M1
M3
Al3
Al2
Al1
Ap6
Ap5
Ap4
Ap3
Ap2
Ap1
Barr6
Barr5
Douvilleiceras mammillatum
Leymeriella tardefurcata
Hypacanthoplites jacobi
Acanthoplites nolani
Parahoplites melchioris
Epicheloniceras martini
Dufrenoyia furcata
Deshayesites deshayesi
Deshayesites forbesi
Deshayesites oglanlensis
Martelites sarasini
Imerites giraudi
Gerhardtia sartousiana
Utrillas Facies
Benassal Fm
Benassal Fm
Benassal Fm
Villarroya de los Pinares Fm
OAE1a
Forcall Fm
Xert Fm
Morella Fm
Cervera del Maestrat Fm
Artoles Fm
B1
B2
V1
V2
V3
F1
X1
C1
A1
A2
A3
Parengonoceras caneroti
Parengonoceras baseei
"Hyacanthoplites" sp.
Parahoplites sp.
Douvilleiceras monile
Parahoplites nutfieldensis
Acanthohoplites bergeroni
Dufrenoyia dufrenoyi
Dufrenoyia furcata
Deshayesites deshayesi
Roloboceras hambrovi
Epicheloniceras cf. debile
Deshayesites forbesi
Epicheloniceras sp.
Deshayesites luppovi
Argvethites sp.
Martelites sp.
Deshayesites antiquus
Mesorbitolina parva
Mesorbitolina texana
Palorbitolina lenticularis
Praeorbitolina sp.
Mesorbitolina lotzei
Rectodictyoconus giganteus
Orbitolinopsis simplex
Orbitolinopsis praesimplex
Caprina parvula, Pachytraga sp. and Offneria sp.
Archaeoradiolites sp.
Eoradiolites sp.
Polyconites hadriani
Caprina douvillei
Horiopleura dumortieri
Key
Basinal marine marls and limestones
Platform and transitional limestones, sandy limestones and marls
Continental clastics
Coastal and shallow-subtidal clastics
Correlative conformity
Eorsional unconformity
Surface of subaerial exposure
Lithostratiraphic boundary lacking absolute dating
Drowning surface
Sr-derived absolute numerical age range
Deeply incised subaerial unconformity
A1-3 Samples collected in the Artoles Formation, Salzedella sub-basin
C1 Sample collected in the Cervera del Maestrat Formation, Salzedella sub-basin
X1 Sample collected in the Xert Formation, Salzedella sub-basin
F1 Sample collected in the Forcall Formation, Galve sub-basin
V1-3 Samples collected in the Villarroya de los Pinares Formation, Galve sub-basin
B1-2 Samples collected in the Benassal Formation, Galve and Morella sub-basins
T Transgressive
R Regressive
*Global Sequences
(Hardenbol et al.1998, Gradstein et al. 2004)



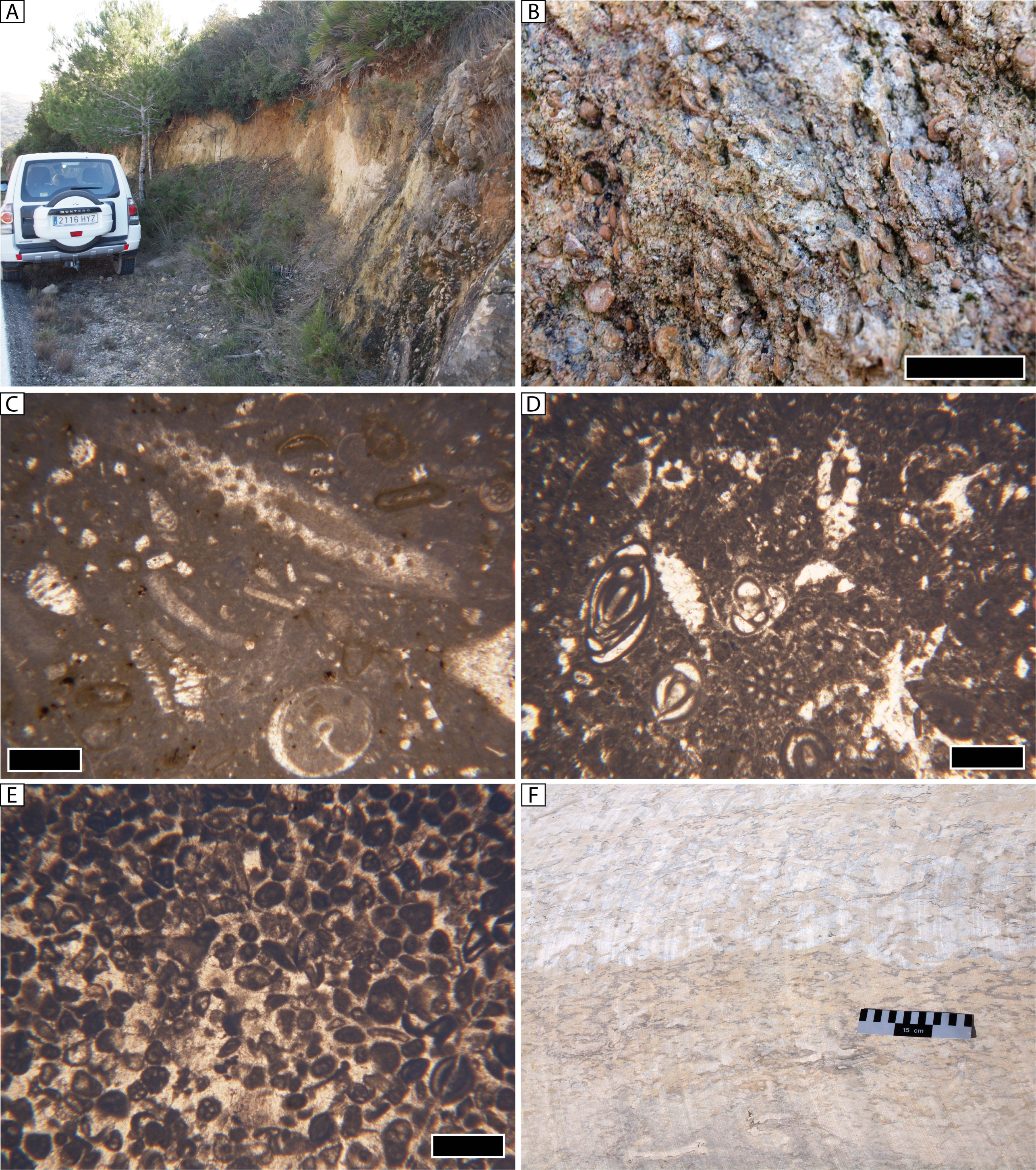
N
GODALL RANGE
S E R R A G R O S S A
B A R Q U E T A
Godall
Coll Redó
Tossal Redó
Farga de Larion
Mas de Larion
Larion
Mas de Valdés
Granges Boveda
la Curra
Carreteres
Corral de la Curra
Moleta de la Curra
lo Molló
247163001
Coll Gros
Mas del Dengo
Mola de la Torre
Mola de les Bruixes
Barranc del Capella
B. de la Barqueta
Corral de Montoliu
Mas de la Torre
Marbres Sénia, SA
Pedrera del Xertolí
Ulldecona
Mola del Valencia
Marbres Castell, SA
Industrial Marmol Export, SA
les Moles
les Tosses
lo Pantanet
les Cases del Pas
Mas de Samper
Molí de l'Arboli
la Casa Negra
Puig Garrets
Castell d'Ulldecona
Ulldecona
TV-3314
TV-3319
TV-3313
0º 24′
0º 27′
40º 37′
40º 35′
A
A′
B
B′
C
1
.5
0
1 km
Key
Quaternary
Limestones and dolostones of the Mosqueruela Fm. (Cenomanian)
Clays and sandstones of the Utrillas Facies (Albian)
Marls and limestones of the Benassal Fm. (uppermost lower Aptian-upper Aptian)
Limestones and dolostones of the Villarroya de los Pinares Fm. (lower Aptian)
Marls of the Forcall Fm. (lower Aptian)
Concordant contact
Discordant contact
Strike and dip of bedding
B - - - B′ Cross section
Stratigraphic section logged
Anticline
Syncline
Active quarry
Abandoned quarry

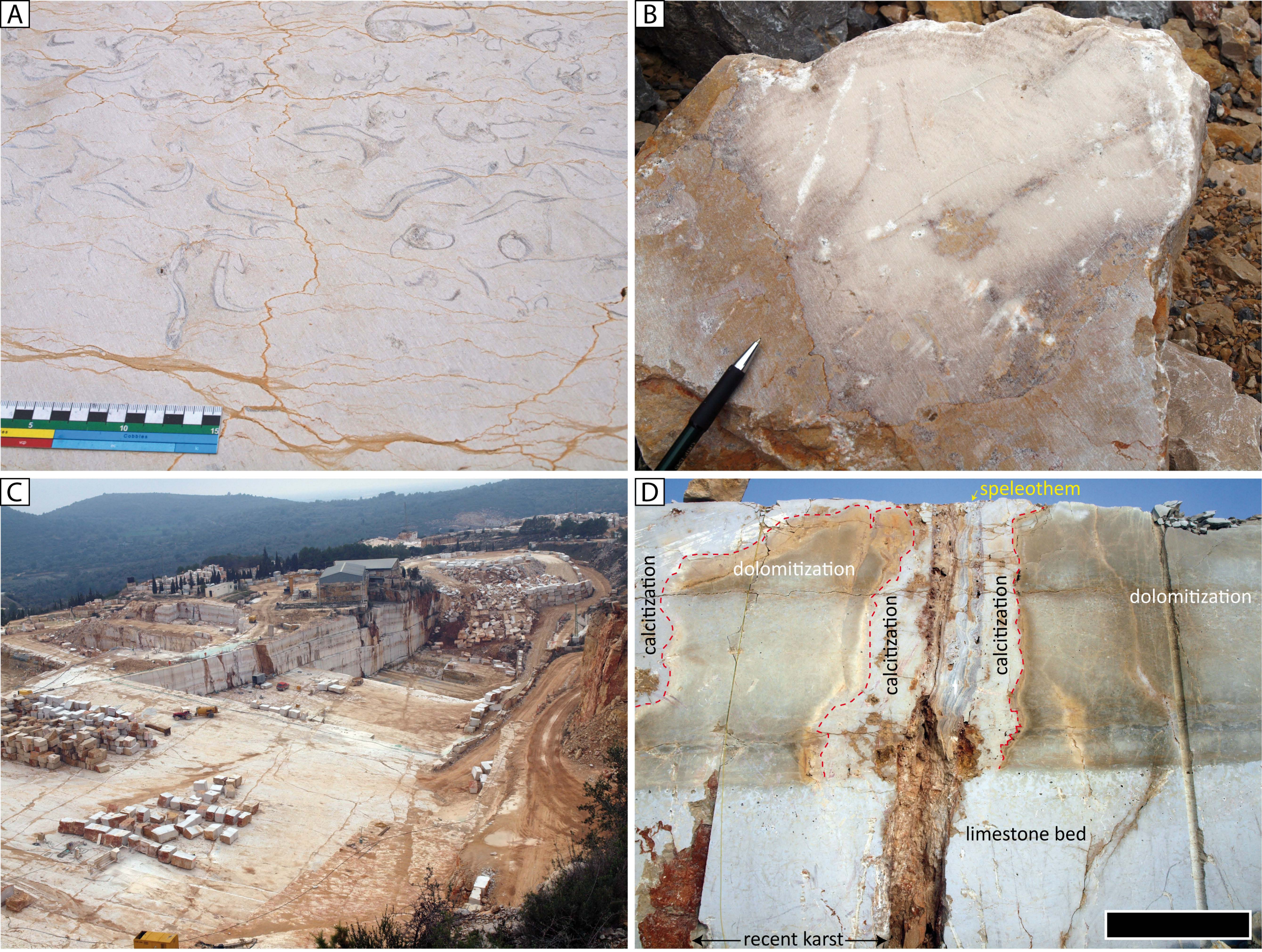

NW-SE
A-A'
Mas del Dengo
TV-3313 (km 3)
La Barqueta
Barranc de la Barqueta
300
200
100
0m
NNW-SSE
B-B'
Lo Molló
Mola del Valencià
Ulldecona
400
300
200
100
0m
SW-NE
C-C'
Les Tosses
TV-3314
Mas del Dengo
400
300
200
100
0m
1
.5
0
1 km
Key
Quaternary
Limestones and dolostones of the Mosqueruela Fm. (Cenomanian)
Clays and sandstones of the Utrillas Facies (Albian)
Marls and limestones of the Benassal Fm. (uppermost lower Aptian-upper Aptian)
Limestones and dolostones of the Villarroya de los Pinares Fm. (lower Aptian)
Marls of the Forcall Fm. (lower Aptian)
Concordant contact
Discordant contact

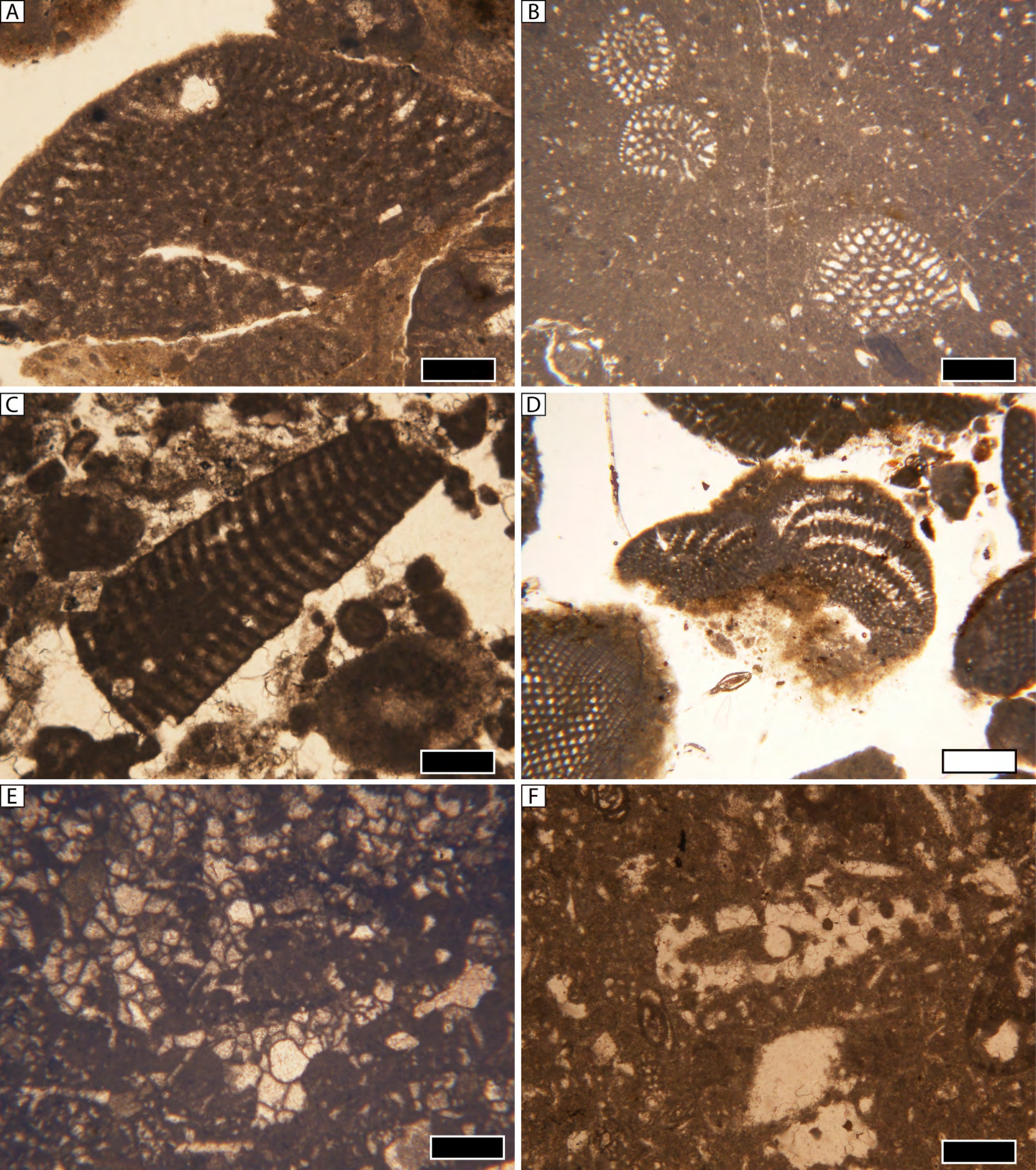

Lower Cretaceous
Series
lower Aptian
u. Aptian
Stage
Forcall
Villarroya de los Pinares
Benassal
Formation
m0
25
50
75
100
125
150
175
200
225
250
275
300
324
Marl/Mudstone
Wackestone-Packstone
Packestone-Grainstone
Floatstone/Rudstone
Crystalline
Stratigraphic interval quarried as an ornamental stone
Sequence stratigraphy
MFS
MFS
MRS
Rudists
Chondrodonta
Oysters
Gastropods
Undetermined molluscs
Orbitolinids
Choffatella
Miliolids
Textularids
Undetermined foraminífera
Echinoids
Dasycladales
Red algae
Corals
Serpulids
Peloids
Coated grains
Intraclasts
Glauconite
Bioturbation

Stratigraphic log's key:

- Marl
- Marly-limestone
- Limestone
- Dolomitic limestone
- Calcitic dolomite and dolostone
- Facies-characteristic component
- Common component or presence of bioturbation structures
- Rare component
- Mouldic porosity
- Transgression
- Regression
- MRS Maximum regressive surface
- MFS Maximum flooding surface
- Perforated hardground
- Iron crust
- Nodular stratification
- *Chondrodonta* and/or elevator rudists in life position


A
B
C
D
E
F
MONTERO
2116 HYZ
15 cm

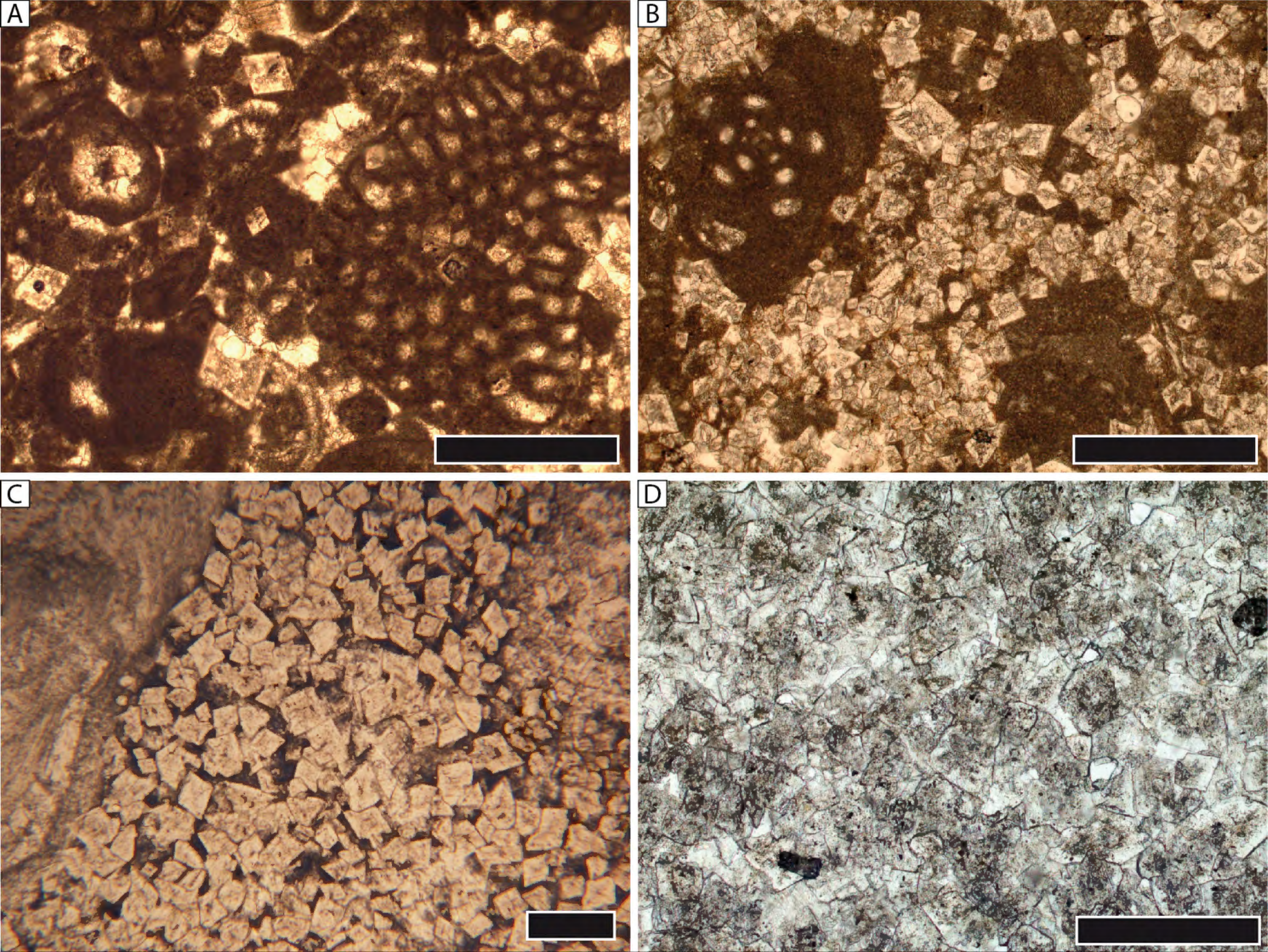

A
B
C
D
speleothem
calcitization
dolomitization
calcitization
calcitization
dolomitization
limestone bed
recent karst


A
B
C
D
E
F


A
OLYMPUS
B
C
D


A
B
C
D
15 cm
OLYMPUS


A
Stratabound dolostone
level (ca. 40 m)
B
C
D


A
B
C
D