Geologica Acta, Vol.1, Nº2, 2003, 201-229
Available online at www.geologica-acta.com

An inventory of the marine and transitional Middle/Upper Eocene deposits of the Southeastern Pyrenean Foreland Basin (NE Spain)

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ABSTRACT

In the southeastern Ebro Foreland Basin, the marine deposits of Lutetian and Bartonian age show excellent outcrop conditions, with a great lateral and horizontal continuity of lithostratigraphic units. In addition, the rich fossil record -mainly larger foraminifers-, provides biostratigraphic data of regional relevance for the whole Paleogene Pyrenean Basin, that can be used for the Middle Eocene biocorrelation of the western Tethys. This contribution is a sedimentary and biostratigraphic synthesis of the basic outcrops and sections of the Lutetian and Bartonian marine and transitional deposits in the southeastern sector of the Ebro Foreland Basin.

KEYWORDS **Middle/Upper Eocene. Lithostratigraphy. Biostratigraphy. Chronostratigraphy. Southern Pyrenean basin.**

INTRODUCTION

This paper introduces the Middle Eocene (Lutetian and Bartonian) marine and transitional outcrops and sections in the southeastern sector of the Ebro Foreland Basin that were visited during the Second Meeting of IGCP 393, held in Vic in September 1997. The aim of this field trip was to provide the members of IGCP 393 with larger foraminifer material from the various Lutetian and Bartonian stratigraphic units that yielded the paleontological samples used to the establish the so called Shallow Benthic Zones (SBZ) defined by Serra-Kiel et al. (1998a, b). This new larger foraminifers new biozoning of the Paleocene-Eocene of the Tethys is in part based on the data resulting from the study of this material.

The outcrops and sections presented here are grouped in three distinct areas: Empordà, Vic and Igualada (Fig. 1), and they were selected according to the following criteria:

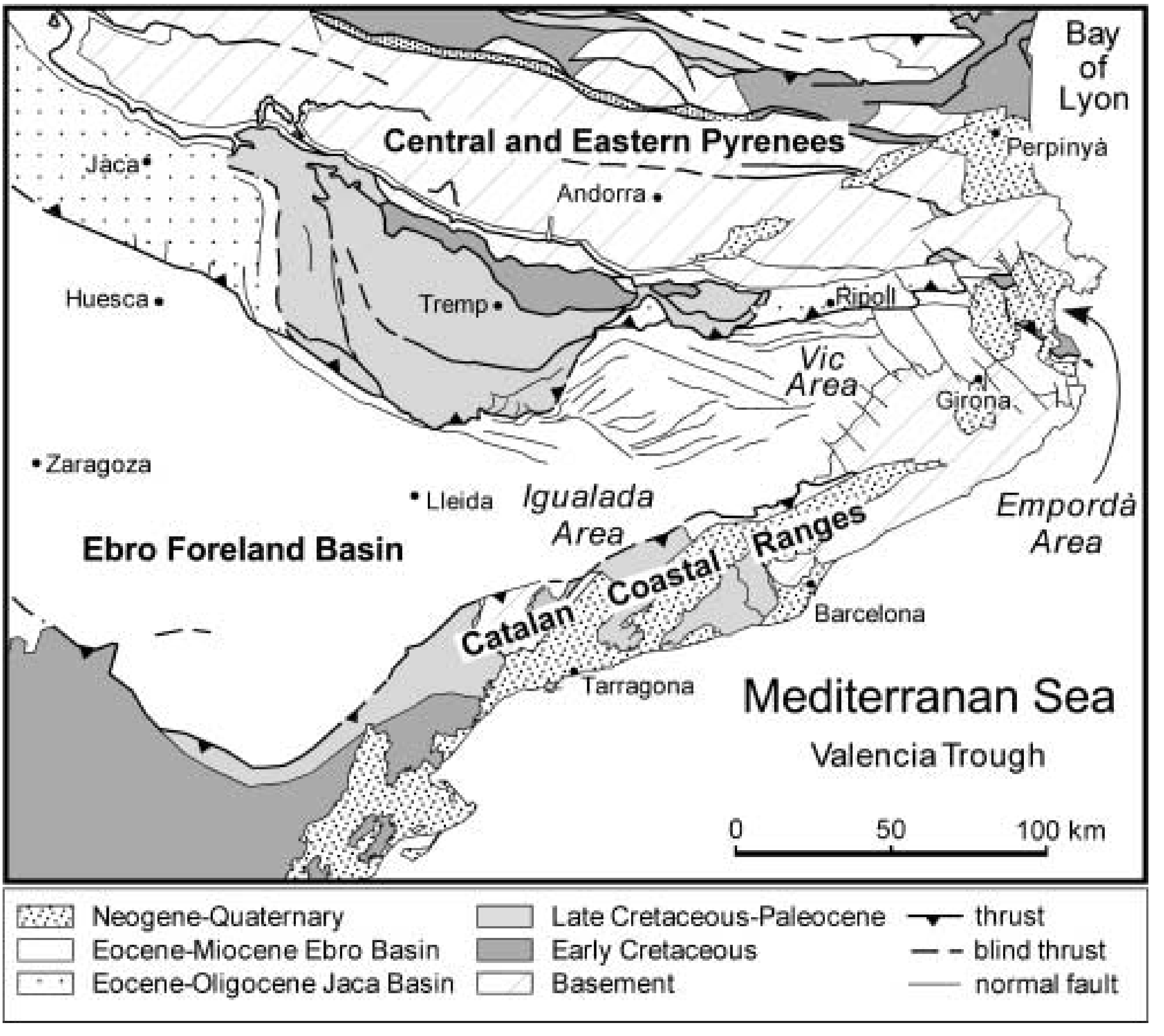

FIGURE 1 **Geological sketch showing the situation of the described areas.**

1) They should be ideally situated with regard to both the lithostratigraphic units and the transgressive-regressive cycles that constitute the Middle Eocene marine and transitional units of this sector of the Ebro Foreland Basin.

2) The samples of larger foraminifers contained in the outcrops and sections should be representative of different sedimentary environments. Transitional and shallow marine environment outcrops contain porcellaneous larger foraminifers, such as *Alveolina*, *Orbitolites*, *Fabularia*, *Malatyna*, and *Rhabdorites*. Inner and middle shelf marine environments contain nummulitids (*Nummulites*, *Assilina*, *Operculina*, and *Heterostegina*) and orthophragminids (*Discocyclina*, *Orbitoclypeus*, and *Asterocyclina*). A further consideration was the existence of samples containing genera of larger foraminifers such as the Bartonian genera *Pellatispira* and *Biplanispira*, whose biostratigraphic location had not, at that time, been clearly determined.

3) Further, the samples should be, as far as possible, correlatable in the field with magnetostratigraphic data and with previously published information on planktic foraminifers.

4) Outcrops corresponding to the type-localities of species of larger foraminifers of the Middle Eocene defined in this sector of the Ebro Foreland Basin were also selected.

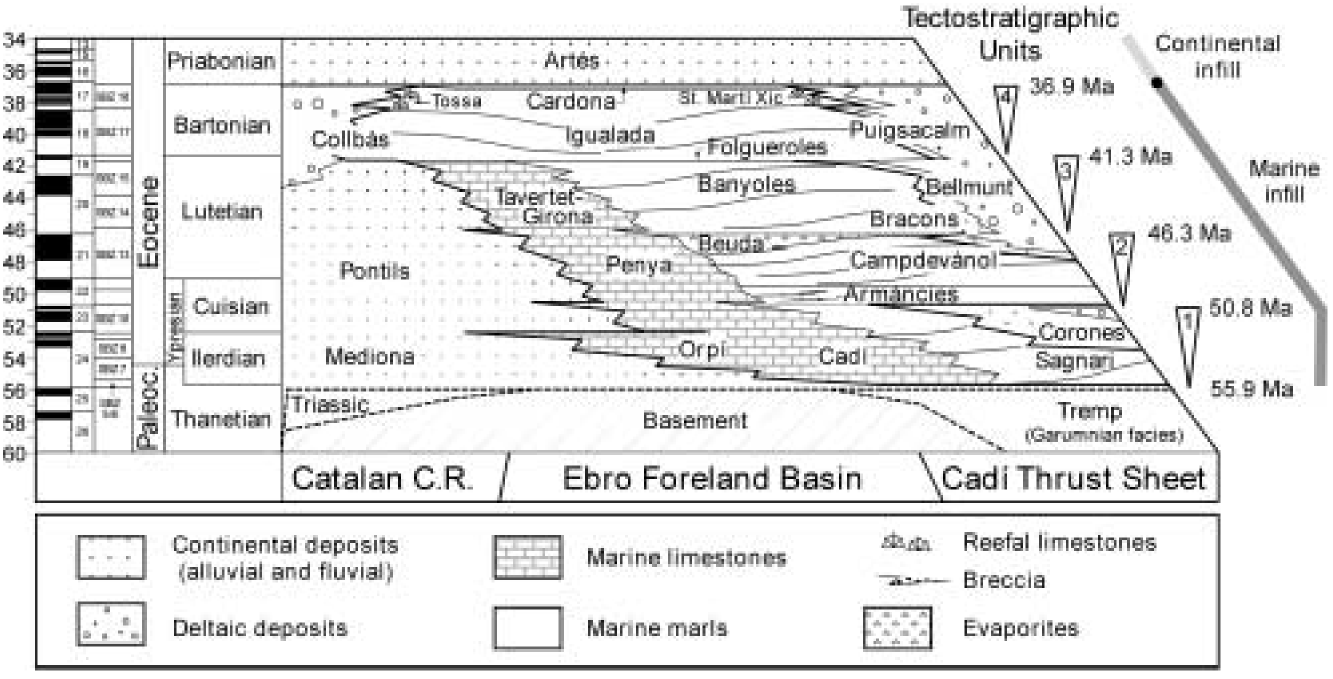

FIGURE 2 **Stratigraphic panel across the Ebro Foreland Basin between the Cadí Thrust Sheet and the Catalan Coastal Ranges, modified from Vergés et al., (1998). Biostratigraphic data combined with magnetostratigraphic information (Burbank et al. 1992a,b; Vergés and Burbank 1996; Serra-Kiel et al. 1994) define the chronostratigraphic framework of this area. Global polarity time scale from Cande and Kent (1995). Larger foraminifers Shallow Benthic Zones (SBZ) from Serra-Kiel et al. (1998a, b).**

5) Finally, the outcrops and sections selected and sampled should be representative of the whole range of Middle Eocene marine and transitional biofacies in the Pyrenean basin. Thus, there are outcrops and sections that correspond to the outer aphotic shelf, the outer euphotic shelf, the middle and inner shelves, reefal bioconstructions, and the inner carbonate shelf. These material also allowed the members of IGCP 393 to study other taxons, such as hermatypic and ahermatypic corals, bryozoa and siliceous sponges.

Serra-Kiel et al. (in this volume) give a detailed description of the stratigraphic framework of the Lutetian and Bartonian transitional and marine units of this sector of the Ebro Foreland Basin. Figure 2, modified from Vergés et al. (1998), shows the correlation between (a) the magnetostratigraphic scale from Cande and Kent (1995) and the Shallow Benthic Zones of Serra-Kiel et al. (1998a, b), and (b) the Paleogene lithostratigraphic units of the Ebro Foreland Basin situated between the Cadí Thrust Sheet and the Catalan Coastal Ranges.

The legend to the symbols used in the figures is in Figure 3, and the list of species cited in this issue is included as Appendix II at the end of the volume.

THE LUTETIAN MARINE RECORD IN THE EMPORDÀ AREA

Pals Beach and Racó Beach sections

Location: The outcrops are located on the cliff-face between the southern end of Pals Beach and Racó Beach (1 in Fig. 4 and Fig. 5A).

Lithostratigraphic Unit: Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972).

Chronostratigraphic Unit: Early, Middle and Late Lutetian.

Biostratigraphic Unit: SBZ 13, SBZ 14 and SBZ 16.

Unconformity-Bounded Units: 1st, 2nd and 4th Lutetian Cycles.

Two stratigraphic sections can be visited. The first section is located on Racó Beach, and the second one is located close to the car park at the southern end of Pals Beach (Fig. 5A).

The Racó Beach Section

In this section (Fig. 5B) it is possible to observe the contact between the continental units and the marine units of the 1st Lutetian cycle in the southeasternmost part of the

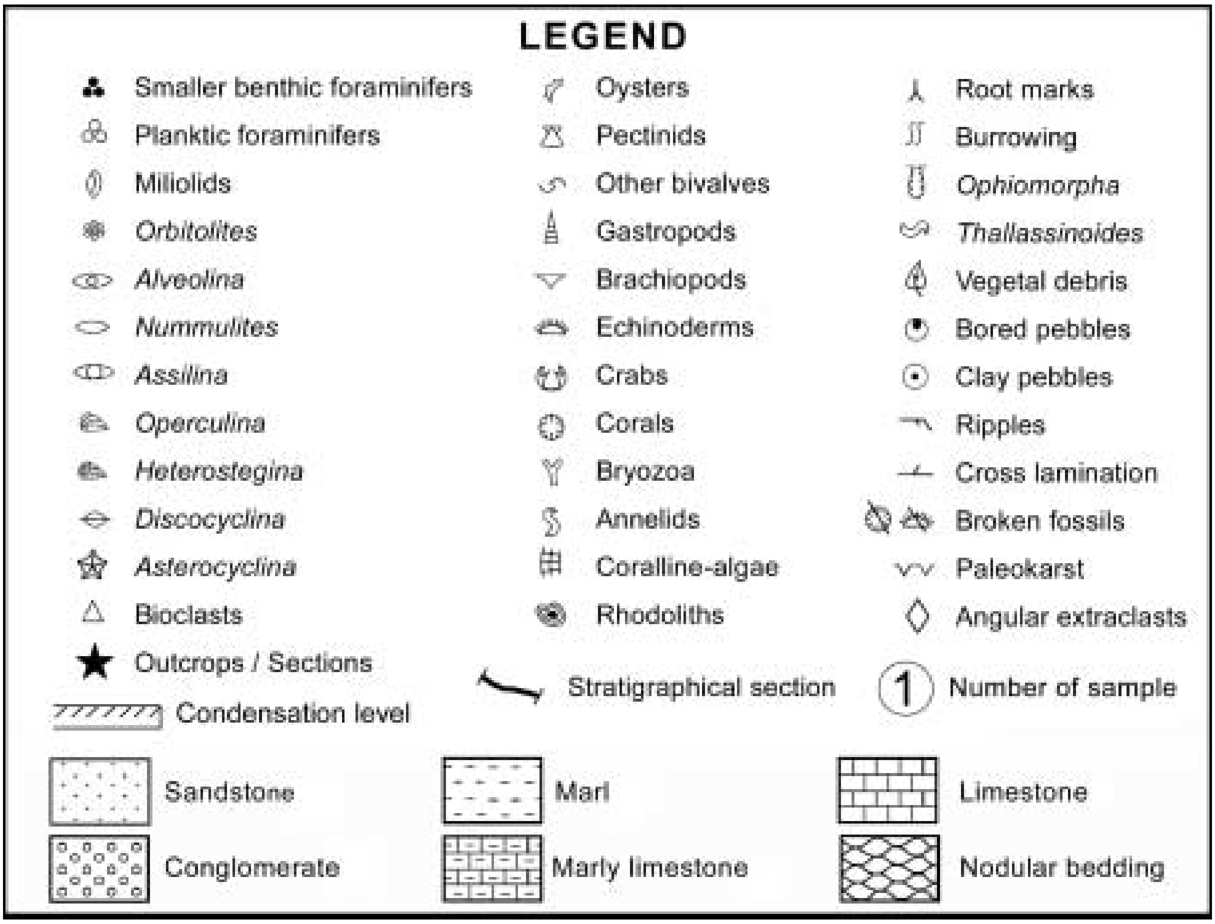

FIGURE 3 **Legend to the symbols used in the figures.**

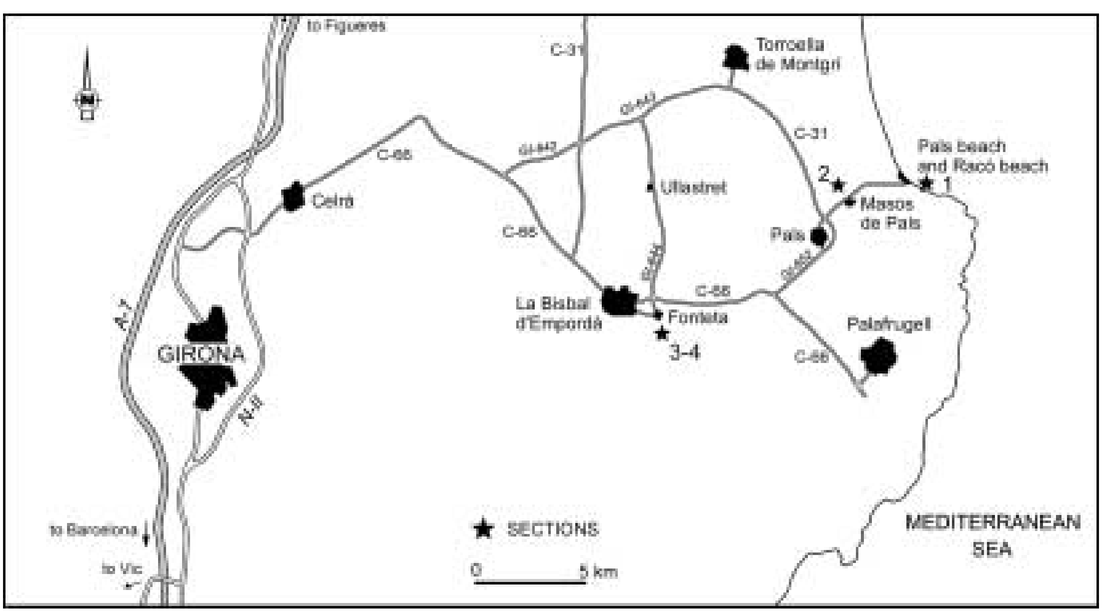

FIGURE 4 **Location of the Lutetian sections in the Empordà area.**

basin, and to collect Early Lutetian (SBZ 13) porcellaneous larger foraminifers such as *Alveolina*.

The lower part of this section consists of sandstone and conglomerate of braided alluvial origin, lying unconformaly on top of the Paleozoic. The imbricated disposition of the clasts within the conglomerate indicates that the supply was from the SSW.

Higher up in the sequence, with a sharp contact, there is a bed of coarse conglomerate with sandstone, fine conglomerate and bioclast matrix. This conglomerate shows an imbricated disposition in an opposed direction to that of the lower part of the section, resulting from reworking by waves of the lower alluvial facies at the beginning of the marine transgression of the 1st Lutetian cycle.

Further up, toward the top of this section, there is a carbonate sequence of packstone and grainstone with abundant bioclasts and porcellaneous larger foraminifers (point 1 in Fig. 5B), particularly abundant at the top of the section. This carbonate sequence, of regressive character, is interpreted as a protected shelf facies with continental siliciclastic supply indicated by the presence of angular extraclasts, especially in the upper part of the succession.

The Pals Beach Section

This second section (Fig. 5C) provides good exposures of the marine Lutetian units in the southeasternmost part of the basin, which enable one to collect nummulitids from the Late Lutetian (SBZ 16).

The lower part of this section (Fig. 5C), lateral equivalent to the braided alluvial facies, consists of boulders (up to 2 m in diameter) interpreted as a scree slope facies. This facies, and its correlation with the first section, indicate the highly irregular paleorelief that existed prior to the Eocene sedimentation. Further up in the section, a basal conglomerate sequence and a carbonate sequence similar to those of the Racó Beach can be seen. These facies are overlain by a second carbonate interval made up of packstone and grainstone with intervals of more marked stratification, which probably correspond to the 2nd Lutetian cycle.

The uppermost part of the section is composed of laminated bioclastic sandstone and grainstone with *Nummulites herbi* SCHAUB 1981, *N. praepuschi* SCHAUB 1981, and *N. discorbinus* (SCHLOTHEIM, 1820) (point 1 in Fig. 5C) from the 4th Lutetian cycle. The 3rd cycle is missing.

At Pals Beach, a paleokarst system is filled up with laminated bioclastic sandstone similar to that of the 4th

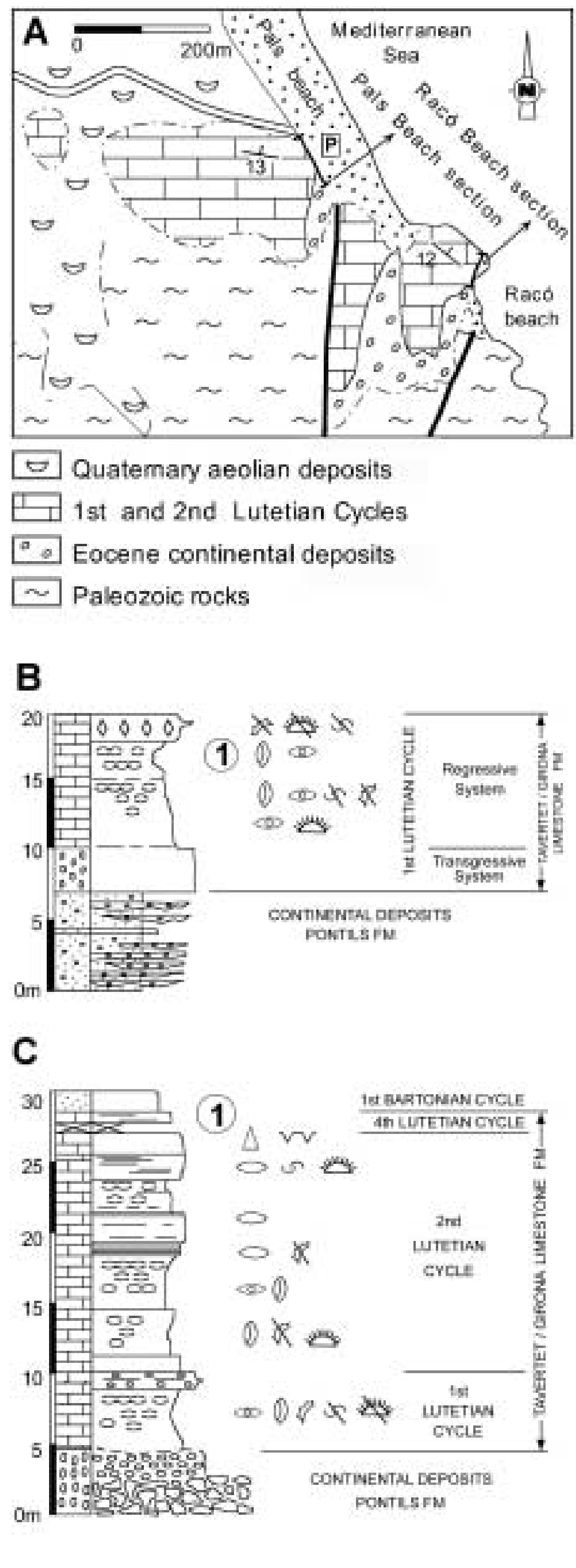

FIGURE 5 **A) Location of the Pals Beach and Racó Beach sections. B) Stratigraphic section at Racó Beach. C) Stratigraphic section at Pals Beach.**

cycle in this section, suggesting that the paleokarst was formed prior to the deposition of the 4th Lutetian cycle.

Arkosic sandstone attributed to the 1st Bartonian cycle are found on top of the laminated bioclastic sandstone and grainstone.

Masos de Pals section (Mas Sardó - Water Treatment Plant)

Location: The outcrop is located to the left of the road from Masos de Pals to the Water Treatment Plant, close to Mas Sardó, 900 m north of the road from Pals to Pals Beach (2 in Fig. 4 and Fig. 6A).

Lithostratigraphic Units: Banyoles Marl Formation (Almela and Ríos, 1943) and Folgueroles Sandstone Formation (Reguant, 1967).

Chronostratigraphic Unit: Middle Lutetian, Late Lutetian and Early Bartonian.

Biostratigraphic Unit: SBZ 15, SBZ 16 and SBZ 17.

Unconformity-Bounded Units: 3rd and 4th Cycles of the Lutetian, and 1st Bartonian Cycle.

In this locality it is possible to observe the upper part of the Lutetian marine succession (3rd and 4th cycles) and the contact with the 1st Bartonian units in the southeastern area of the basin.

The stratigraphic section extends from the top of the 2nd Lutetian cycle to the base of the 1st Bartonian cycle.

The section (Fig. 6B) begins with a millimetrically stratified silty sequence with intercalated centimetric bioclastic marly limestone and fine grained sandstone layers. The main bioclastic components are thin-wall miliolids.

Moving up, grey-ochre marl without fossils are found. All these deposits are interpreted as lagoon-type facies corresponding to the regressive system of the 3rd Lutetian cycle.

Further up, separated by a sharp contact, there is a grainstone layer consisting of porcellaneous larger foraminifers, particularly *Alveolina*, *Idalina*, *Fabularia* and *Orbitolites* (point 1 in Fig. 6B). This layer has been interpreted as a protected shelf facies, corresponding to the transgressive system of the 4th Lutetian cycle.

The section continues with a marly interval with centimetric bioclastic siltstones, marly limestone and sporadic intercalations of calcareous packstone layers. These beds contain abundant miliolids, and occasionally *Alveolina* and *Velates*. This part of the section has been attributed to the regressive system of the 4th Lutetian cycle.

Further up in the sequence there is an interval of bioclastic limestone (point 2 in Fig. 6B) containing porcellaneous foraminifers (*Alveolina*) and glauconite in the upper part. This interval has been interpreted as the base of the transgressive system of the 1st Bartonian cycle. The section finishes with arkosic sandstone with glauconite, present along the whole of the southern margin of the basin, and attributed to the 1st Bartonian cycle.

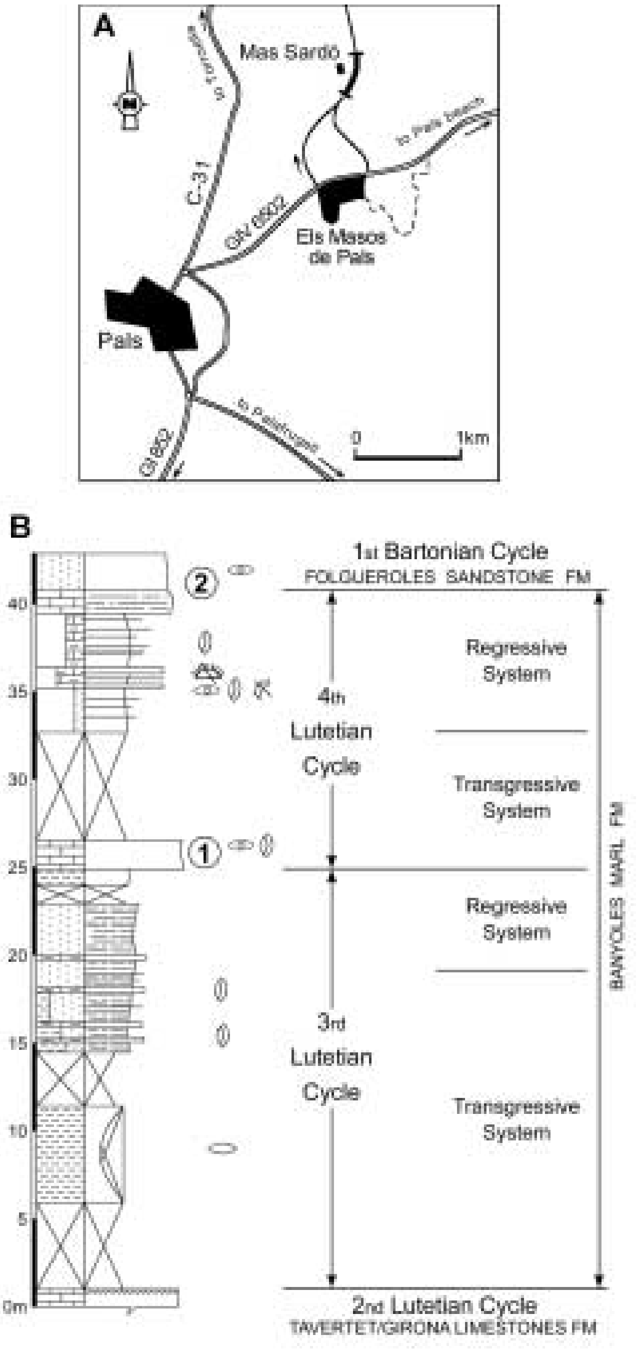

FIGURE 6 **Location (A) and stratigraphic section (B) at Masos de Pals.**

Fonteta section (Can Barrabàs)

Location: The outcrop is located at the beginning of the track south of Can Barrabàs farm. To reach the farm from the village of Fonteta, take the first path on the right after passing through Cases Noves (3 in Fig. 4 and Fig. 7A).

Lithostratigraphic Unit: Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972).

Chronostratigraphic Unit: Early Lutetian.

Biostratigraphic Unit: SBZ 13.

Unconformity-Bounded Unit: 1st Lutetian Cycle.

In this locality it is possible to observe the transitional facies at the base of the 1st Lutetian cycle and to collect porcellaneous larger foraminifers (*Alveolina stipes* HOTTINGER 1960, *Idalina*, *Fabularia* and *Orbitolites*).

This section (Fig. 7B) shows the transitional facies characteristic of the base of the 1st Lutetian cycle. It corresponds to a more distal depositional area than in the Pals Beach and Racó Beach sections.

Above the continental sandstone and conglomerate beds, there is a siliciclastic sequence characterised by alternating millimetric-centimetric layers of marl, siltstone, sandstone and microconglomerate. The section begins with grey-white azoic marl, followed by a fining upward sequence with an erosive base, a coarsening-upwards sequence also with erosive base, and finishes with a new fining upward sequence. The interval, characterised by an important siliciclastic supply from the continent, is interpreted as lagoon and barrier island facies, where the lower fining upward sequence would correspond to channel filling, the coarsening-upward sequence would correspond to the progradation of a stream mouth bar responsible for the barrier island development, and the upper fining upper upwards sequence would correspond to the retrogradation, in a transgressive context, of the barrier island.

Further up the section, a limestone interval with an erosive base, containing siliciclastic and bioclastic components, has been interpreted as a channel cutting through the barrier island. Immediately on top, a carbonate interval formed of grainstone containing abundant porcellaneous larger foraminifers, such as *Alveolina stipes* HOTTINGER 1960, *Idalina*, *Fabularia* and *Orbitolites* (point 1 in Fig. 7B), is interpreted as a protected shelf facies. These facies are truncated by a predominantly siliciclastic interval, made up of ochre sandstone and marl layers, interpreted as the result of a new siliciclastic supply from the continent.

At the top of the section, a carbonate interval formed of packstone and grainstone consisting of *Alveolina stipes* HOTTINGER 1960, *Idalina* and *Orbitolites* (point 2 in Fig. 7B) is interpreted as a protected shelf facies.

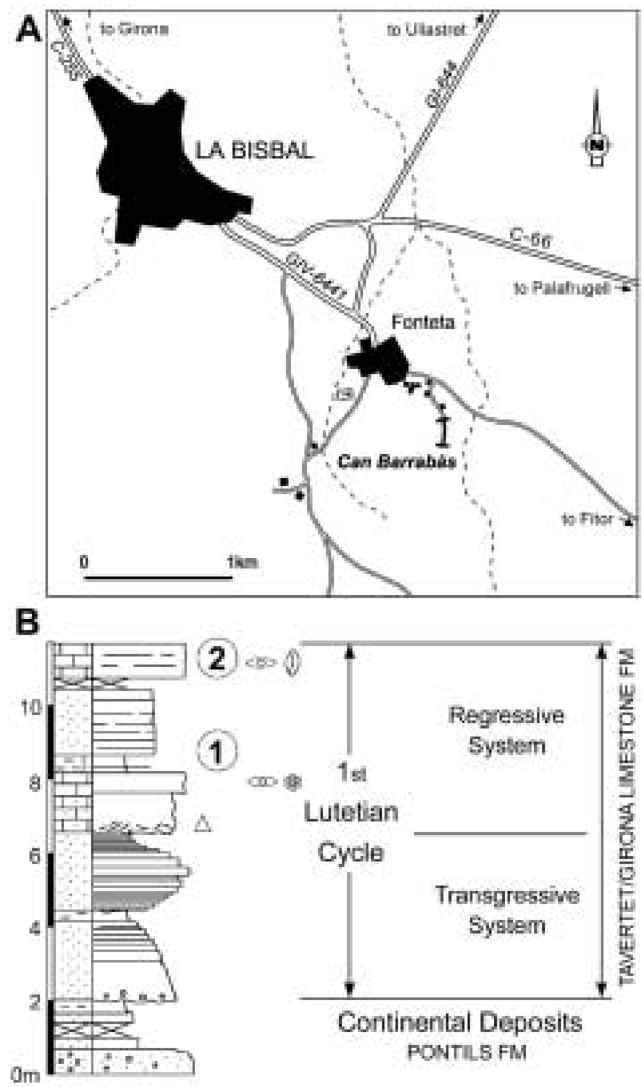

FIGURE 7 | **Location (A) and stratigraphic section (B) at Fonteta (Can Barrabàs).**

Fonteta section (Can Ametller)

Location: The section extends from the track located south of Can Ametller to the farmhouse. To reach Can Ametller from Fonteta village follow the track towards the cementery, after 500 m turn south at the junction, and continue 250 m further (4 in Fig. 4 and Fig. 8A).

Lithostratigraphic Units: Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972), Banyoles Marl Formation (Almela and Ríos, 1943) and Bracons Formation (Gich 1969, 1972).

Chronostratigraphic Unit: Early and Middle Lutetian.

Biostratigraphic Unit: SBZ 13, SBZ 14 and SBZ 15.

Unconformity-Bounded Units:1st, 2nd and 3rd Lutetian Cycles.

In this outcrop it is possible to identify the 1st, 2nd and 3rd Lutetian cycles and the boundary between the 2nd and the 3rd cycles, as well as to collect larger foraminifers such as *Alveolina stipes* HOTTINGER 1960, *Idalina* and *Orbitolites* from the 1st cycle (points 1 and 2 in Fig. 8B), *Nummulites crusafonti* REGUANT and CLAVELL 1967 and *N. tavertetensis* REGUANT and CLAVELL 1967, from the base

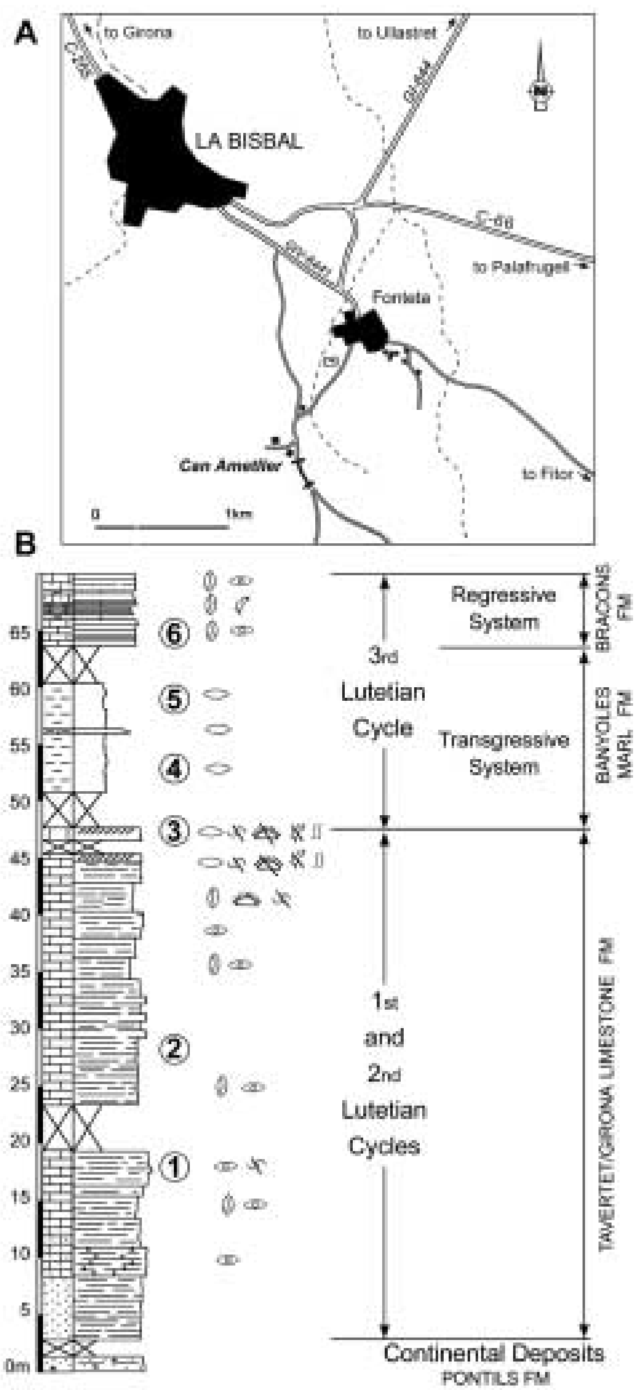

FIGURE 8 **Location (A) and stratigraphic section (B) at Fonteta (Can Ametller).**

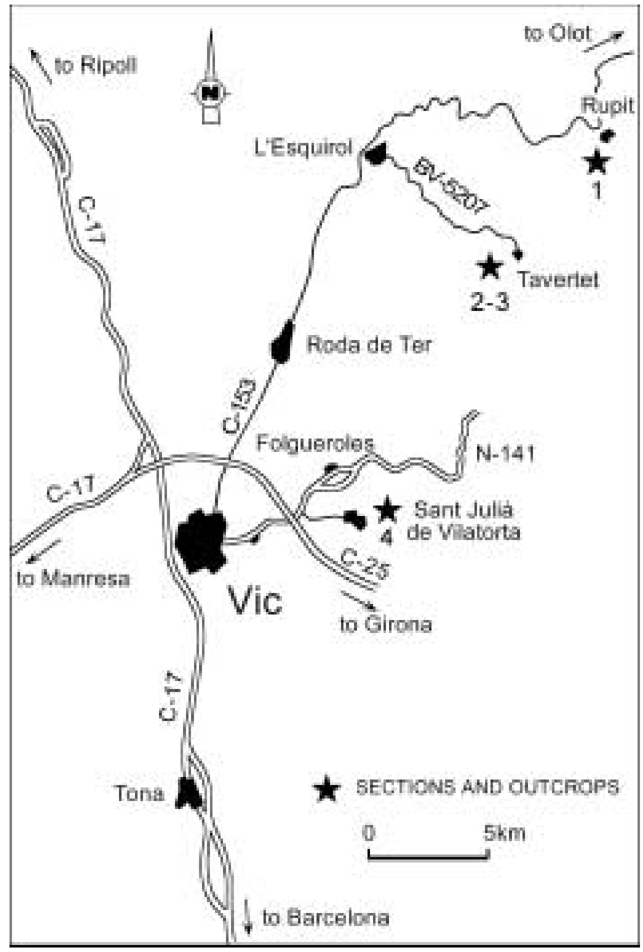

FIGURE 9 **Location of the Lutetian outcrops and sections in the Vic area.**

and lower part of the 3rd cycle (points 3 and 4 in Fig. 8B), and *Nummulites* aff. *tavertetensis* REGUANT and CLAVELL 1967, *N. migiurtinus* AZZAROLI 1950, *N. discorbinus* (SCHLOTHEIM 1820) (point 5 in Fig. 8B) and alveolinids and miliolids from the middle and upper part of the 3rd cycle (point 6 in Fig. 8B).

The stratigraphic section extends from the base of the 1st cycle to the regressive system of the 3rd cycle. The thickness of the 1st and 2nd cycles in this section (45 m) is greater than at outcrop 1 (20 m) located further east.

The section (Fig. 8B) starts with decimetric beds of ochre sandstone, interpreted as a transitional facies from the base of the 1st cycle. Above, bioclastic packstone and grainstone, with siliciclastic extraclasts in the initial metres, and a biocalcarenitic layer, intensively burrowed and with ferruginous concretions on top, are interpreted as a protected shelf facies from the 1st and 2nd cycles bounded in its upper part by a condensation level. *Alveolina* *stipes* HOTTINGER 1960, *Orbitolites*, miliolids, echinoids, oysters and other bivalves are present.

Further up, there is a succession of marl with intercalations of marly limestone containing abundant *Nummulites*, where sirenid ribs have been found. They have been interpreted as an inner shelf facies with banks of *Nummulites* from the transgressive system of the 3rd Lutetian cycle.

Continuing upwards, after a section which is covered, there is a carbonate interval formed of grainstone-packstone rich in miliolids and alveolinids, followed by decimetric layers of packstone and grainstone, and sandy limestone containing miliolids and oysters. This interval is interpreted as a protected shelf facies with siliciclastic input from the regressive system of the 3rd Lutetian cycle.

THE LUTETIAN MARINE RECORD IN THE VIC AREA

Sant Joan de Fàbregues section

Location: The outcrop is located near Sant Joan de Fàbregues Hermitage, south of the village of Rupit (1 in Fig. 9 and Fig. 10).

Lithostratigraphic Unit: Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972).

Chronostratigraphic Unit: Early Lutetian.

Biostratigraphic Unit: SBZ 13.

Unconformity-Bounded Unit: 1st Lutetian Cycle.

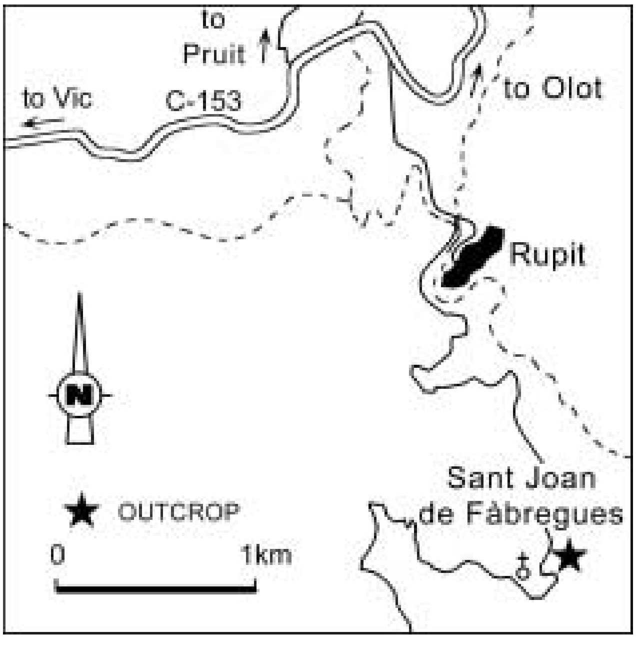

FIGURE 10 **Location of the Sant Joan de Fàbregues outcrop.**

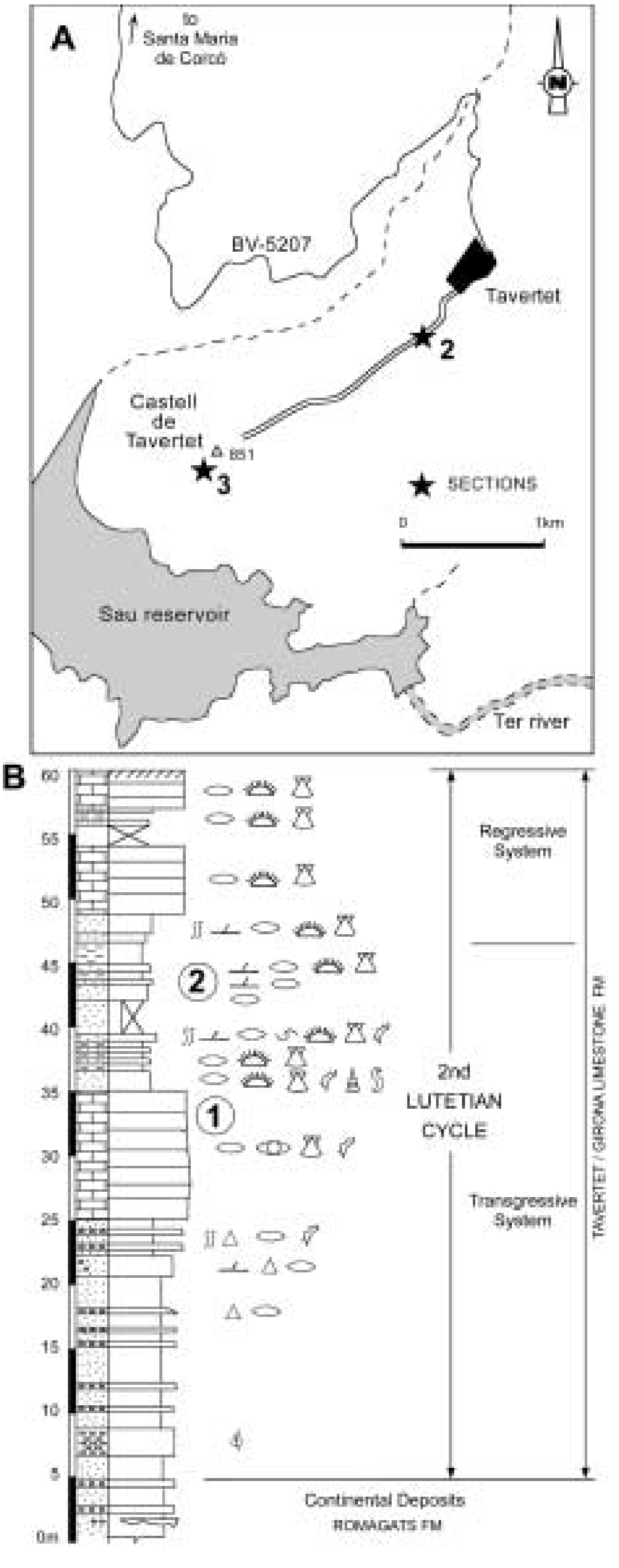

FIGURE 11 **A) Location of the Tavertet and Castell de Tavertet sections. B) stratigraphic section at Tavertet (Serra-Kiel, 1984).**

This outcrop corresponds to the lower part of the Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972), and it is possible to collect samples of *Nummulites verneuili* D'ARCHIAC and HAIME 1853, characteristic of the Early Lutetian (SBZ 13) from the 1st Lutetian cycle on the southeastern border of the basin.

Tavertet section

Location: The outcrop is located on the cliff south-east of the village of Tavertet, following the old path from Sau to Tavertet (2 in Fig. 9 and Fig. 11A).

Lithostratigraphic Unit: Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972).

Chronostratigraphic Unit: Middle Lutetian.

Biostratigraphic Unit: SBZ 14.

Unconformity-Bounded Unit: 2nd Lutetian Cycle.

Near Tavertet village it is possible to observe the transition between near-shore facies and inner shelf facies of the 2nd Lutetian cycle, and to collect samples of *Nummulites tavertetensis* REGUANT and CLAVELL 1967 (point 1 in Fig. 11B) and *N. crusafonti* REGUANT and CLAVELL 1967 (point 2 in Fig. 11B) from their type-localities.

The stratigraphic section extends from the red continental alluvial fan of the Romagats Formation (Colombo, 1980) to the top of the carbonate shelf of the Tavertet/Girona Limestone Formation (Fig. 11B).

The bottom of the transgressive system are the transitional facies from continental to marine environments are represented by conglomerate and high-angle cross-bedded coarse sandstone, interpreted as alluvial fan deposits and sand bars reworked by waves.

Further up in the sequence, a carbonate interval formed of grainstone made up of imbricated *Nummulites* with pressure-solution processes is interpreted as a long-shore bar.

The section continues with low-angle cross-bedded siltstone and sandstone intercalated with marl intervals rich in *Nummulites*, interpreted as sand bars and inner shelf facies, respectively.

The upper part of the section is made up of bioclastic sandstone, intensively burrowed and with ferruginous concretions on top, locally with cross-bedding structures, interpreted as prograding shelf facies of the regressive system. The upper limit is a condensation level that corresponds to the boundary between the 2nd and the 3rd Lutetian cycle.

This section contains the type-localities of *Nummulites tavertetensis* REGUANT and CLAVELL 1967 and *N. crusafonti* REGUANT and CLAVELL 1967 (points 1 and 2 in Fig. 11B).

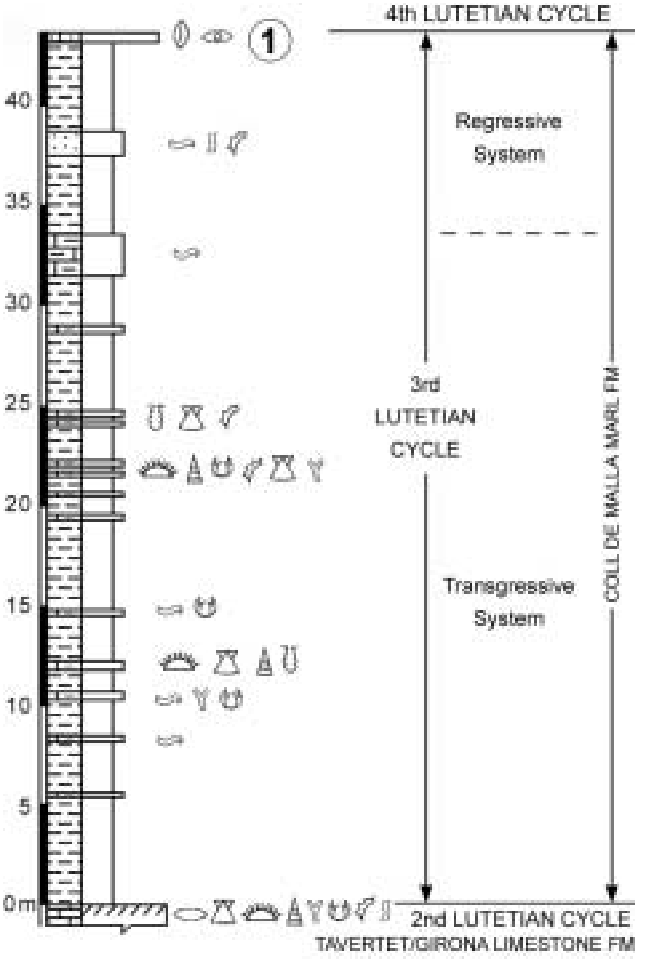

FIGURE 12 **Stratigraphic section at Castell de Tavertet.**

Castell de Tavertet section

Location: The stratigraphic section is located on the hill called Castell de Tavertet, southwest of the village of Tavertet (3 in Fig. 9 and Fig. 11A).

Lithostratigraphic Unit: Coll de Malla Marl Formation (Clavell et al., 1970).

Chronostratigraphic Unit: Middle and Late Lutetian.

Biostratigraphic Unit: SBZ 15 and SBZ 16.

Unconformity-Bounded Units: 3rd and 4th Lutetian Cycles.

In this outcrop it is possible to observe the siliciclastic units of the 3rd Lutetian cycle (Fig. 12), and to collect porcellaneous larger foraminifers samples from the 4th Lutetian cycle corresponding to the Late Lutetian (SBZ 16).

As in the previous outcrop (Tavertet section), the boundary between the 2nd and the 3rd Lutetian cycle is represented by an intensively burrowed and ferruginous concretion-rich horizon on top of a bioclastic sandstone interval, interpreted as a condensation level. This bioclastic interval contains: *Nummulites variolarius* (LAMARCK 1804); the molluscs *Turritella*, *Volutilithes*, *Natica*, *Sigmesalia*, *Architectonica* (*Solarium*), *Scalaria*, *Ancilla*, *Vulsella* and *Cypraeaovula*; the decapods *Callianassa fraasi* NOETLING 1885, *Eocalcinus eocenicus* VIA 1959 and *Montezumella amenosi* VIA 1959; the echinoids *Prionicidaris bofilli* (LAMBERT *in* ALMERA 1898), *Ditremaster covazii* (TARAMELLI 1874), *Coelopleurus* and *Eupatagus* and bryozoa.

Higher up, the transgressive system of the 3rd Lutetian cycle is represented by marl with horizons that contain: molluscs, such as *Pholadomya*, *Meretrix* gr. *incrassata*, *Cardita*, *Venus*, *Natica*, *Chlamys*, *Sigmesalia*, *Volutilithes*, *Cardita* gr. *suborbicularis*, *Modiola*, *Cypraeaovula*, *Clanculus*, and oysters bored by sponges; echinoids such as *Coelopleurus* and *Eupatagus*; decapods such as *Callianassa pseudonilotica* LORENTHEY 1929, *Colneptunus hungaricus* (LORENTHEY 1898), *Callianassa fraasi* NOETLING 1885, *Ctenocheles* cf. *burlesonensis* (STENZEL 1935) and *C. cultellus* (RATHBUN 1935); and the larger foraminifer *Nummulites crusafonti* REGUANT and CLAVELL 1967. These horizons of fossils are intensively affected by *Thalassinoides*-type and *Ophiomorpha*-type burrowing, and are interpreted as condensation horizons.

The 3rd Lutetian regressive system is represented by marl and sandstone in coarsening-upward sequences, interpreted as deltaic facies. Further up, a carbonate interval rich in larger porcellaneous foraminifers, such as *Alveolina* aff. *fusiformis* SOWERBY 1850, *Orbitolites*, *Fabularia*, and *Idalina*, (point 1 of Castell de Tavertet section, Fig. 12) is interpreted as the transgressive deposits of the 4th Lutetian cycle (SBZ 16).

Puigsec section

Location: The outcrop is located in the forest, to the left of the path that leads to the Puigsec farm-house, about 300 m behind the house (4 in Fig. 9 and Fig. 13A).

Lithostratigraphic Unit: Upper part of the Coll de Malla Marl Formation (Clavell et al., 1970).

Chronostratigraphic Unit: Late Lutetian.

Biostratigraphic Unit: SBZ 16.

Unconformity-Bounded Unit: 4th Lutetian Cycle.

In this outcrop it is possible to collect samples of *Nummulites puigsecensis* REGUANT and CLAVELL 1967 from its type-locality. This species is characteristic of the Late Lutetian (SBZ 16).

The stratigraphic section (Fig. 13B) starts with the red beds corresponding to continental deposits from the regressive system of this 3rd Lutetian cycle. Southwards,

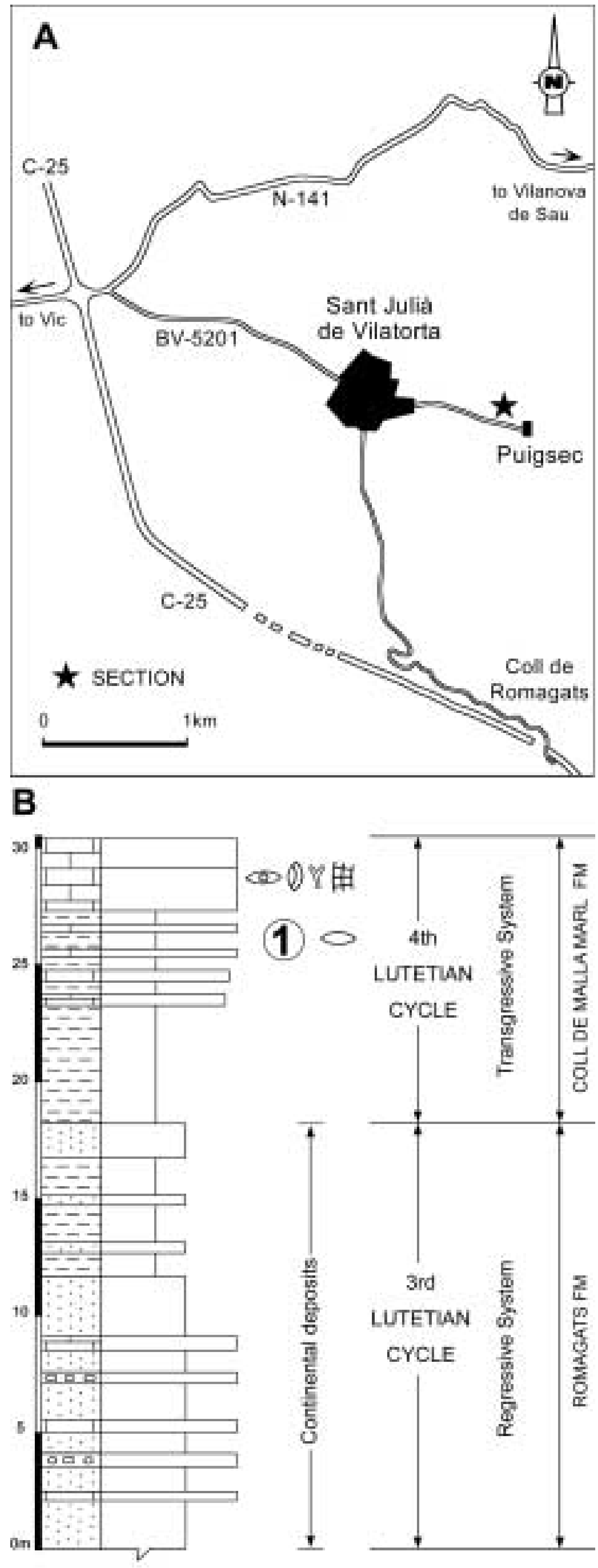

FIGURE 13 **Location (A) and stratigraphic section (B) at Puigsec.**

this interval is indented into the continental layers of the Romagats Formation (Colombo, 1980).

Further up, there is a marine interval with *Nummulites puigsecensis* REGUANT and CLAVELL 1967, corresponding to the transgressive system of the 4th Lutetian cycle (Late Lutetian, SBZ 16).

The top of the section is represented by a carbonate interval with *Alveolina fusiformis* SOWERBY 1850 and *Idalina* (point 1 in Fig. 13B) which is equivalent to the upper part of the Castell de Tavertet section.

THE BARTONIAN AND TERMINAL COMPLEX MARINE RECORD IN THE VIC AREA

Santa Cecília de Voltregà outcrop

Location: The outcrop is located on the small hill to the north of the village of Santa Cecília de Voltregà (1 in Fig. 14).

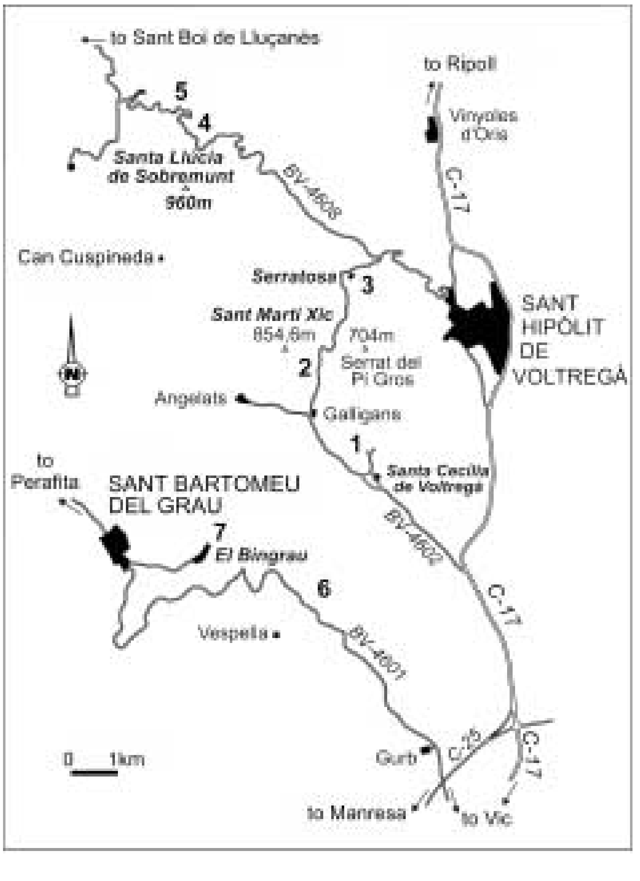

FIGURE 14 **Location of the Bartonian and Terminal Complex outcrops and sections in the Vic area.1: Santa Cecília de Voltregà; 2: Sant Martí Xic; 3: Serratosa; 4: La Trona reef; 5: Patch reef facies overlying the La Trona reef; 6: Gurb; 7: Sant Bartomeu del Grau.**

Lithostratigraphic Unit: La Guixa Marl Member (Reguant, 1967; Barnolas et al., 1983).
Chronostratigraphic Unit: Late Bartonian.
Biostratigraphic Unit: SBZ 18.
Unconformity-Bounded Unit: 2nd Bartonian Cycle. Transgressive System.

This outcrop shows surfaces colonized by siliceous sponges, sponge nodules and event beds in an aphotic shelf context.

In this area, the marl contains centimetric-thick, highly cemented beds with positive reliefs characterised by the predominance of siliceous sponges. The positive relief of the colonized beds increases towards the top of the stratigraphic section (Figs. 15A and 15B).

Conical forms (*Laocaetis*) and conical star-shaped forms (*Guettardiscyphia*) belonging to the Dyctida order, range in size from 10 to 20 cm and grow vertically. Meandrosponges of labyrinthine lamellar morphology and *Plocoscyphia* belonging to the Lychniskida order, also of centimetric size, grow on the surface (Fig. 15D).

In the marl, scattered specimens of *Guettardiscyphia* and *Laocaetis*, in life position, form nodules. They indicate that the sedimentation rate was low.

The bottom was colonized by both types of sponges during periods of non-sedimentation. In some areas, the positive reliefs are truncated by centimetric-thick beds which extend laterally over kilometric distances. They are made up largely of fragments of bryozoa and of reworked sponges in the lower part (Fig. 15C). These beds are interpreted as being composed of reworked material (event beds) coming from areas further onshore of the aphotic shelf (Serra-Kiel and Reguant, 1991).

Thus, periods of non sedimentation alternated with periods of low sedimentation and, eventually, event beds carrying material from further up in the shelf homogenized the reliefs.

Sant Martí Xic outcrop

Location: The outcrop is located on the path to Sant Martí Xic Hermitage (2 in Fig. 14).
Lithostratigraphic Unit: Sant Martí Xic Limestone Formation (Reguant, 1967).
Chronostratigraphic Unit: Late Bartonian.
Biostratigraphic Unit: SBZ 18.
Unconformity-Bounded Unit: 2nd Bartonian Cycle. Regressive System.

This outcrop provides a general view of the deltaic progradation (Fig. 16) and it is possible to collect samples

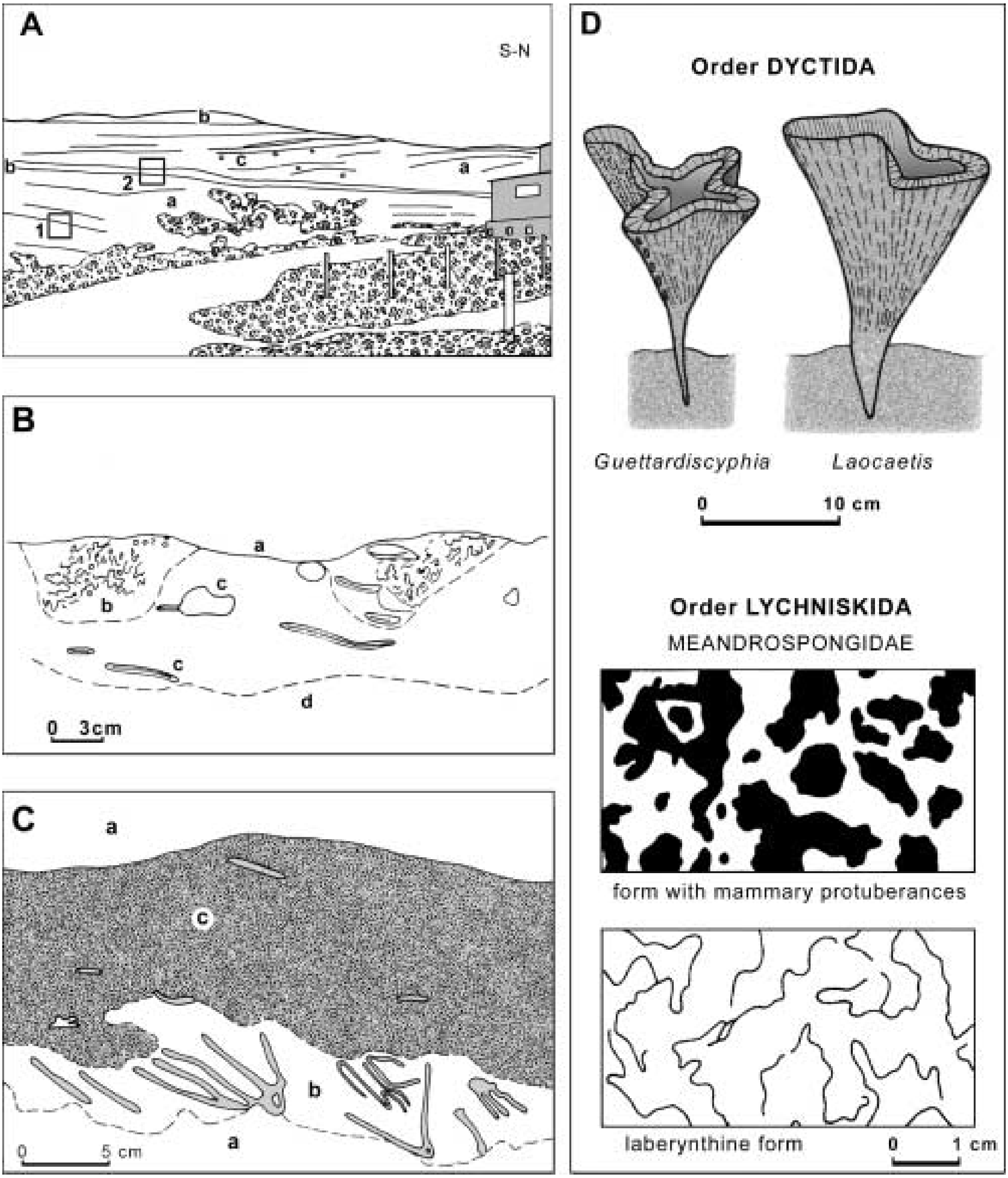

FIGURE 15 **Santa Cecília de Voltregà outcrop. A) Geometric relationships between the event beds and the surfaces colonized by siliceous sponges, a: sponge mounds; b: event beds; c: isolated nodules. B) Detail of 1 in A showing a sponge colonized surface, a and d: marl; b: meandrosponges; c: *Guettardiscyphia* and *Laocoetis*. C) Detail of 2 in A showing an event bed, a: marl; b: lag deposits with reworked sponges, c: event bed including bryozoa debris. D) Different kinds of siliceous sponges found in the Santa Cecília de Voltregà outcrop (drawn from photographs).**

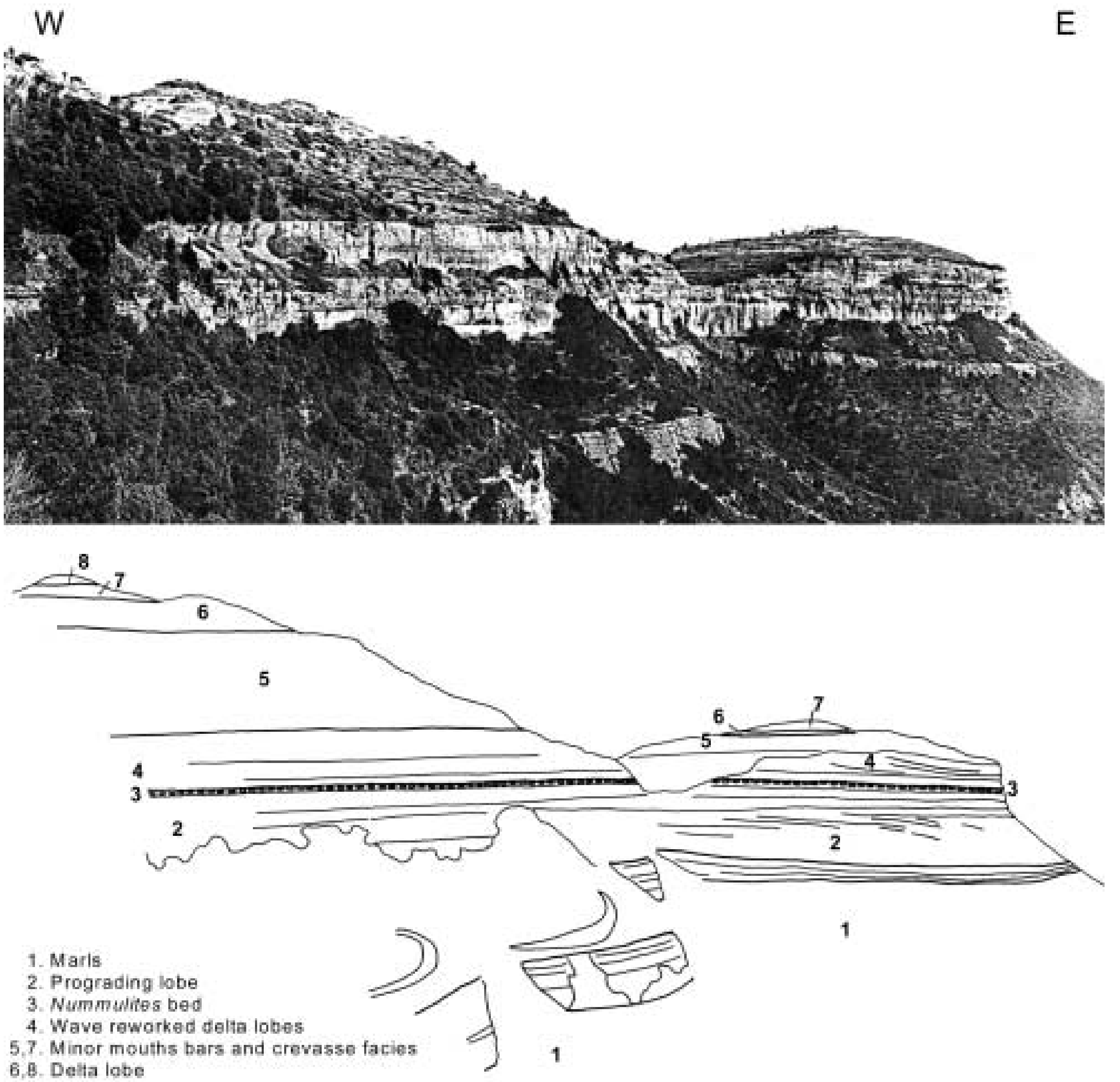

FIGURE 16 **Panoramic view of the deltaic and marine sequences of the Sant Martí Xic Limestone Formation (Reguant, 1967).**

containing *Nummulites biedai* SCHAUB 1962, *N. praegarnieri* SCHAUB 1981, *N. ptukhiani* KACHARAVA 1969, *N. cyrenaicus* SCHAUB 1981 and *Assilina schwageri* (SILVESTRI 1928).

This outcrop corresponds to the 2nd Bartonian regressive cycle. This cycle consists of the alternation of offlap episodes, represented by deltaic deposits, and onlap episodes, represented by marine deposits with larger foraminifer layers and reef facies.

Serratosa outcrop

Location: This outcrop is located on the hill 100 m east of Serratosa farm, on the road (BV-4608) from Sant Hipòlit de Voltregà to Sant Boi de Lluçanès (3 in Fig. 14).

Lithostratigraphic Unit: La Guixa Marl Member (Reguant, 1967; Barnolas et al., 1983).

Chronostratigraphic Unit: Late Bartonian.

Biostratigraphic Unit: SBZ 18.

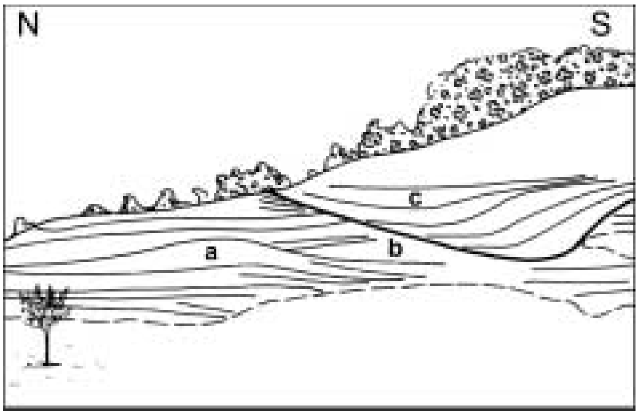

FIGURE 17 **Bryozoa-colonized surfaces in Serratosa outcrop, a: mud-mounds with bryozoa on one of the surfaces; b: spoon-shaped scar slump marked by the presence of bryozoa colonizing the surface; c: bryozoa-colonized beds infilling the scar (drawn from photographs).**

Unconformity-Bounded Unit: 2nd Bartonian Cycle. Transgressive System.

This outcrop shows biofacies of mud mounds with bryozoa in an aphotic shelf context. Hardened beds with positive reliefs, scar slumps and bryozoa colonized beds infilling the scar can be observed.

The litho-biofacies of this outcrop consists of marl with hardened beds of lumachellic character, made up of *in situ* colonies of small, fallen bryozoa, of vinculariform or hollow cylindrical type, and some giant plurilamellar colonies in life position. These beds form positive reliefs with gentle slopes. Scattered colonies are also found within the marly intervals. Spoon-shaped scars are marked by the presence of bryozoa colonizing the surface (Fig. 17).

The positive reliefs have been interpreted as mud mounds formed by the baffle effect of the erect bryozoa during periods of very low sedimentation (Serra-Kiel and Reguant, 1991). During the episodes of non-sedimentation, the bottom surface was intensively colonized by bryozoa, producing the lumachellic beds.

La Trona reef sections

Location: This outcrop is located on the road (BV-4608) from Sant Hipòlit de Voltregà to Sant Boi de Lluçanès between km 9 and km 10 (4 in Fig. 14).

Lithostratigraphic Unit: Sant Martí Xic Limestone Formation (Reguant, 1967).

Chronostratigraphic Unit: Late Bartonian.

Biostratigraphic Unit: SBZ 18.

Unconformity-Bounded Unit: 2nd Bartonian Cycle. Regressive System.

In this locality it is possible to observe the slope facies of a fringing reef complex and the reef framework, and to collect larger foraminifer samples from the bottom of the onlap sequence (Figs. 18 and 19).

Two different outcrops can be visited. The first outcrop, on the road at km 9, shows two carbonate beds formed of wackestone-packstone mainly made up of coral fragments, brachiopods and larger foraminifers. The angular geometry between these two beds, the mixture of fossils, the dominance of fragments, their location in front of the reef buildup and the geographical proximity to it (200

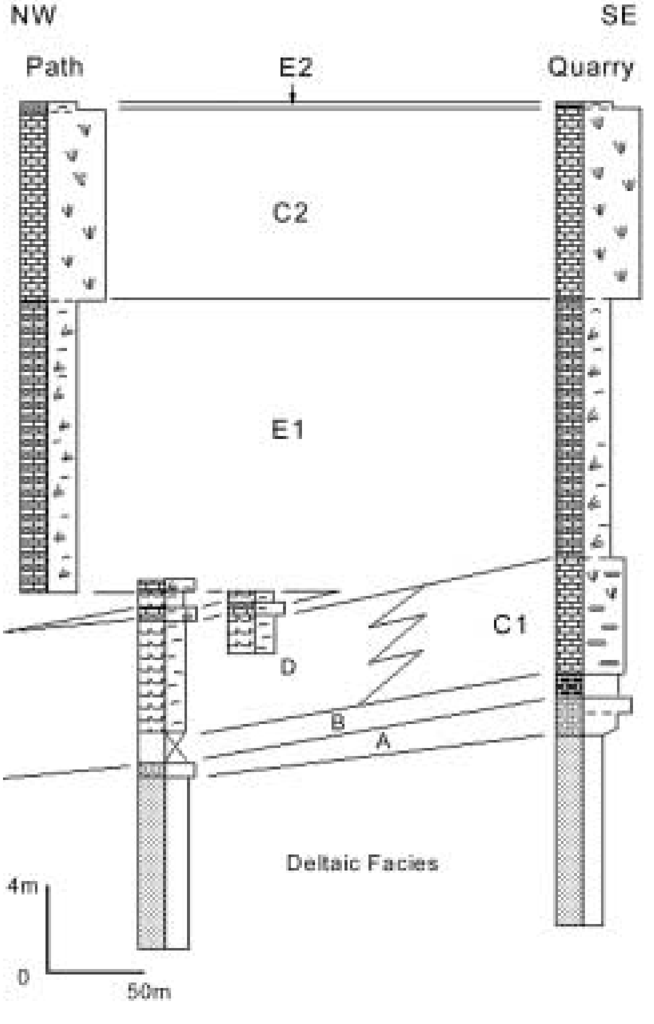

FIGURE 18 **Geometric relationships between the different litho-biofacies in the La Trona reef outcrop. A: Sandstone with coral fragments and larger foraminifers. B: Massive packstone of coral fragments encrusted by coralline-algae. C1: Planar coral framework. C2: Branching and massive coral framework. D: Encrusting coralline-algae bindstone. E1: Coral fragments encrusted by coralline-algae, undulating stratified packstone. E2: Coral fragments encrusted by coralline-algae, planar stratified packstone.**

m) allows us to interpret these two beds as reef-slope facies (Fig. 19).

Below the reef-slope facies, there is a carbonate siltstone interval containing abundant larger foraminifers. According to Papazzoni and Sirotti (1995) and revised by Franquès in Serra-Kiel et al. (1997), the species present are: *Nummulites chavannesi* DE LA HARPE 1878, *N. ptukhiani* KACHARAVA 1969, *Assilina schwageri* (SILVESTRI 1928), *Heterostegina reticulata reticulata* RÜTIMEYER 1850, *Discocyclina augustae augustae* WEIJDEN 1940, and *Asterocyclina*.

The second outcrop is located below the road, at a point which is known locally as La Trona. The analysis of the association of coral, coralline-algae, and small and larger foraminifers allows us to characterise different litho-biofacies within the reef complex and to establish the geometric relationships between them (Fig. 18).

A: Sandstone with coral fragments and larger foraminifers

This facies is found below and above the reef facies. It is formed of siliciclastic sandstone in coarsening- and thickening-upward sequences displaying low angle cross-bedding. Below the reef facies, the fossils are only found in the uppermost decimetres of the underlying units. Imbricated specimens of the larger foraminifers *Nummulites ptukhiani* KACHARAVA 1969, *Assilina schwageri* (SILVESTRI 1928), *Heterostegina*, *Discocyclina*, and *Asterocyclina*, the small foraminifers miliolids and textularids, and encrusting acervulinids and victoriellids are found. Abundant horizontal burrowing, such as *Thallassinoides suevicus* (RIETH 1932), and holes coated with larger foraminifers, such as *Nummipera eocenica* HÒLDER 1989, occur.

Above the reef facies, fragments of corals, miliolids and acervulinids are found in the sandstone. This facies is

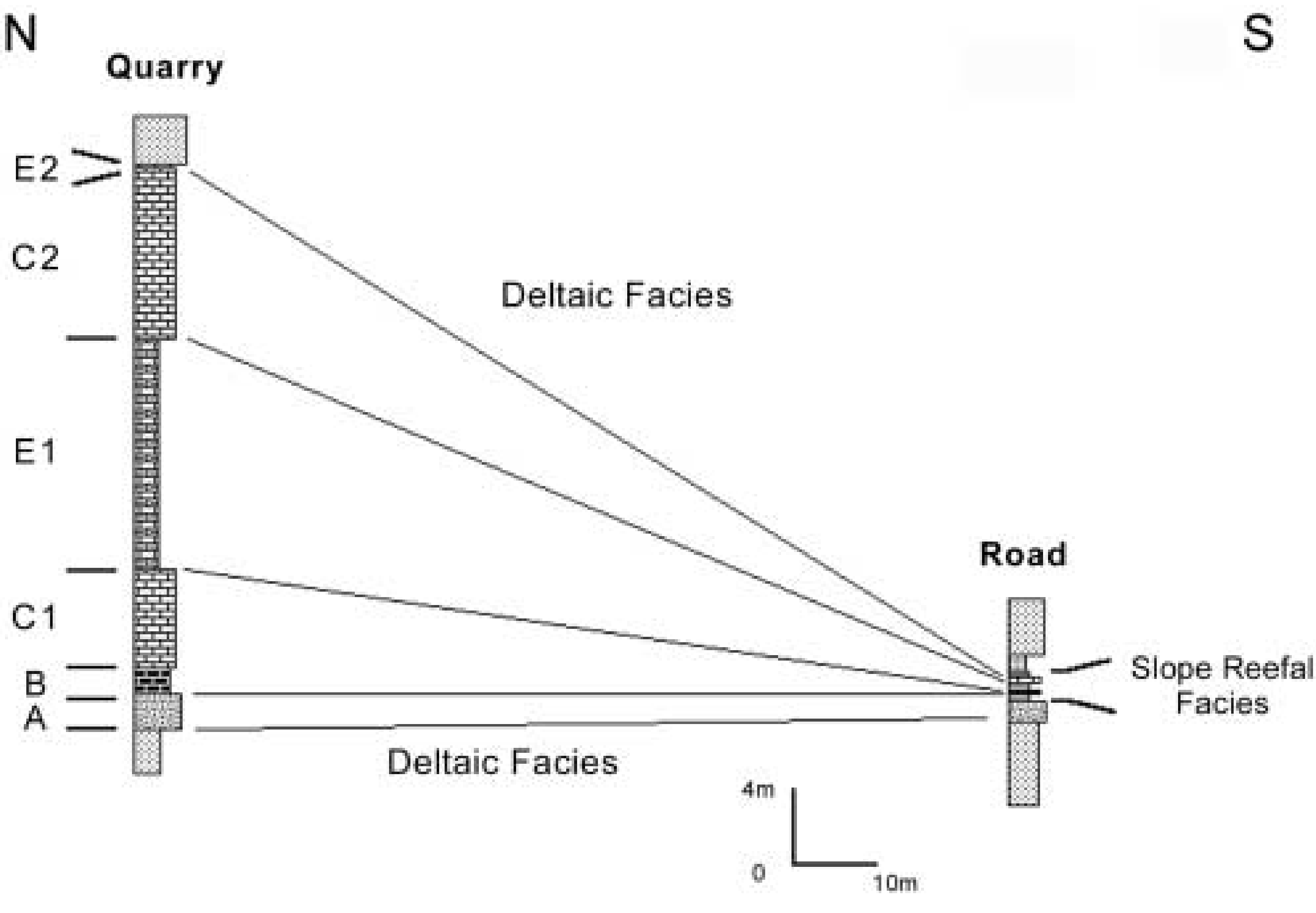

FIGURE 19 **Correlation between the reef-slope facies (at the road-side) and the reef-building facies (in the quarry) in the La Trona reef outcrop. A: Sandstone with coral fragments and larger foraminifers. B: Massive packstone of coral fragments encrusted by coralline-algae. C1: Planar coral framework. C2: Branching and massive coral framework. D: Encrusting coralline-algae bindstone. E1: Coral fragments encrusted by coralline-algae, undulating stratified packstone. E2: Coral fragments encrusted by coralline-algae, planar stratified packstone.**

interpreted as a stream mouth bar deposited during deltaic progradation.

Below the reef facies, the presence of low angle cross-bedding and the imbricated disposition of the larger foraminifers suggests that this facies was formed during the initial part of a transgressive episode, due to reworking by waves of the underlaying deltaic sandstone.

B: Massive packstone of coral fragments encrusted by coralline-algae

This facies consists of massive tabular packstone made up of coral fragments encrusted by coralline-algae, bivalves, fragments of the octocoralline *Parisis dachiardii* (OPPENHEIM 1923) and the larger foraminifers *Nummulites ptukhiani* KACHARAVA 1969, *N. striatus* (BRUGUIÈRE 1792), *Assilina schwageri* (SILVESTRI 1928) and *Heterostegina*.

This facies is interpreted as being formed in a high energy environment where bioclastic accumulation occurred.

C: Coral reef framework

C1) Planar coral framework. This subfacies consists of a massive framestone formed of *Cyathoseris castroi* MALLADA 1887, and corals with a wackestone matrix. The planar coral is found *in situ*, locally encrusted by coralline-algae and small foraminifers (haddonids, acervulinids, coscinophragmatids, victoriellids and planorbulinids). The presence of colonies of the branching coral *Actinacis cognata* OPPENHEIM 1901, and fragments of *Parisis dachiardii* (OPPENHEIM 1923), increases towards the top of the interval. The predominance of *in situ* colonies of planar corals indicates that this subfacies developed in the deeper part of the euphotic zone in meso-oligotrophic conditions. A basal-interstitial eutrophic level allowed the growth of the encrusting small foraminifers.

Moving up within the sequence, the coral morphology changes from planar to massive and branching colonies, indicating an increase in the light level probably resulting from a decrease in water turbulence or depth.

C2) Branching and massive coral framework. This subfacies consists of massive framestone formed of *in situ* massive and branching corals with higher diversity than in subfacies C1. The principal species are *Cereiphyllia tenuis* (REUSS 1868) and *Actinacis cognata* OPPENHEIM 1901, though *Astreopora tecta* (CATULLO 1856) and *Stylophora contorta* (LEYMERIE 1846) are also present. Small foraminifers such as miliolids and acervulinids, coral fragments encrusted with coralline-algae, and corals perforated by bivalves are also present. Between the corals there is a muddy matrix in which *Nummulites*, *Assilina schwageri* (SILVESTRI 1928) and *Heterostegina* are found.

In the north-western sector of the reef, massive sandstone with fragments of corals in the bottom part are intercalated and cover the reef framework facies.

The abundance of branching and massive coralline colonies indicates higher light intensity than in subfacies C1. The sandstone beds, located only in the north-western area, are interpreted as event deposits. The supply of these terrigenous deposits was practically instantaneous and did not interrupt the reef growth in the rest of the area.

D: Encrusting coralline-algae bindstone

This facies is formed of bindstone with encrusting and *in situ* branching coralline algae, with a wackestone matrix. In the lower part, coralline algae are found as rhodoliths with a coralline nucleus or as crusts over the muddy substrate, whereas in the upper part the coralline algae have a branching morphology. *Assilina schwageri* (SILVESTRI 1928) in the lower part, *Nummulites* in the lower and middle part, and *Heterostegina* throughout the unit, as well as small foraminifers, planorbulinids and miliolids, are found in association with the coralline algae. Locally, still articulated branches of the octocoralline *Parisis dachiardii* (OPPENHEIM 1923) and oysters in life position are present.

This facies is interpreted as having developed laterally to, and in a shallower situation than the C1 subfacies. The lateral change between C1 and D has been ascribed to trophic factors: Nutrients, more abundant in this area, favoured coralline-algae rather than coral growth. The presence of still articulated segments of *Parisis dachiardii* (OPPENHEIM 1923) indicates a low level of water energy.

E: Stratified packstone of coral fragments encrusted by coralline-algae

E1) Coral fragments encrusted by coralline-algae, undulating stratified packstone. This subfacies is the predominant facies in the reef. It consists of undulating stratified packstone of coral fragments encrusted by coralline algae. *Actinacis cognata* OPPENHEIM 1901 is the dominant coral taxon. The top of each stratum is marked by the presence of oysters in life position. Bioclastic sandstone beds with algal fragments and nummulitids are found discontinuously between the limestone. Branching coralline-algae (*Mesophyllum*, *Lithophylum*, *Lithoporella*, *Archaeolithoporella* and *Archaeolithothamnion*) are present. The octocoralline *Parisis dachiardii* (OPPENHEIM 1923), *Nummulites*, *Assilina schwageri* (SILVESTRI 1928), *Heterostegina*, and small foraminifers (miliolids, bolivinids, textular-

TABLE 1 | **Summary of the Scleractinian species identified in La Trona reef outcrop in the different reef environments.**

	Reef crest Algae ridge	Framework wall	Reef talus	Bottom reef wall
Order SCLERACTINIA				
Family STYLOPHORIDAE (1) — POCILLOPORIDAE (2)				
Stylophora contorta (LEYMERIE 1846)		◊		
Family STYLOCAENIDAE (1) — ASTROCOENIINAE (2)				
Stylocoenia taurinensis (MICHELIN 1842)		◊		
Stylocoenia macrostyla REUSS 1870		◊		
Astrocoenia lobatorotundata (MICHELIN 1842)		◊		
Family FAVIIDAE (1) — parts FAVIINAE (2) (3)				
Colpophyllia stellata (CATULLO 1852)				◊
Petrophylliella callifera OPPENHEIM 1912				◊
Cereiphyllia tenuis (REUSS 1868)	◊ ●	◊ ●	◊	◊
Astreopora tecta (CATULLO 1856)		◊		
Antiguastraea cvijici (OPPENHEIM 1906)		◊		
Family PARASMILIIDAE				
Placosmiliopsis bilobatus (D' CHIARDI 1868)				◊
Desmophyllum castellolensis ÁLVAREZ PÉREZ 1993				◊
Family MUSSIDAE				
Leptomussa variabilis D'ACHIARDI 1868		◊		
Family PHYLLOCAENIIDAE (1)				
Montastrea guettardi (DEFRANCE 1826)		◊		
Family MEANDRIIDAE (1) (2)				
Sinuosiphyllia macrogira (REUSS 1867)	◊	◊		
Euphyllia pachecoi Solé 1942		◊		
Family AGARICIDAE (1) (2)				
Cyathoseris castroi MALLADA 1887	◊	◊		◊ ●
Pavona bronni (HAIME 1850)	◊	◊		
Family LATOMEANDRIIDAE (1) = FAVIIDAE (2)				
Ellipsocaenia bauzai (MALLADA 1887)	◊	◊		
Family THAMNASTERIIDAE (1) (2)				
Siderastraea morloti (REUSS 1864)		◊		
Siderastraea hemisphaerica D'ACHIARDI 1875		◊		
Siderastraea forojuliensis D'ACHIARDI 1875		◊		
Family ACTINACIDIDAE (1) (2)				
Actinacis cognata OPPENHEIM 1901	◊	◊ ●	◊ ●	◊ ●
Family PORITIDAE				
Goniopora elegans (LEYMERIE 1846)	◊		◊	
Goniopora ameliana (DEFRANCE 1826)		◊	◊	
Dictyaraea octopartita OPPENHEIM 1901		◊		
Order GORGONACEA				
Family ISIDIDAE				
Parisis dachiardii (OPPENHEIM 1923)			◊	◊ ●
Order COENOTHECALIA				
Family HELLIOPORIDAE				
Parapolytremacis bellardii (HAIME 1852)		◊		

(1) Alloiteau (in Piveteau) 1952
(2) Wells (in Moore) 1956
(3) Catullo 1856

◊ Ocurrence of the species in the reef facies
● Species widespread in the reef facies.

ids, homotrematids and victoriellids) are also present. Towards the top of the sequence, the abundance of coralline-algae decreases and the coral abundance increases.

E2) Coral fragments encrusted by coralline-algae, planar stratified packstone. This subfacies is found in the uppermost part of the reef. It consists of packstone, with planar stratification, made up of coral fragments encrusted by coralline-algae. Locally, there are massive colonies in life position bored by bivalves and covered by oysters in life position. Larger foraminifers are less abundant than in subfacies E1. The dominant coral fragments belong, as in subfacies E1, to *Actinacis cognata* OPPENHEIM 1901. The coralline-algae are *Mesophyllum*, *Lithophylum*, *Lithoporella* and *Archaeolithoporella*. The stratification of this facies is interpreted as the result of cyclical changes in the clastic supply intensity, with coralline-algae development in the lower clastic supply periods, the growth of oysters indicating the beginning of the clastic supply, and the sandstone deposition representing the higher clastic supply periods.

The facies and the geometric relationships of this reef system were described by Àlvarez-Pérez et al. (1994, 1999) and Franquès (1996), and they are shown in Figures 18 and 19.

The scleractinian species identified in this reef complex by Àlvarez-Pérez and Busquets (Àlvarez-Pérez et al. 1994, 1999) are summarized in Table 1.

Patch reef facies overlying the La Trona reef

Location: The outcrop is located (5 in Fig. 14) on the road (BV-4608) from Sant Hipòlit de Voltregà to Sant Boi de Lluçanès (km 9.1).

Lithostratigraphic Unit: Sant Martí Xic Limestone Formation (Reguant, 1967).

Chronostratigraphic Unit: Late Bartonian.

Biostratigraphic Unit: SBZ 18.

Unconformity-Bounded Unit: 2nd Bartonian Cycle. Regressive System.

In this outcrop it is possible to observe the patch reef and nummulitic facies, and to collect samples of larger foraminifers. This reef system onlaps the third deltaic sandstone cycle within the 2nd Bartonian regressive system. The lower facies of the onlap deposits are characterised by marl with abundant larger foraminifers, which change progressively upwards to the reefal facies (Fig. 20).

The species of larger foraminifers identified by Papazzoni and Sirotti (1995) and revised in Serra-Kiel et al. (1997) are: *Nummulites chavannesi* DE LA HARPE 1878, *N. praegarnieri* SCHAUB 1981, *N. ptukhiani* KACHARAVA 1969, *Operculina roselli* HOTTINGER 1977, *Assilina schwageri* (SILVESTRI 1928), *Orbitoclypeus varians* (KAUFMANN 1867), *Asterocyclina*, *Halkyardia minima* (LIEBUS 1919) and *Sphaerogypsina globula* (REUSS 1848).

The coralline species identified by Àlvarez-Pérez and Busquets *in* Àlvarez-Pérez et al. (1994) are: *Actinacis cognata* OPPENHEIM 1901, *Cereiphyllia tenuis* (REUSS 1868), *Cyathoseris castroi* MALLADA 1887, *Colphophyllia stellata* (CATULLO 1856), *Petrophylliella callifera* OPPENHEIM 1912, *Goniopora elegans* (LEYMERIE 1846), *Stylocoenia taurinensis* (MICHELIN 1842), *Parisis dachiardii* (OPPENHEIM 1923), *Eusmillia* and *Stylophora*.

Gurb outcrop

Location: The outcrop is located (6 in Fig. 14) on the road (BV-4601) from Vic to Sant Bartomeu del Grau (km 5.5).

Lithostratigraphic Unit: Gurb Marl Member (Reguant, 1967; Barnolas et al. 1983).

Chronostratigraphic Unit: Late Bartonian.

Biostratigraphic Unit: SBZ 18.

Unconformity-Bounded Unit: 2nd Bartonian Cycle. Transgressive System.

Here it is possible to observe the biofacies of the deep euphotic shelf and to collect specimens of larger foraminifers.

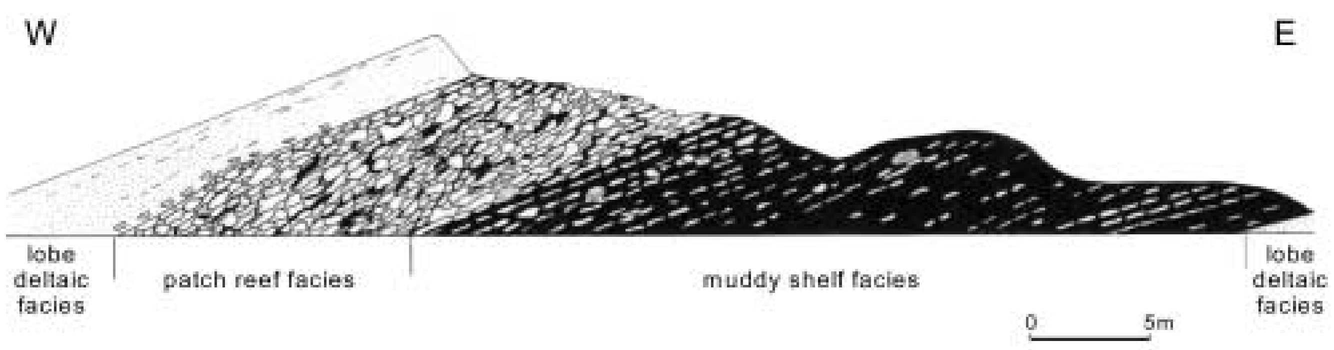

FIGURE 20 **Patch reef facies outcrop. Muddy shelf facies on the bottom, grading upwards to patch-reef facies. The building of the reef was stopped by the supply of siliciclastic deposits.**

In this outcrop, the lithofacies is characterised by the alternation of marl and marly limestone.

The marly limestone shows a lumachellic character and is mainly made up of vinculariform bryozoa, siliceous sponges such as *Laocaetis*, *Guettardiscyphia*, and *Xylospongia* in life position or fallen, brachiopods, bivalves and decapods.

The species of larger foraminifers identified by Ferràndez-Cañadell in Serra-Kiel et al. (1997) are: *Discocyclina radians radians* (D'ARCHIAC 1850), *D. augustae augustae* WEIJDEN 1940, *Asterocyclina stellaris* (BRÜNNER 1848 *in* RÜTIMEYER 1850), *Orbitoclypeus daguini* (NEUMANN 1958), *Assilina schwageri* (SILVESTRI 1928) and small *Nummulites*.

The marly limestone levels normally have a flat geometry, although locally they form small rounded positive reliefs. The marl almost exclusively contain bryozoa.

The fossil association of the marly limestone indicates the deep and euphotic character of the shelf (Caus and Serra-Kiel, 1984; Teixell and Serra-Kiel, 1988).

The alternation between marl and marly limestone is interpreted as the result of cyclical processes of sedimentation/non-sedimentation. A low sedimentation rate permitted the life of organisms such as bryozoa and sponges, and produced the marly intervals. Non-sedimentation periods led to an intense colonisation of the depths, producing the lumachellic character of the more calcareous levels.

The geometry of the marly limestone levels forming small positive reliefs is interpreted as being the result of the baffle effect of organisms living fixed to the bottom.

Sant Bartomeu del Grau outcrop

Location: The outcrop is located along the cliff, 800 m east of the village of Sant Bartomeu del Grau (7 in Fig. 14).

Lithostratigraphic Unit: Sant Martí Xic Limestone Formation (Reguant, 1967), and Terminal Complex (Barnolas et al. 1983; Travé, 1992).

Chronostratigraphic Unit: Late Bartonian and Early Priabonian?.

Biostratigraphic Unit: SBZ 18 and SBZ 19?.

Unconformity-Bounded Unit: Regressive System of the 2nd Bartonian Cycle and Terminal Complex.

In this outcrop it is possible to collect samples of the uppermost nummulitids of the 2nd Bartonian cycle and the porcellaneous larger foraminifers of the first carbonate unit of the Terminal Complex.

The last Eocene marine units of the South-Pyrenean Foreland Basin that outcrop in this locality were named Terminal Complex by Barnolas et al. (1983) and were described by Travé (1992).

The last onlapping reef system is developed on top of prograding deltaic facies (Fig. 21). The beginning of the onlap facies is represented by larger foraminifer facies with *Nummulites chavannesi* DE LA HARPE 1978, *Discocyclina*, *Asterocyclina stellata* (D'ARCHIAC 1846) and *Sphaerogypsina globula* (REUSS 1848), according to Papazzoni and Sirotti (1995) and revised by Serra-Kiel in Serra-Kiel et al. (1997).

On top of this larger foraminifer facies, the Sant Bartomeu del Grau reef facies developed, affected in its uppermost part by a paleokarst, indicating the emergence of the marine units in the marginal parts of the basin.

Above the reef facies, the Terminal Complex developed. This complex is composed of three siliciclastic units and three carbonate units. The siliciclastic units are made up of marl and shallow turbiditic sandstone with rain drop marks and bird tracks.

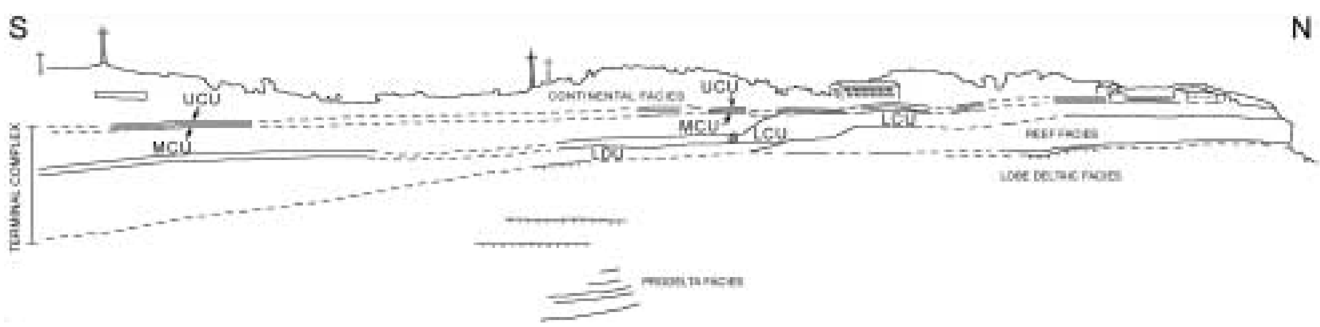

FIGURE 21 **Sant Bartomeu del Grau outcrop. Geometric relationships between the regressive system of the 2nd Bartonian cycle and the Terminal Complex. LDU: Lower Detritic Unit; LCU: Lower Carbonate Unit; MDU: Middle Detritic Unit; MCU: Middle Carbonate Unit; and UCU: Upper Carbonate Unit.**

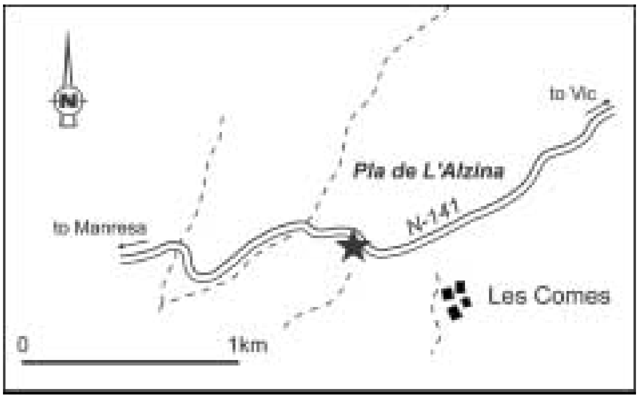

FIGURE 22 **Location of the Collsuspina outcrop.**

The Lower Carbonate Unit is composed of wackestone-packstone with abundant porcellaneous larger foraminifers such as *Orbitolites*, *Rhabdorites malatyaensis* (SIREL 1976) and *Malatyna vicensis* SIREL and AÇAR 1998. According to Sirel and Açar (1998) this outcrop is the type-locality of the *Malatyna vicensis.*

The Middle Carbonate Unit is composed of lithoclasts and bioclasts with abundant oolithic coatings, locally developing oolithic bars.

The Upper Carbonate Unit is mainly formed by stromatolithic limestone and shows evidences of pedogenic processes and subaerial exposure.

The geometric relationships between the last deltaic facies, the last reef facies and the Terminal Complex are shown in Figure 21.

Collsuspina outcrop

Location: This outcrop is located (1 in Fig. 25 and Fig. 22) on the road (N-141) between Tona and Moià (km 31).

Lithostratigraphic Unit: Terminal Complex (Barnolas et al., 1983).

Chronostratigraphic Unit: Late Bartonian - Early Priabonian?.

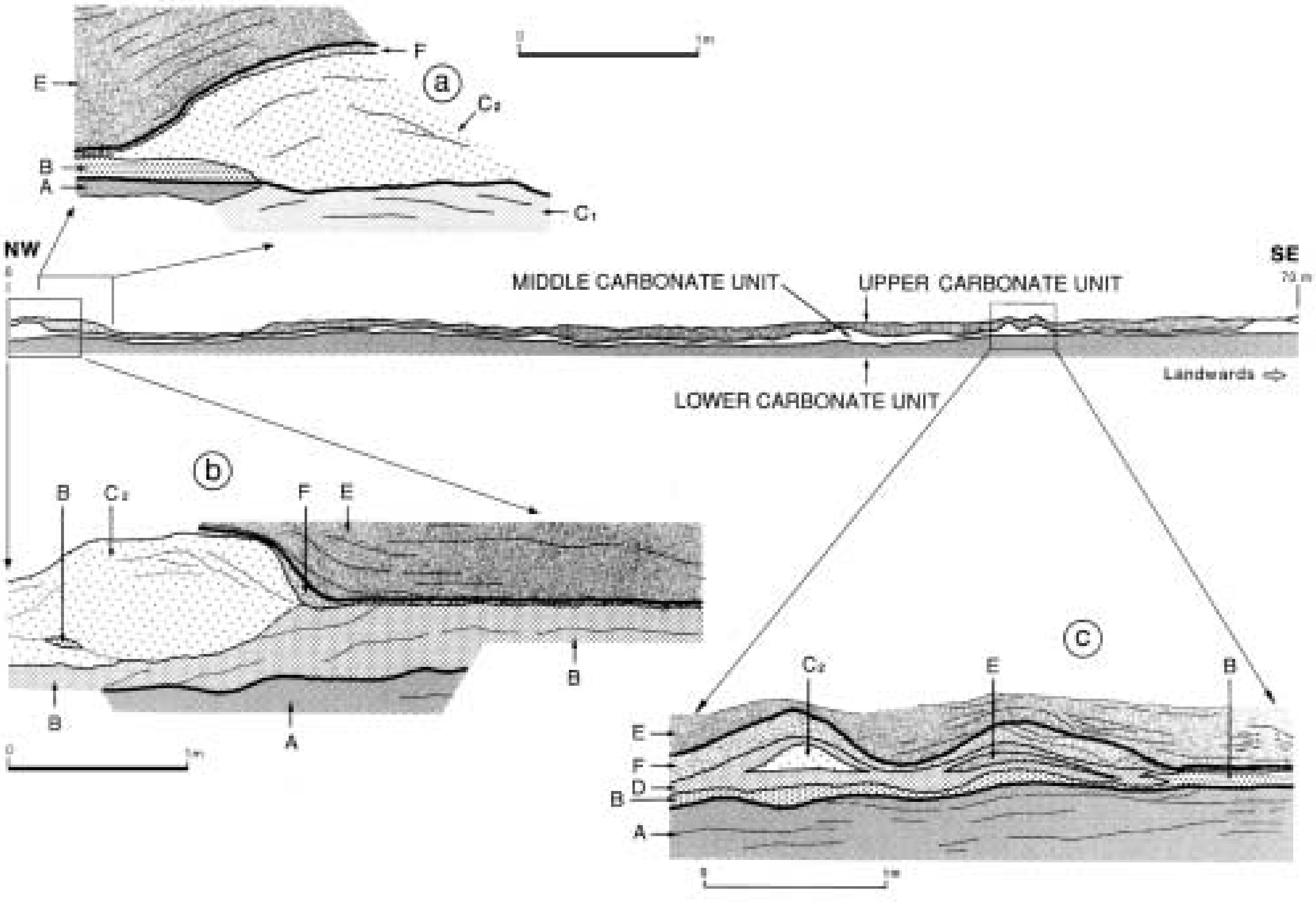

FIGURE 23 **Collsuspina outcrop. Sketch (based on photographs) of the studied outcrop of the Terminal Complex. Thicker lines: local unconformities between the three carbonate units. The letters correspond to the different microfacies described in the text.**

Biostratigraphic Unit: SBZ 18 - SBZ 19?.
Unconformity-Bounded Unit: Terminal Complex.

In this outcrop it is possible to observe the microfacies and geometry of the three carbonate units of the Terminal Complex and to collect porcellaneous larger foraminifers samples from the Late Bartonian-Early Priabonian? (SBZ 18 - SBZ 19?).

Here the Terminal Complex consists of three carbonate units separated by local unconformities (Fig. 23). The siliciclastic intervals found in other areas between the carbonate units are lacking in this area.

The Lower Carbonate Unit, up to two metres thick, is made up of light grey tabular limestone with local development of carbonate mounds, up to 0.4 m high and 1 m across. This unit contains two microfacies: A) Porcellaneous foraminifers and coralline-algae wackestone-packstone, and C1) Crustose coralline-algae, bryozoa and attached foraminifer boundstone.

The Middle Carbonate Unit, ranging from 20 cm up to 1 metre in thickness, contains light grey, thin-bedded limestone with local development of centimetric to metric carbonate mounds. This unit is formed by five microfacies: B) Porcellaneous foraminifers and coralline-algae grainstone, C2) Crustose coralline-algae, bryozoa and attached foraminifer boundstone, D) Porcellaneous foraminifer grainstone alternating with micritic laminations, E) Micritic and microsparitic laminations, and F) Serpulid packstone.

The Upper Carbonate Unit, up to 1.75 m thick, consists mainly of light brown laminated limestone containing microfacies E.

The foraminifer associations in microfacies A and B consist of larger porcellanous foraminifers such as *Malatyna vicensis* SIREL and ACAR 1998, *Rhabdorites malatyaensis* (SIREL 1976) and *Orbitolites*, together with peneroplids, miliolids, nubeculariids, fischerinids, agglutinated foraminifers such as ammodiscids and valvulinids, and hyaline foraminifers such as bolivinids, discorbids, cibicids, acervulinids and asterigerinids.

The most abundant coralline-algae are *Corallina*, *Jania* and *Lithoporella*. Ostracods, echinoids, bryozoa, bivalves, gastropods, dasycladales, udotacean, and sporadically some oysters are also present.

The fossil association of microfacies C1 and C2 comprises: the articulated coralline-algae *Jania* and *Corallina*, the crustose *Lithoporella* and *Lithothamnion* the hyaline attached foraminifers victoriellids and homotrematids, the agglutinated haddoniids and coscinophragmatids, and the small foraminifers valvulinids, ammodiscids, fischerinids, bolivinids, asterigerinids, miliolids and peneroplids.

Microfacies D is made up of millimetric thick alternations of grainstone and micritic laminations. The grainstone is made up of: peloids, porcellaneous foraminifers such as *Rhabdorites malatyaensis* (SIREL 1976), *Spirolina*, miliolids and *Peneroplis*; agglutinated foraminifers such as textularids; echinoid fragments, branching bryozoa, ostracods, bivalves, small gastropods, dasycladales and coralline-algae, such as the crustose *Lithoporella* and the articulated *Jania*. Most components show a superficial oolithic coating. The micritic laminations are composed of continuous crinkly cyanobacterial laminations with pelsparitic patches and abundant fenestral structures.

Microfacies E consists of millimetric crinkly laminations of alternating dark micritic laminae and light microsparitic laminae with abundant fenestral structures.

Microfacies F is made up of a framework of sinuous tubes of rounded morphology reaching 250-300 mm in diameter with a micritic wall, set in a micritic matrix.

The base to top distribution of the microfacies in the three units of the Terminal Complex shows an shallowing-upward character and a progressive change from mesotrophic to eutrophic conditions. The maturation cycle of the epiphytic fauna indicates a change from perennial vegetation (in the Lower Unit) to seasonal vegetation (in the Middle Unit). During the formation of the Upper Unit the environment was colonized by cyanobacterial mats.

A detailed description of these facies and their interpretation was made by Travé (1992) and Travé et al. (1994, 1996).

Calders section

Location: The outcrop is located (2 in Fig. 25 and Fig. 24A) on the road (B-124) from Monistrol de Calders to Calders (km 36).

Lithostratigraphic Unit: Collsuspina Limestone Formation (Reguant, 1967; Barnolas et al., 1983).

Chronostratigraphic Unit: Late Bartonian.

Biostratigraphic Unit: SBZ 18.

Unconformity-Bounded Unit: 2nd Bartonian Cycle. Regressive System.

In this section, studied by Vilaplana (1977) and Serra-Kiel (1984) it is possible to observe the sedimentary facies of the 2nd Bartonian regressive system and to collect samples of *Nummulites biedai* SCHAUB 1962, characteristic of SBZ 18, from its type-locality.

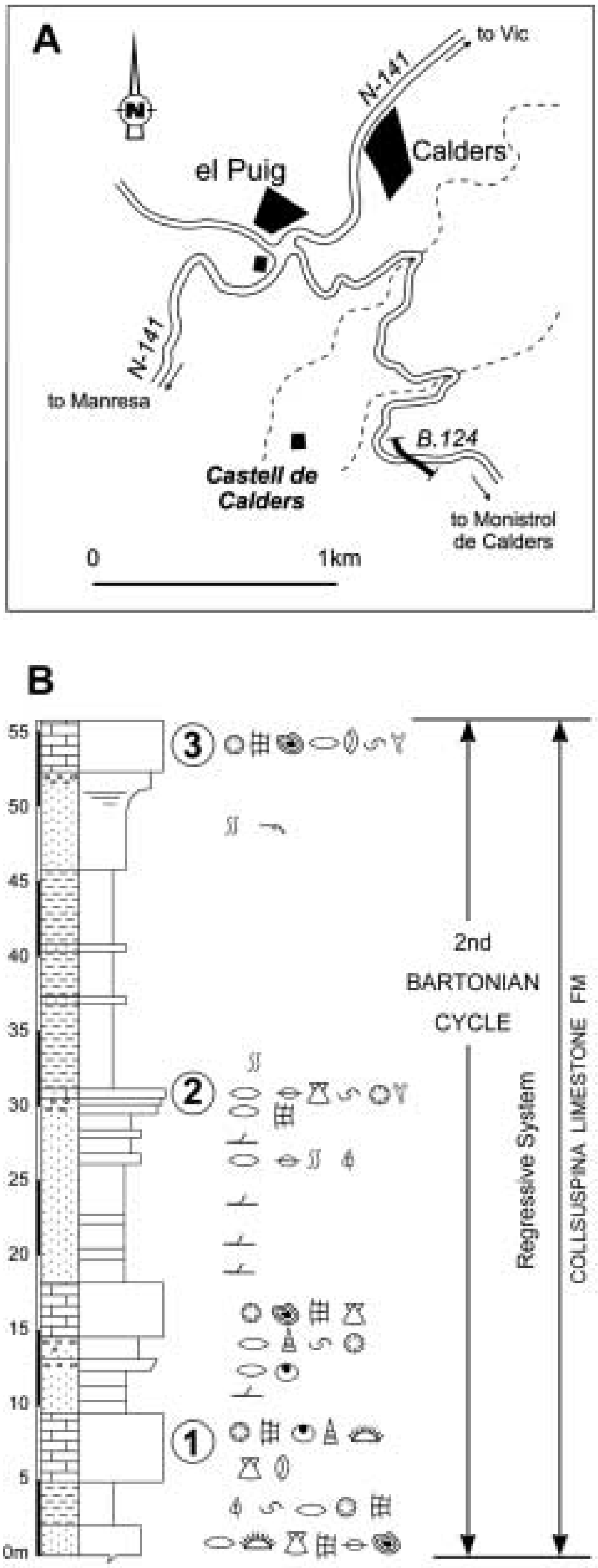

FIGURE 24 | **Location (A) and stratigraphic section (B) at Calders (Serra-Kiel, 1984).**

In this area, the stratigraphic section of the 2nd Bartonian regressive system (Fig. 25B) consists of siliciclastic intervals intercalated with carbonate intervals.

The siliciclastic intervals, made up of marl, sandstone and conglomerate distributed in thickening- and -coarsening-upward sequences, have been interpreted as deltaic facies.

The carbonate intervals consist of corals and crustose coralline-algae, interpreted as reef facies, and of the *in situ* accumulation of large-sized *Nummulites* (such as *N. biedai* SCHAUB 1962), interpreted as *Nummulites* banks.

Sampling points 1, 2 and 3 are from the carbonate intervals (Fig. 25B). Sampling points 1 and 3 correspond to reef facies, and point 2 corresponds to *Nummulites* bank facies.

Points 1 and 2 contain *Nummulites biedai* SCHAUB 1962, *N. ptukhiani* KACHARAVA 1969, and *N. cyrenaicus* SCHAUB 1981. Sampling point 3 contains *N. ptukhiani* KACHARAVA 1969, and *N. cyrenaicus* SCHAUB 1981. The location of point 2 is the type-locality of *N. biedai* SCHAUB 1962.

THE BARTONIAN MARINE RECORD IN THE IGUALADA AREA

Puig Aguilera section

Location: The outcrop is located on the Puig Aguilera hill (1 in Fig. 25 and Fig. 26A).

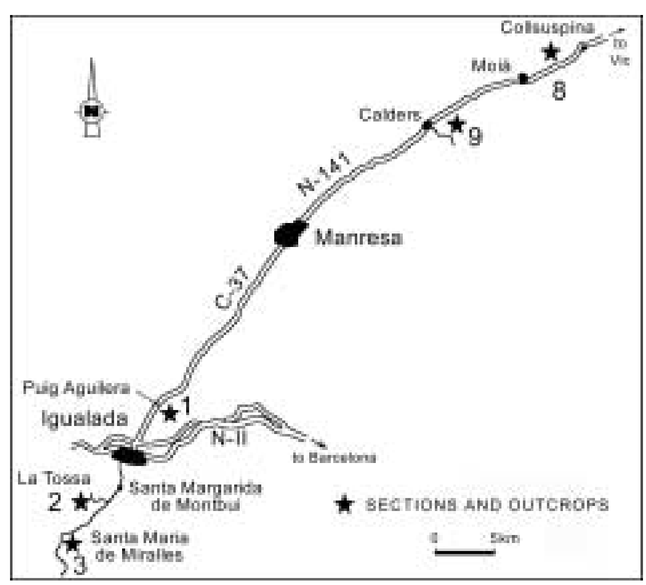

FIGURE 25 | **Location of the Bartonian sections in the Igualada area, and outcrop 8 and section 9 of the Vic area.**

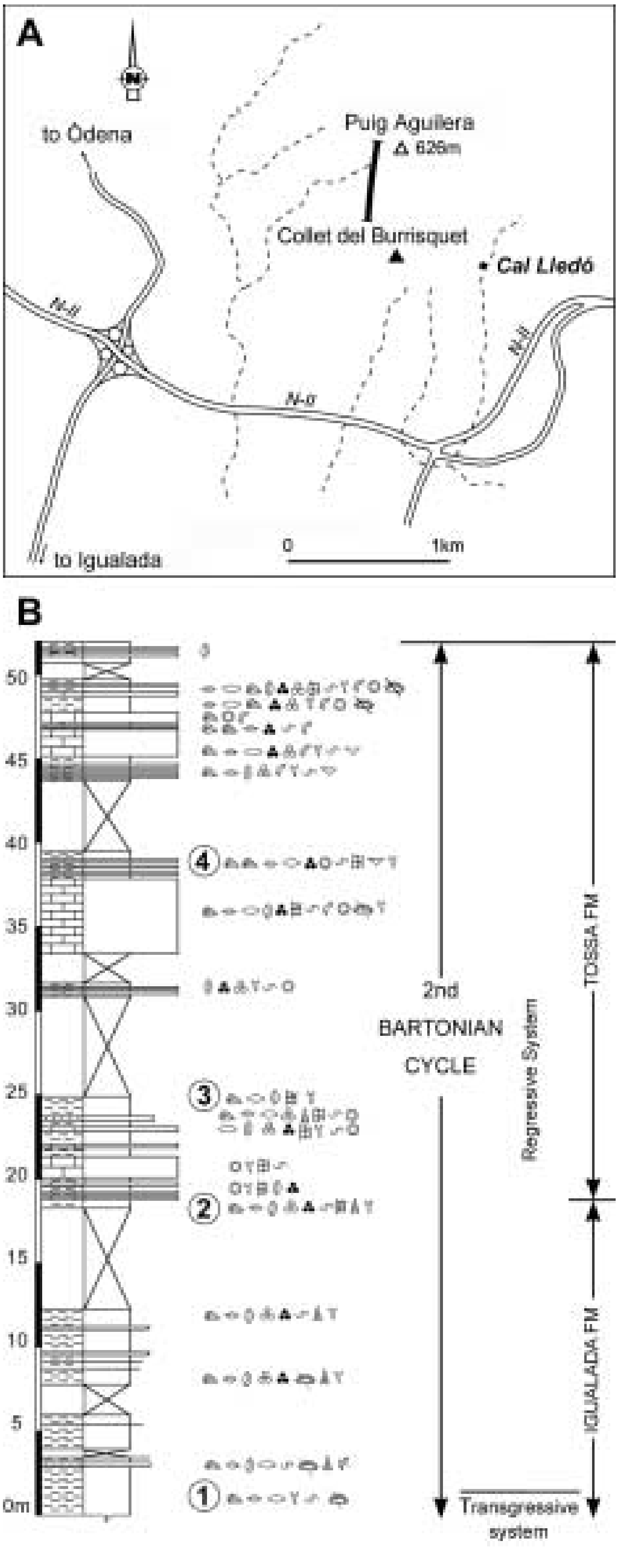

FIGURE 26 **Location (A) and stratigraphic section (B) at the Puig Aguilera (Romero, 1996, 2001).**

Lithostratigraphic Unit: Igualada Formation (Ferrer, 1971) and Tossa Formation (Ferrer, 1971).

Chronostratigraphic Unit: Late Bartonian.

Biostratigraphic Unit: SBZ 18.

Unconformity-Bounded Unit: 2nd Bartonian Cycle. Transgressive and Regressive Systems.

In this outcrop it is possible to observe the regressive system from the 2nd Bartonian cycle in a position closer to the basin centre than in the previously visited outcrops, and to collect larger foraminifer samples, especially of *Pellatispira madaraszi* (HANTKEN 1875) and *Biplanispira absurda* UMBGROVE 1938.

The stratigraphic section (Fig. 26B) begins at the bottom with marl with abundant larger foraminifers, especially orthophragminids (*Discocyclina*, *Asterocyclina*), interpreted as belonging to the upper part of the 2nd Bartonian transgressive system.

The overlying interval consists of marl and sandstone alternating with limestone beds. The marl is rich in larger foraminifers, whereas the limestone intervals are rich in corals, coralline-algae, bryozoa and larger foraminifers. The interval has been interpreted as distal facies of a deltaic system alternating with reef facies, resulting in a succession of offlap-onlap cycles, and belonging to the regressive system of the 2nd Bartonian cycle. Details on the paleocological features of this section can be found in Romero and Caus (2000) and Romero et al. (2002).

Sampling point 1 is in the marl corresponding to the 2nd Bartonian transgressive system. Points 2, 3 and 4 are in the regressive system of the 2nd Bartonian cycle (Fig. 26B).

According to Romero (1996, 2001), Romero et al. (1999) and Hottinger et al. (2001) the following species have been identified:

Point 1: *Asterocyclina stellaris* (BRÜNNER 1848 *in* RÜTIMEYER 1850), *Discocyclina pratti* (MICHELIN 1846), *D. augustae olianae* Almela and Ríos 1942, *Operculina roselli* HOTTINGER 1977, *Assilina schwageri* (SILVESTRI 1928), and *Nummulites*.

Point 2: *Asterocyclina stellaris* (BRÜNNER 1848 *in* RÜTIMEYER 1850), *A. stellata* (D'ARCHIAC 1846), *Discocyclina pratti* (MICHELIN 1846), *D. radians radians* (D'ARCHIAC 1850), *D. augustae olianae* Almela and Ríos 1942, *Heterostegina reticulata reticulata* RÜTIMEYER 1850, *Assilina schwageri* (SILVESTRI 1928), and *Halkyardia minima* (LIEBUS 1919).

Point 3: *Asterocyclina stellaris* (BRÜNNER 1848 *in* RÜTIMEYER 1850), *Discocyclina pratti* (MICHELIN 1846), *D. radians radians* (D'ARCHIAC 1850), *D. augustae olianae* Almela and Ríos 1942, *Heterostegina reticulata*

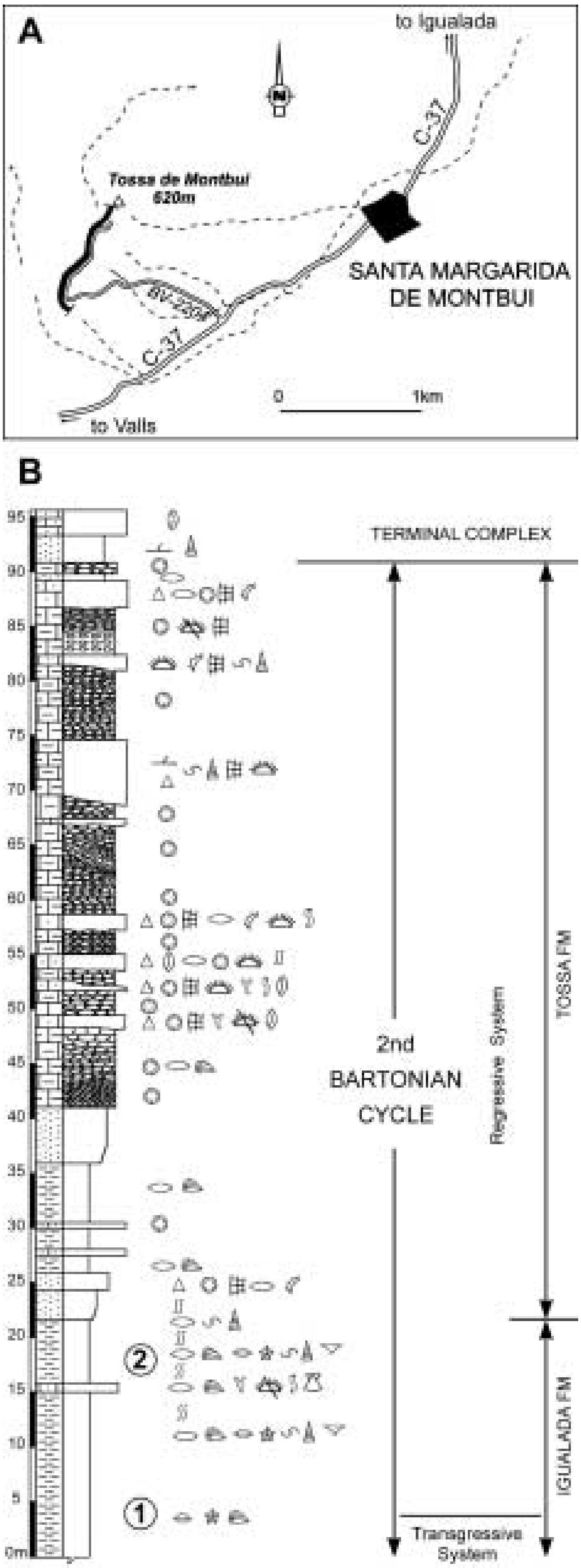

FIGURE 27 **Location (A) and stratigraphic section (B) at La Tossa de Montbui (Salas, 1979).**

reticulata Rütimeyer 1850, *H.* aff. *reticulata italica* Herb 1978, *Assilina schwageri* (Silvestri 1928), *Halkyardia minima* (Liebus 1919), *Orbitoclypeus varians* (Kaufmann 1867), and *Nummulites*.

Point 4: *Asterocyclina stellaris* (Brünner 1848 *in* Rütimeyer 1850), *Discocyclina pratti* (Michelin 1846), *D. augustae olianae* Almela and Ríos 1942, *Heterostegina reticulata reticulata* Rütimeyer 1850, *H.* aff. *reticulata italica* Herb 1978, *Assilina schwageri* (Silvestri 1928), *Pellatispira madaraszi* (Hantken 1875), *Biplanispira absurda* Umbgrove 1938, *Orbitoclypeus varians* (Kaufmann 1867), and *Nummulites*.

La Tossa de Montbui section

Location: The outcrop is located on the road (BV-2204) from Santa Margarida de Montbui to La Tossa hill (2 in Fig. 25 and Fig. 27A).

Lithostratigraphic Unit: Igualada Formation, Tossa Formation (Ferrer, 1971) and Terminal Complex (Barnolas et al., 1983; Travé, 1992).

Chronostratigraphic Unit: Late Bartonian and Early Priabonian?.

Biostratigraphic Unit: SBZ 18 and SBZ 19?.

Unconformity-Bounded Unit: Upper part of the transgressive system and regressive system of the 2nd Bartonian Cycle, and Terminal Complex.

In this outcrop it is possible to observe the sedimentary facies of the upper part of the transgressive and regressive systems of the 2nd Bartonian cycle, and to collect larger foraminifer samples from these levels.

The stratigraphic section (Fig. 27B) begins with marl of the Igualada Formation (Ferrer, 1971) rich in orthophragminids (point 1), interpreted as the top of the transgressive system of the 2nd Bartonian cycle. Higher up, there is an interval of marl rich in orthophragminids and nummulitids (point 2).

Further up, there are two coarsening- and thickening-upward sequences made up of marl and fine sandstone interpreted as deltaic facies that correspond to the beginning of the 2nd Bartonian regressive system.

Over the previous sequence, there is an interval of undulating stratified limestone, rich in coral colonies and coralline-algae, with centimetric marly horizons intercalated. The reef buildups are often truncated by carbonate beds with erosive base made up of broken and reworked bioclasts. This interval is interpreted as reef facies that developed in a shallow environment subject to periodic siliciclastic supply. The carbonate beds made up of broken bioclasts are interpreted as the filling, by fragments produced by reef abrasion, of channels crossing the reef buildup.

The top of the reef system is truncated by cross-stratified sandstone rich in the gastropod *Velates*. They are interpreted as the bottom of the Terminal Complex. The top of the section is represented by a carbonate interval with abundant porcellaneous foraminifers corresponding to the first carbonate unit of the Terminal Complex.

Sampling point 1 contains the larger foraminifer species: *D. radians radians* (D'ARCHIAC 1850), *D. augustae augustae* WEIJDEN 1940 and *Asterocyclina stellaris* (BRÜNNER 1848 *in* RÜTIMEYER 1850), according to Ferràndez-Cañadell (1999).

Sampling point 2 contains the larger foraminifer species: *Nummulites chavannesi* DE LA HARPE 1878, *N. praegarnieri* KACHARAVA 1969, *N. ptukhiani* KACHARAVA 1969, *N. incrassatus incrassatus* DE LA HARPE 1883, *Assilina schwageri* (SILVESTRI 1928), *Operculina roselli* HOTTINGER 1977, *Discocyclina*, *Asterocyclina stellata* (D'ARCHIAC 1846), and *Asterigerina*, according to Papazzoni and Sirotti (1995) and revised by Serra-Kiel in Serra-Kiel et al. (1997).

Santa Maria de Miralles section

Location: The stratigraphic section is located (3 in Fig. 25 and Fig. 28A) on the road (C-37) between Valls and Igualada (km 43-44).

Lithostratigraphic Unit: Collbàs Formation (Ferrer, 1971).

Chronostratigraphic Unit: Early Bartonian.

Biostratigraphic Unit: SBZ 17.

Unconformity-Bounded Unit: 1st Bartonian Cycle. Transgressive System.

In this outcrop it is possible to observe the 1st Bartonian transgressive system and to collect larger foraminifer samples, mainly nummulitids characteristic of SBZ 17. This section contains the *Nummulites hottingeri* SCHAUB 1981 and the *Alveolina fragilis* HOTTINGER 1960 type-localities.

The stratigraphic section (Fig. 28B) begins with grey marl with vegetal remains and bioclasts followed by conglomerate and planar cross-stratified sandstone. The conglomerate contains bored clasts and clay pebbles. The interval is interpreted as a barrier island-lagoon complex (Teixell and Serra-Kiel, 1988) and corresponds to the bottom part of the transgressive cycle.

Further above, there are two biocalcarenitic beds grading into a marly interval with horizons rich in *Nummulites*, pectinids, gastropods, and bryozoa (point 1 in Fig. 28B), interpreted as condensation horizons developed in an inner shelf environment.

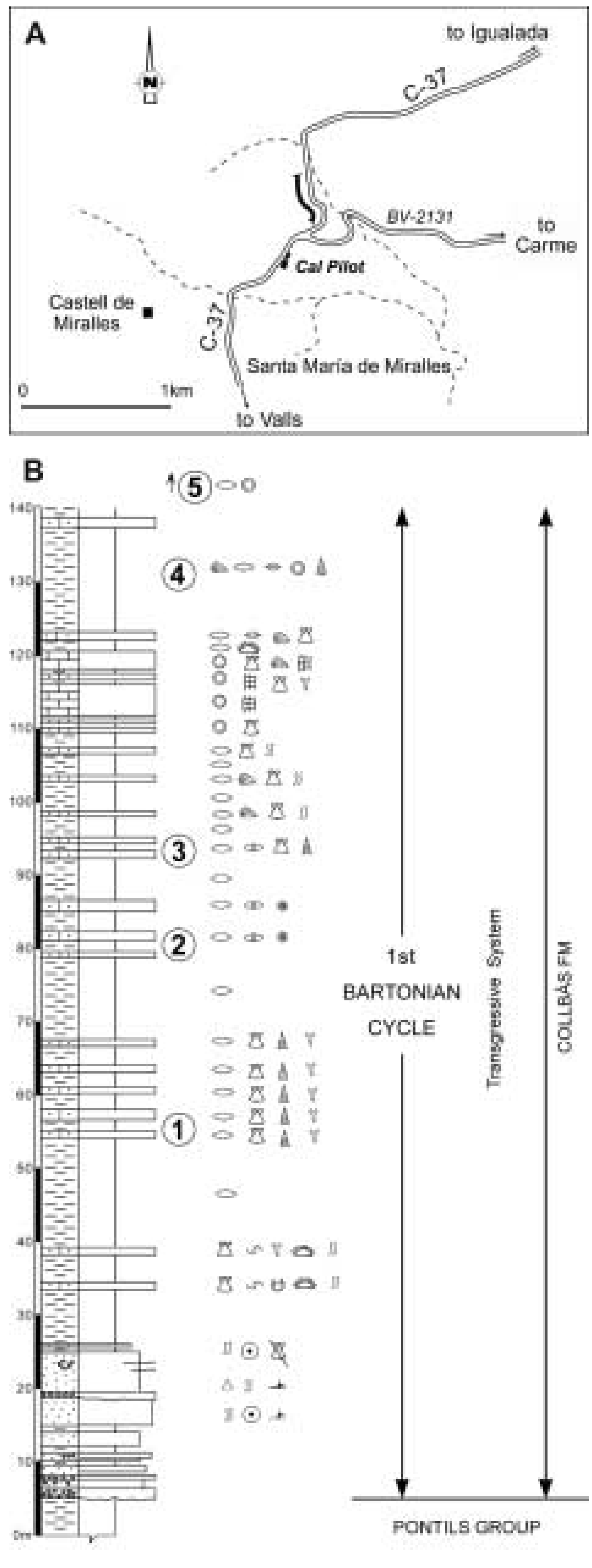

FIGURE 28 **Location (A) and stratigraphic section (B) at Santa Maria de Miralles (Serra-Kiel, 1984).**

Further up, there is an interval of marl (point 2 in Fig. 28B), very rich in *Nummulites perforatus* (MONTFORT 1808), interpreted as *Nummulites* banks by Serra-Kiel and Reguant (1984). Alternating with the marl, there are carbonate beds rich in *N. perforatus* (MONTFORT 1808), with abundant porcellaneous larger foraminifers on top, such as *Alveolina fusiformis* SOWERBY 1850, *A. fragilis* HOTTINGER 1960, and *Orbitolites*. These carbonate beds are interpreted as back-bank facies developed on top of the shallowing upward sequences made up of the *Nummulites* bank facies (Serra-Kiel and Reguant, 1984; Teixell and Serra-Kiel, 1988).

Further up in the section, there is an interval made up of an alternation of marl and carbonate beds (point 3 in Fig. 28B) changing progressively to limestone with abundant coral colonies and coralline-algae. These deposits are interpreted as reef facies. On top of the reef facies, a marly interval (point 4 in Fig. 28B) rich in orthophragminids, *Assilina*, *Operculina* and *Nummulites*, has been interpreted as a middle shelf facies (Teixell and Serra-Kiel, 1988), and indicates a deepening of the depositional environment (Caus and Serra-Kiel, 1984).

The top of the section is formed of marl with *Nummulites* and solitary corals such as *Cyclolitopsis patera* (D'ACHIARDI, 1867) (point 5 in Fig. 28B) corresponding to the deeper settings of the middle shelf.

According to Hottinger (1960), Ferrer (1973), Schaub (1981), Serra-Kiel (1984), and revised by Tosquella in Serra-Kiel et al. (1997), the larger foraminifers present in this section are:

Point 1: *Nummulites vicaryi* SCHAUB 1981, *N. striatus* (BRUGUIÈRE 1792), *N. praegarnieri* SCHAUB 1981, *N. variolarius* (LAMARCK 1804) and *Assilina schwageri* (SILVESTRI 1928).

Point 2: It is the type-locality of *Alveolina fragilis* HOTTINGER 1960 and also contains *Nummulites perforatus* (MONTFORT 1808), *N. cyrenaicus* SCHAUB 1981, *N. vicaryi* SCHAUB 1981, *N. ptukhiani* KACHARAVA 1969, *N. praegarnieri* SCHAUB 1981, *N. variolarius* (LAMARCK 1804) and *Assilina schwageri* (SILVESTRI 1928).

Point 3: It is the type-locality of *Nummulites hottingeri* SCHAUB 1981 and *N. praegarnieri* SCHAUB 1981, and also contains *N. cyrenaicus* SCHAUB 1981, *N. striatus* (BRUGUIÈRE 1792) and *Assilina schwageri* (SILVESTRI 1928).

Point 4: *Nummulites perforatus* (MONTFORT 1808), *N. cyrenaicus* SCHAUB 1981, *N. beaumonti* D'ARCHIAC and HAIME 1853, *N. praegarnieri* SCHAUB 1981, *N. variolarius* (LAMARCK 1804), *Assilina schwageri* (SILVESTRI 1928) and *Operculina roselli* (HOTTINGER 1977).

Point 5: *Nummulites vicaryi* SCHAUB 1981, *N. striatus* (BRUGUIÈRE 1792), *N. praegarnieri* SCHAUB 1981, *N. variolarius* (LAMARCK 1804) and *Assilina schwageri* (SILVESTRI 1928).

CONCLUDING REMARKS

The outcrops and sections that we show in this inventory belong to the following lithostratigraphic units and larger foraminifer biozones:

1) The Empordà outcrops and sections belong to the Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972), Banyoles Marl Formation (Almela and Ríos, 1943), Bracons Formation (Gich, 1969, 1972) and Folgueroles Sandstone Formation (Reguant, 1967). These lithostratigraphic units comprise the Early Lutetian-Early Bartonian interval, and contain porcellaneous larger foraminifers and nummulitids that are representative of SBZs 13, 14, 15, 16 and 17.

2) The Vic outcrops and sections are Lutetian and Bartonian in age. The Lutetian levels belong to the Tavertet/Girona Limestone Formation (Reguant, 1967; Pallí, 1972), the Coll de Malla Marl Formation (Clavell et al., 1970), and the Folgueroles Sandstone Formation (Reguant, 1967), and contain porcellaneous larger foraminifers and nummulitids representative of SBZs 13, 14, 15 and 16. The Tavertet/Girona Limestone Formation contains the type-localities of *Nummulites crusafonti* REGUANT and CLAVELL 1967, and *Nummulites tavertetensis* REGUANT and CLAVELL 1967, while the Coll de Malla Marl Formation provides the type-locality of *Nummulites puigsecensis* REGUANT and CLAVELL 1967. The Bartonian levels belong to the La Guixa Marl Member (Reguant, 1967; Barnolas et al., 1983), the Gurb Marl Member (Reguant, 1967; Barnolas et al., 1983), the Igualada Formation (Ferrer, 1971), the Sant Martí Xic Limestone Formation (Reguant, 1967), the Terminal Complex (Barnolas et al., 1983; Travé, 1992), and the Collsuspina Limestone Formation (Reguant, 1967; Barnolas et al., 1983) equivalent to the Sant Martí Xic Limestone Formation and the Terminal Complex together. The Collsuspina Limestone Formation contains the type-locality of *Nummulites biedai* SCHAUB 1962, and the Terminal Complex contains the type-locality of *Malatyna vicensis* SIREL and AÇAR 1998. These Bartonian units correspond to SBZ 18. The biostratigraphic situation of the Terminal Complex is open to doubt, being located between the top of SBZ 18 (Late Bartonian) and the base of SBZ 19 (Early Priabonian).

3) The Igualada sections belong to the Collbàs Formation (Ferrer, 1971), Igualada Formation and Tossa Formation (Ferrer, 1971). These units belong to SBZs 17 and 18. The Collbàs Formation provides the type-locali-

ties of *Nummulites hottingeri* SCHAUB 1981, *N. praegarnieri* SCHAUB 1981, and *Alveolina fragilis* HOTTINGER 1960.

ACKNOWLEDGMENTS

This research was supported by DGICYT grant PB 98-1293, and is a contribution to IGCP 393 and of the Grup Consolidat de Recerca "Geodinàmica i Anàlisi de Conques" of the Barcelona University and the Research Commission of the Generalitat de Catalunya. We thank J. Telford and D. Brown for the revision of the English version.

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Manuscript received January 2002;
revision accepted December 2002.