

Palaeoenvironmental and stratigraphic significance of Pliocene rhodolith beds and coralline algal bioconstructions from the Carboneras Basin (SE Spain)

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Aguirre J., Braga J. C., Martín J. M. & Betzler C. 2012. — Palaeoenvironmental and stratigraphic significance of Pliocene rhodolith beds and coralline algal bioconstructions from the Carboneras Basin (SE Spain). *Geodiversitas* 34 (1): 115–136. <http://dx.doi.org/10.5252/g2012n1a7>

ABSTRACT

Thick rhodolith beds occur in the transgressive and highstand systems tracts of the early Pliocene sequence in the Carboneras Basin in SE Spain. Rhodolith beds accumulated in mid-to-outer ramp settings and in the leeward of a spit platform during the transgressive interval, whereas rhodolith concentrations in the highstand deposits only formed in the mid-to-outer ramp at the southern margin of the basin. The elevation of rhodolith beds compared with coeval shore deposits suggests that the beds developed at water depths of several tens of metres (probably less than 50 m). This palaeodepth estimate is consistent with the composition of algal assemblages, which are dominated by melobesioids common in relatively deep platform environments in the modern Mediterranean Sea. *Lithothamnion minervae* Basso, 1995, *L. philippii* Foslíe, 1909, and *Mesophyllum alternans* (Foslíe) Mendoza & Cabioch, 1998 with subordinate *Phymatolithon calcareum* (Pallas) Adey & McKibbin, 1970 and *M. macroblastum* (Foslíe) Adey, 1970 and lithophylloids of the *Lithophyllum incrustans* Philippi, 1837-*L. racemus* (Lamarck) Foslíe, 1901 complex are the most common of a total of 21 recorded species. All the identified algal species are also living in the present-day Mediterranean except for the extinct *Lithothamnion ramosissimum* (Reuss) Piller, 1994 and for the recent *Spongites decipiens* (Foslíe) Chamberlain, 1993, which has been reported in the Indo-Pacific and South Atlantic, but not in the Mediterranean. Moderate energy and low sedimentation rates promoted development of rhodolith beds in the transgressive deposits, but they are not exclusive to the transgressive systems tract as they continued to accumulate at the southern margin during the highstand, beyond the influx of siliciclastics that reduced carbonate production in the rest of

KEY WORDS

Rhodolith beds,
coralline
bioconstructions,
Pliocene,
coralligène,
Carboneras Basin,
SE Spain.

the basin. Isolated pillars (up to 90 cm high) or irregular patches (up to 2 m high and 7 m wide) of coralline algal-bryozoan-bivalve bioconstructions occur in outer-ramp fine-grained calcarenites. Despite their similarities to pillars and low relief buildups constructed by coralline algae (“coralligène de plateau”) in the present-day Mediterranean Sea, these bioconstructions are unique as bryozoans are the main builders and coralline algae (*L. philippii* and *M. lichenoides*) play only a secondary role. In contrast with modern Mediterranean coralline algal buildups, the lack of bioclastic debris derived from the build-ups in the surrounding fine-grained sediments and their general morphology suggest that the Pliocene bioconstructions in the Carboneras Basin did not create significant positive relief on the seafloor.

RÉSUMÉ

Paléoenvironnements et stratigraphie des couches à rhodolithes et des constructions à algues corallines du Pliocène du Bassin de Carboneras (SE de l'Espagne).

Dans le bassin de Carboneras (SE de l'Espagne), on observe d'épaisses couches à rhodolithes dans le cortège transgressif et dans celui de haut niveau de la séquence du Pliocène inférieur. Ces accumulations se sont produites sur la portion moyenne à externe d'une rampe. Durant la phase de transgression, on les trouve du côté sous le vent d'un cordon littoral, alors que, durant la phase de haut niveau relatif qui lui succède, ce même type de dépôts est restreint à la seule marge méridionale du bassin. L'élévation des couches à rhodolithes comparée avec celle des dépôts littoraux contemporains suggère que ces couches se sont développées à des profondeurs de quelques dizaines de mètres, mais probablement sans dépasser 50 mètres. Cette estimation de la paléo-profondeur est cohérente avec la composition de l'association phycologique, dominée par les mélobésioïdes communes dans les environnements de plates-formes relativement profonds dans l'actuelle mer Méditerranée. Le complexe à *Lithophyllum incrustans* Philippi, 1837-*L. racemus* (Lamarck) Foslíe, 1901 avec *Lithothamnion minervae* Basso, 1995, *Lt. philippii* Foslíe, 1909 et *Mesophyllum alternans* (Foslíe) Mendoza & Cabioch, 1998 dominants et *Phymatolithon calcareum* (Pallas) Adey & McKibbin, 1970, *M. macroblastum* (Foslíe) Adey, 1970 et lithophylloïdes minoritaires est le plus fréquent avec un total de 21 espèces enregistrées. Toutes ces espèces d'algues se retrouvent dans l'actuelle Méditerranée à l'exception de *Lithothamnium ramosissimum* (Reuss) Piller, 1994, qui est éteinte, et de *Spongites decipiens*, présente dans l'aire indo-pacifique et dans l'océan Atlantique sud mais inconnue en Méditerranée. Au cours de l'intervalle transgressif, un hydrodynamisme modéré et un faible taux de sédimentation ont favorisé la formation des rhodolithes. Durant la période de haut niveau qui suit, ces conditions persistent sur la marge sud du bassin tandis qu'ailleurs les apports silico-clastiques entraînent une réduction de la part de la production carbonatée. On observe alors des bioconstructions à algues, bryozoaires et bivalves, sous forme de piliers isolés, jusqu'à 90 cm de hauteur, ou des taches irrégulières, de 2 m de hauteur et de 7 m d'extension, au sein des calcarenites fines de la rampe externe. Malgré leur ressemblance avec les piliers et constructions peu protubérantes dues aux algues corallines de la Méditerranée actuelle, appelé « coralligène de plateau », ces bioconstructions sont originales car ce sont les bryozoaires qui sont les principaux contributeurs, les algues corallines (*Lt. philippii* et *M. lichenoides*) n'y jouant qu'un rôle secondaire. À la différence de ce qui s'observe dans la Méditerranée actuelle, l'absence de débris bioclastiques dans les sédiments à granulométrie fine à proximité des constructions algaires pliocènes du bassin de Carboneras suggère que celles-ci ne devaient pas créer de relief significatif sur le fond marin de l'époque.

MOTS CLÉS

Couches à rhodolithes,
constructions à algues
corallines,
Pliocène,
coralligène,
bassin de Carboneras,
Espagne.

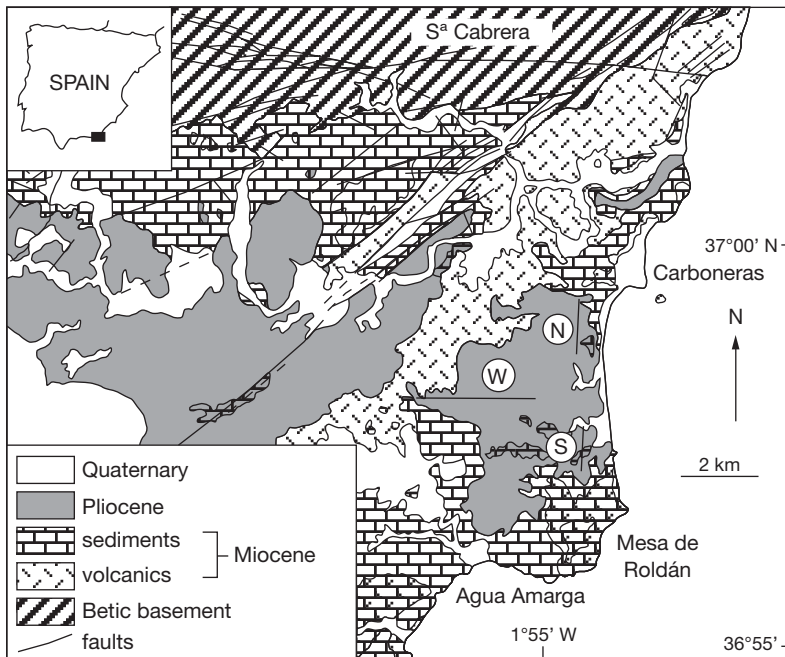


FIG. 1. — Geological map with the location of the study area. Abbreviations: **N**, northern transect; **S**, southern transect; **W**, western transect.

INTRODUCTION

Rhodoliths are unattached, nodular structures mostly built up by non-geniculate coralline algae (Bosellini & Ginsburg 1971). Rhodoliths can possess a nucleus, whether organic or inorganic, and can be monospecific or multispecific in terms of coralline algal components. In some cases, other organisms might be equally, or even more, important builders than corallines, as in the case of for-algaliths, mostly constituted by benthic foraminifers plus coralline algae (Reid & MacIntyre 1988; Prager & Ginsburg 1989), or serpulid nodules, consisting mainly of serpulids with some laminar thalli of corallines encrusting the annelids (Aguirre *et al.* 1993). These nodular structures grow due to hydraulic movement (Bosellini & Ginsburg 1971; Bosence 1983a) or to the activity of organisms (Prager & Ginsburg 1989; Marrack 1999).

In present-day marine platforms, there are wide areas where rhodoliths concentrate to form the so-called rhodolith-maerl beds. Despite the ecological

relevance of rhodolith beds in present-day ecosystems, what local factors may trigger their formation and what processes control their long-term development are not fully understood. Advances in ecological studies over recent decades have offered clues on environmental factors affecting these organisms (Adey & Vassar 1975; Bosence 1976, 1983b; Steneck & Paine 1986; Steller & Foster 1995; Halfar *et al.* 2004; Harvey & Bird 2008). The fossil record, however, provides the unique possibility of analysing factors controlling the long-term development of rhodolith beds.

Dense concentrations of rhodoliths in the geological record have attracted the interest of many researchers (reviews in Adey & MacIntyre 1973; Bosence 1983b, 1991). Corallines have been important primary producers in varied shelf settings, from the tropics to the poles. In temperate platforms, coralline algae may be the dominant component in the so-called rhodalgal carbonate lithofacies (Carannante *et al.* 1988).

The morphology of the rhodoliths (the growth form of the algal components) and the algal as-

semblages of the rhodoliths are both useful tools for palaeoecological reconstructions and palaeobiogeographic inferences (Bosence & Pedley 1982; Bosence 1983c; Braga & Martín 1988; Aguirre *et al.* 1993; Bassi 1995, 2005; Vannucci *et al.* 1996; Basso 1998; Basso *et al.* 1998; Rasser 2000; Stockar 2000; Braga & Aguirre 2001, 2004; Webster *et al.* 2004a, b, 2006, 2009; Bassi *et al.* 2006; Nalin *et al.* 2008; Braga *et al.* 2009; Checconi *et al.* 2010, among many others). Less well-known are the prevailing conditions to produce thick, dense concentrations of rhodoliths for long timespans, and of rhodolith beds. Rhodolith beds can be preferentially associated to transgressive deposits (Friebe 1993; Nalin *et al.* 2008) but, as shown below, the ecological conditions required to produce profuse rhodolith growth can also be achieved in other contexts of sea-level variation.

In addition to rhodoliths, coralline red algae are known to contribute to reef growth and to generate rigid structures attached to stable substrates in which they are the main components (Pérès 1967a, b; Bosence 1985a). In the warm temperate waters of the modern Mediterranean, these structures are generally referred to as “coralligène de plateau” and they are found in a wide range of water depths. They typically have dominant lateral growth (wider than they are high) and offer a hard substrate for a variety of sessile organisms (Pérès & Picard 1964; Bosence 1985a, b; Gili & Ros 1985; Ros *et al.* 1985; Sartoretto 1994; Garrabou & Ballesteros 2000). In recent years, however, new findings have widened the spectrum of coralline algal buildups in the Mediterranean (Di Geronimo *et al.* 2001, 2002).

The Lower Pliocene deposits of the Carboneras Basin (SE Spain) are mostly temperate carbonates largely dominated by coralline algae together with barnacles, molluscs, echinoids, bryozoans, solitary corals, and serpulids (Aguirre 1998; Braga *et al.* 2003a; Martín *et al.* 2004; Aguirre *et al.* 2008). Rhodoliths are dispersed in the sediment but, more significantly, they are concentrated in particular beds. Coralline algae, together with bryozoans and bivalves, also form buildups in specific settings in the basin. The aims of this paper are: 1) to analyse the palaeoenvironmental conditions that favoured

rhodolith bed formation and discuss their sequence-stratigraphy significance; and 2) to describe the morphology, composition, and palaeoenvironmental context of the coralline algal/bryozoan/bivalve buildups, which are not fully analogous with known present-day counterparts.

MATERIALS AND METHODS

The relative abundance of rhodoliths, measured as percentage of rhodoliths per rock volume (density), was estimated using the templates made by Kidwell & Holland (1991) to assess the percentage of bioclasts per rock volume. These estimations were performed in 10 sampling sites in each of the rhodolith beds examined.

The analysis of the morphology of the rhodoliths was performed measuring shorter, larger, and intermediate axes of 30 rhodoliths in each bed. The data were plotted in ternary diagrams following Bosence (1976).

Algal growth form, species relative abundance, and taxonomic composition were studied in 57 ultrathin sections (4.7 mm × 2.7 mm in size). Growth-form terminology follows that proposed by Woelkerling *et al.* (1993). Relative abundance was calculated using the point-counting method of Perrin *et al.* (1995). Coralline algae were identified at the lowest possible taxonomic level applying taxonomic criteria used for present-day corallines. Based on Le Gall *et al.* (2010), two orders of corallines are recognized: Sporolithales, including the family Sporolithaceae, and Corallinales, including the families Corallinaceae and Hapalidiaceae. The subfamilies within the last two families are those recognized by Harvey & Woelkerling (2007).

STUDY AREA AND GEOLOGICAL CONTEXT

The study area is located in the Carboneras Basin (Almería, SE Spain), a small intermontane basin at the northeastern margin of the Cabo de Gata volcanic province (Fig. 1). The basin basement rocks are Tortonian volcanic rocks (Fernández-Soler 1996)

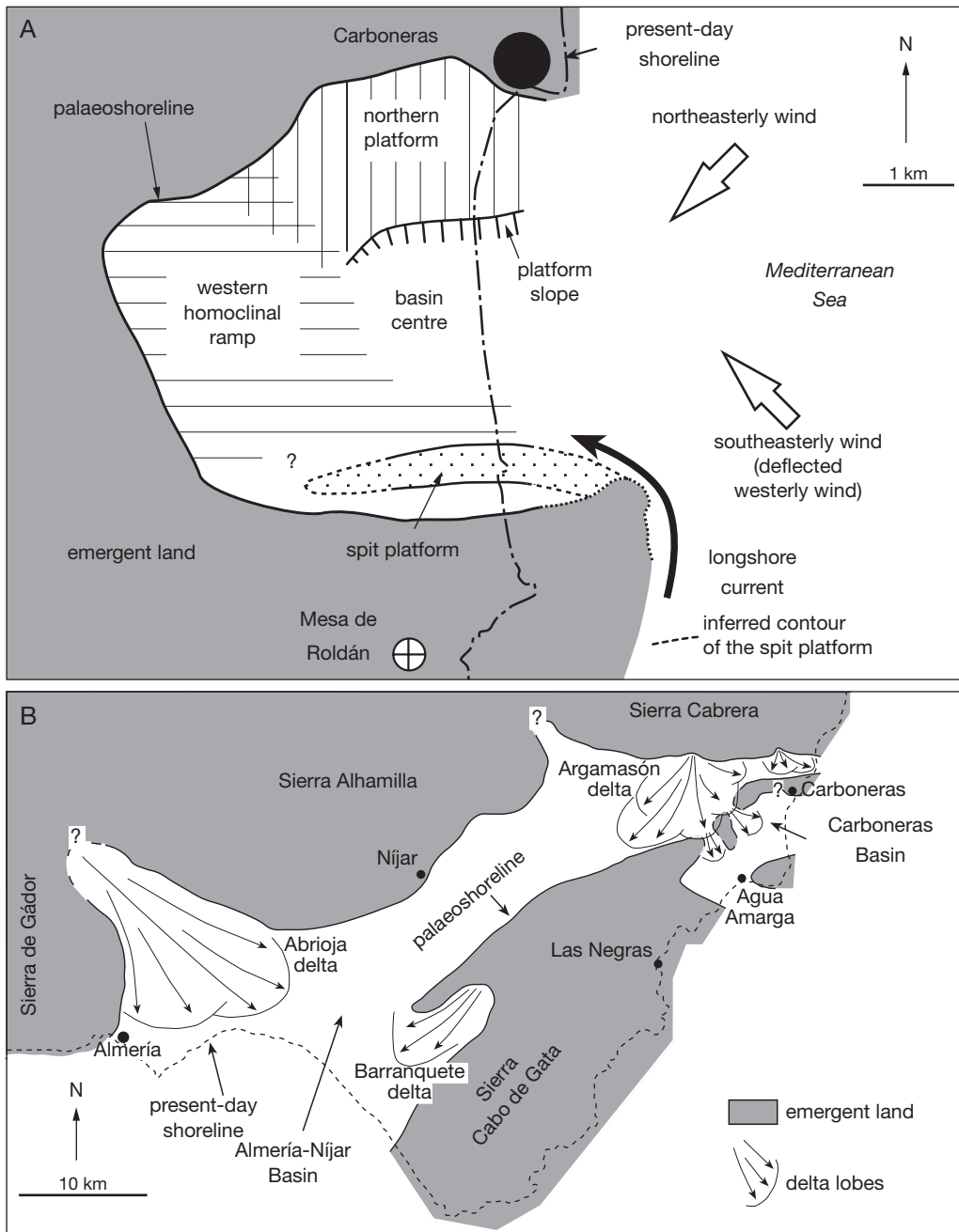


FIG. 2. — Palaeogeographic maps of the Carboneras Basin during the Pliocene: **A**, palaeoenvironmental reconstruction of the Carboneras Basin during the transgressive stage of the Lower Pliocene sequence. Three different shelf types developed at the margins of the basin due to local factors such as hydrodynamics and topography (modified from Martin *et al.* 2004); **B**, reconstruction of the Carboneras and Almería-Níjar basins during the highstand stage of the Lower Pliocene sequence. Terrigenous delta lobes from the north prograded into the Carboneras Basin, endings carbonate deposition except at the southern margin, the farthest from the siliciclastic input (modified from Aguirre *et al.* 2008).

unconformably overlain by upper Tortonian limestones and conglomerates, and Messinian marine marls, coral-reef limestones, and carbonate breccias (Van de Poel *et al.* 1984; Serrano 1990; Montenat *et al.* 1990; Martín *et al.* 2004). Lower Pliocene (Zanclean) marine carbonates complete the Neogene succession (Montenat *et al.* 1990; Aguirre 1998; Braga *et al.* 2003a; Martín *et al.* 2004), overlying and onlapping an irregular palaeotopographic surface (Aguirre 1998).

The emersion of the Betic Cordillera from the middle Miocene onward led to the individualisation of different Mediterranean-linked basins in the southeastern Iberian Peninsula (Montenat 1990; Braga *et al.* 2003b; Martín *et al.* 2003). During the earliest Pliocene, the Carboneras Basin was a small marginal embayment of the Mediterranean Sea bordered by volcanic rocks (Aguirre 1998; Braga *et al.* 2003a, b; Martín *et al.* 2003, 2004) (Fig. 2A). During the latest Early Pliocene-Late Pliocene, the basin was connected to the north and northeast to the Almería-Níjar Basin and to the south to the Agua Amarga sub-basin (Martín *et al.* 2003, 2004; Aguirre *et al.* 2008) (Fig. 2B). Carbonate platform deposits dominated during most of the Early Pliocene, when the Carboneras Basin was isolated from neighbouring basins. On the contrary, widespread siliciclastic sedimentation in delta lobes took place at the western margin of the basin, at the time of its connection to the Almería-Níjar Basin (Martín *et al.* 2004; Aguirre *et al.* 2008).

PLIOCENE DEPOSITS OF THE CARBONERAS BASIN

The detailed sedimentology and stratigraphic architecture of the Pliocene deposits of the Carboneras Basin have been studied elsewhere (Aguirre 1998; Braga *et al.* 2003a; Martín *et al.* 2004; Aguirre *et al.* 2008); therefore, here we focus on the sedimentary context of coralline algal concentrations. The Pliocene deposits in the basin can be divided into three subunits (lower, intermediate, and upper); they have been interpreted as the lowstand, transgressive, and highstand systems tract deposits of a stratigraphic sequence (Martín *et al.* 2004) (Fig. 3).

The coralline algal deposits studied herein belong to the intermediate and upper subunits (Fig. 3).

The intermediate subunit consists of calcarenites-calcirudites that are very rich in bryozoans, coralline algae, bivalves, and benthic foraminifers, with minor echinoids and brachiopods. These deposits show different stratal geometry and facies at the northern, southern, and western margins of the basin due to local hydrodynamic conditions and palaeotopography (Braga *et al.* 2003a; Martín *et al.* 2004) (Fig. 4). At the northern margin, sedimentation in the intermediate subunit started in a gently southward-dipping ramp and changed over time to a distally steepened ramp reflected in sigmoidal (clinoform) stratal geometries (Fig. 4A). Storm beds dominated by bivalves occur among calcarenite and calcirudite in the platform and platform-slope deposits. Downslope, the sediment changes to calcisiltites and fine-grained calcarenites with in-situ bioconstructions of *Neopycnodonte cochlear* (Poli, 1791) and small patches of coralline algae, bryozoans, and serpulids. Decimetric rhodolith beds occur at the platform edge at the top of the subunit. These beds account for a package (max. 13 m thick) that can be followed horizontally for over 600 m (Martín *et al.* 2004).

At the western margin, a gently eastward-dipping ramp developed (Fig. 4B). Bioclastic calcirudites dominated by coralline algae, bivalves, and gastropods occur in the proximal areas of the ramp, whereas fine-grained calcarenites and calcisiltites were deposited in the distal parts, locally containing *Neopycnodonte cochlear* and coralline algal-bryozoan-bivalve buildups. A rhodolith bed, up to 5 m thick, occurs at the top of the subunit in the mid-to-outer ramp deposits (Fig. 3) (Martín *et al.* 2004).

At the southern margin, transgressive deposits formed in a spit platform prograding to the south and southwest (Fig. 4C). Sediments were removed downslope and shoreward at the leeside of the spit-platform and offshore to the basin by storms. The leeside of the spit-platform consists of southward-dipping strata (10°S) with rhodolith concentrations at the toe (Fig. 3). Trough cross-bedded calcarenites and calcirudites at the top of the spit-platform grade to the north to algal-bryozoan rudstone to floatstones rich in rhodoliths (Martín *et al.* 2004).

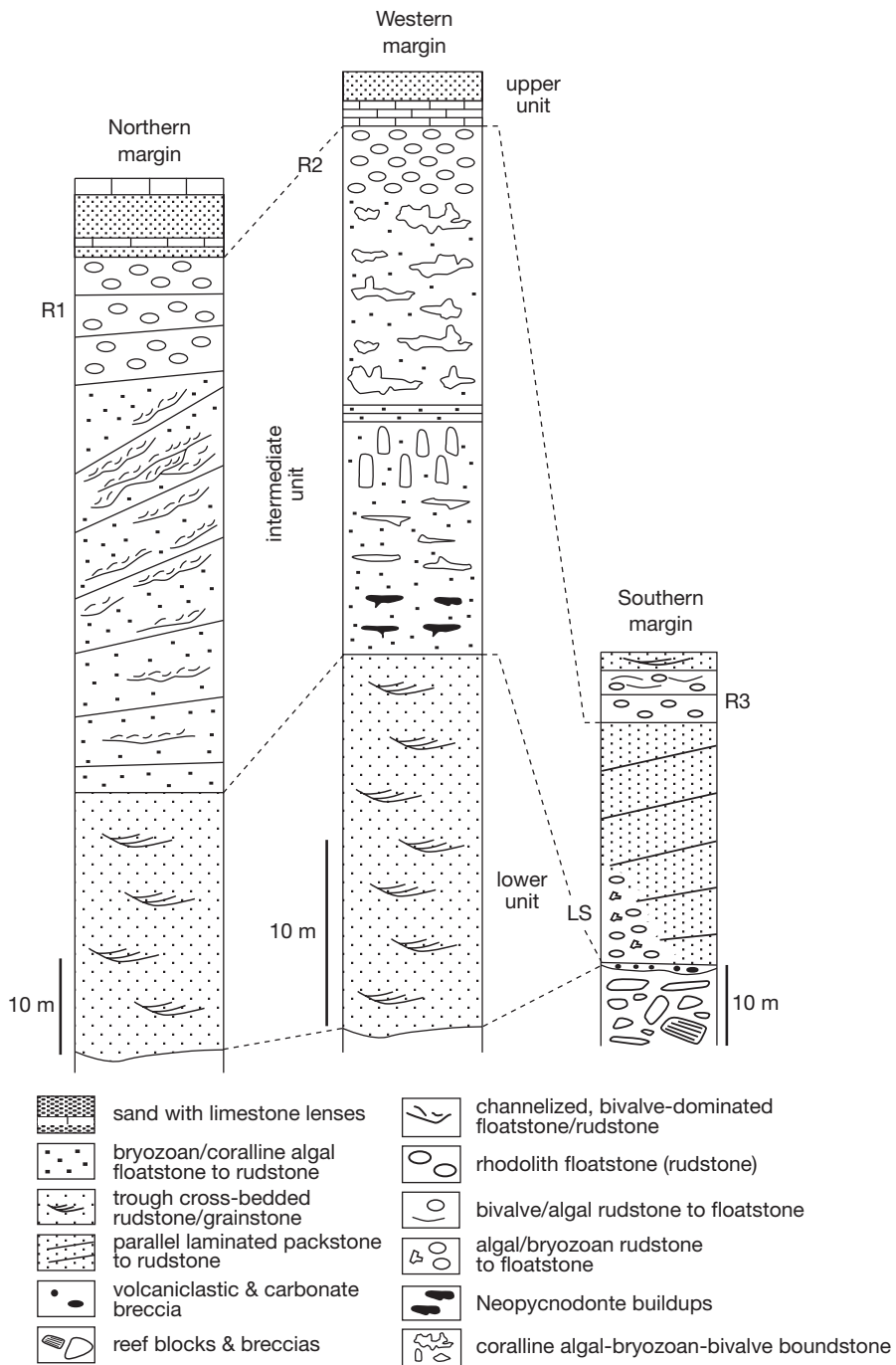


FIG. 3. — Synthetic stratigraphic columns of the three margins of the Carboneras Basin. **R1**, **R2**, and **LS** are the rhodolith beds that formed at the northern, western, and southern margins, respectively, during the transgressive stage. **R3** is the rhodolith bed that formed at the southern margin of the basin during the highstand phase.

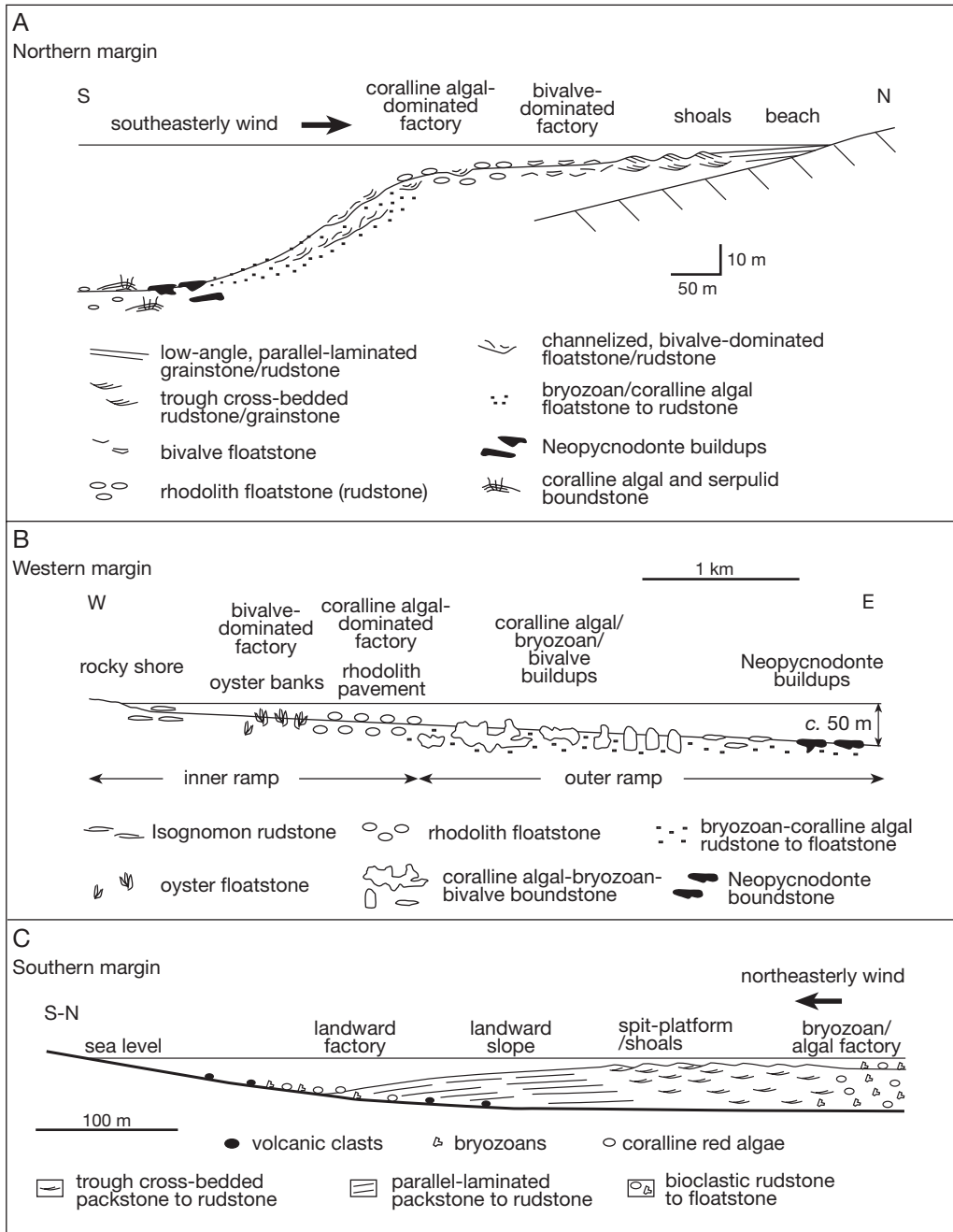


FIG. 4. — Depositional models of the three margins of the Carboneras Basin during the transgressive stage of the Lower Pliocene sequence: **A**, a narrow, distally steepened ramp developed at the northern margin. The rhodolith factory, producing the rhodolith beds, formed on the edge of the shelf; **B**, a gently east-dipping ramp formed on the western margin. Rhodoliths concentrated in the inner-ramp and the bryozoan-coralline-bivalve buildups grew in the outer ramp; **C**, a spit platform developed at the southern margin. Rhodolith beds formed in the protected leeside of the bar (modified from Martin *et al.* 2004).

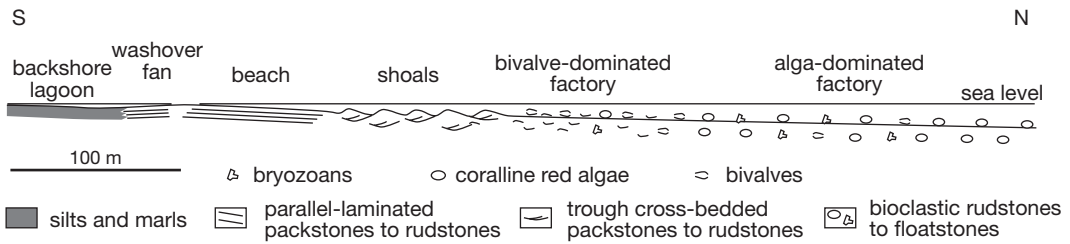


FIG. 5. — Depositional model of the southern margin of the Carboneras Basin during the highstand stage. The rhodolith bed developed in the outer shelf (modified from Braga *et al.* 2003).

At the northern and western margins, the upper subunit mainly consists of siliciclastics (Fig. 3). Locally, at the western margin, barnacle pavements are associated with conglomerates and mixed carbonate-siliciclastic deposits (Aguirre *et al.* 2008). At the southern margin, however, the upper subunit mostly comprises gently dipping and basinward-prograding bioclastic carbonate beds (Fig. 3). These sediments accumulated on a gentle ramp (Fig. 5) in facies belts trending N60-70. Backshore and beach siliciclastic and bioclastic deposits overlie and laterally grade northwards to a trough cross-bedded rudstone, which in turn interfingers and progrades over a coarse-grained floatstone interpreted as a “factory” facies. The factory facies formed in an area where most of the carbonate production on the ramp took place (Braga *et al.* 2003a). Molluscs and bryozoans dominated the shallower factory, whereas coralline algae were the most significant components in the deeper areas. A bed of rhodoliths from this facies, up to 4 m thick (Fig. 3), can be laterally followed for several tens of metres at the Cala de la Pelirroja section (Braga *et al.* 2003a; Martín *et al.* 2004).

CORALLINE ALGAL ASSEMBLAGES

This study focuses on the rhodolith beds at the top of the intermediate subunit at the northern and western margins (R1 and R2 beds, respectively), at the base of the strata in the leeside of the spit platform (LS bed) and in the upper subunit at the southern margin (R3 bed) (Fig. 3). The coralline-bryozoan-bivalve bio-

constructions in the distal ramp of the intermediate subunit on the western margin are also described.

RHODOLITH BEDS

The main characteristics of the rhodoliths in beds R1, R2, R3, and LS are described in Table 1. Rhodolith density is variable (30% to 60% of rock volume) and maximum diameter is 3-4 cm on average (rarely reaching 10 cm). Rhodoliths are mostly spheroidal, although ellipsoidal morphology can be locally abundant (Fig. 6).

Rhodoliths are dominated by coralline algae intergrown with bryozoans, encrusting benthic foraminifers, and serpulids. Occasionally, serpulids are equally or more abundant than corallines, forming serpulid nodules *sensu* Aguirre *et al.* (1993). The nuclei of the rhodoliths consist of fragments of bioclasts (bivalve, bryozoan, or another coralline alga) and rarely sediment. The dominant algal growth form is warty and fruticose, with minor laminar and encrusting forms (Table 1).

Algal assemblages are dominated by members of the subfamily Melobesioideae (family Hapalidiaceae), followed by representatives of the subfamily Lithophylloideae (Table 2; Fig. 7). Mastophoroideae are only minor components. Members of the family Sporolithaceae are very rare, accounting for a very small percentage of the algal constituents at the western margin of the basin (Fig. 7).

At the species level, the R3 bed of the southern margin is the most diversified (18 species), followed by the R2 bed of the western margin (16 species), whereas the LS and R1 beds are the least diversified (10 species). The relative abundance of species varies from bed to bed (Fig. 8). *Lithothamnion minervae*

TABLE 1. — Coralline algae in the rhodolith beds of the Carboneras Basin.

Rhodolith bed	Stratigraphic position	Rhodolith density	Rhodolith morphology	Algal growth form	Main algal components	Additional algal components
Northern margin (R1)	transgressive systems tract deposits	30%-40%	spheroidal-ellipsoidal	fruticose-warty	<i>L. minervae</i> Basso, 1995	<i>L. incrustans</i> - <i>L. racemus</i> , <i>P. calcareum</i> (Pallas) Adey & McKibbin, 1970
Western margin (R2)	transgressive systems tract deposits	30%	spheroidal-ellipsoidal	warty-fruticose	<i>L. philippii</i> Foslie, 1909 <i>L. minervae</i> <i>M. alternans</i> (Foslie) Mendoza & Cabioch, 1998 <i>L. incrustans</i> Philippi, 1837- <i>L. racemus</i> (Lamarck) Foslie, 1901	<i>L. ramosissimum</i> (Reuss) Piller, 1994 <i>M. lichenoides</i> (Ellis) Lemoine, 1928
Southern margin (LS)	transgressive systems tract deposits	50%-60%	spheroidal	encrusting-warty	<i>L. minervae</i> <i>L. incrustans</i> - <i>L. racemus</i>	<i>M. alternans</i> <i>Lithophyllum dentatum</i> (Kützing) Foslie, 1900 <i>L. coralloides</i> (P. & H. Crouan) P. & H. Crouan, 1867
Southern margin (R3)	highstand systems tract deposits	20%	spheroidal	warty-fruticose	<i>L. sonderi</i> Hauck, 1883 <i>L. incrustans</i> - <i>L. racemus</i> <i>M. alternans</i>	<i>M. macroblastum</i> (Foslie) Adey, 1970 <i>L. minervae</i> <i>P. calcareum</i> <i>L. philippii</i>

Basso, 1995 is the most common species in the R1 bed, but in the LS bed it is rivalled in abundance by *Lithophyllum incrustans* Philippi, 1837-*L. racemus* (Lamarck) Foslie, 1901. *Lithothamnion philippii* Foslie, 1909 dominates the R2 bed, followed by *Mesophyllum alternans* (Foslie) Mendoza & Cabioch, 1998 and *L. incrustans*-*L. racemus*. *Lithothamnion minervae*, *L. incrustans*-*L. racemus*, and *M. alternans* are equally abundant in the R3 bed of the southern margin (Fig. 9A-D). The rest of the species in the R2 and R3 beds of the western and southern margins are evenly represented (Fig. 8). Among melobesioids, the extinct species *Lithothamnion ramosissimum* (Reuss) Piller, 1994 (Fig. 9E, F) is relatively abundant in the western and northern margins.

CORALLINE ALGAL-BRYOZOAN-BIVALVE BUILDUPS

The bioconstructions are embedded in a fine-grained calcarenite matrix (Fig. 10). The major builders are robust and delicate branching colonies of bryozoans. Foliose colonies can locally occur. Coralline algae are the second most abundant

component, encrusting the bryozoan colonies intergrown with serpulids and encrusting benthic foraminifers. Coralline algae occur as thin encrusting thalli forming crusts several millimetres thick, locally with small protuberances or warty growth forms. Coralline crusts bind bryozoan colonies and other bioclastic particles, producing a stable hard substrate for the settlement of byssate (*Chlamys*) and cemented (*Spondylus*) bivalves. Occasionally, vermetid gastropods are very important components in these bioconstructions. Voids in the resulting open framework are filled with fine-grained bioclastic sediment. The algal assemblages of the buildups are dominated by melobesioids, with *Lithothamnion philippii* and *Mesophyllum lichenoides* (Ellis) Lemoine, 1928 being almost the only representatives. Unidentifiable, very thin laminar thalli accompany these melobesioids. *Chlamys* occurs as disarticulated complete valves, and *Spondylus* shells are articulated and in the original growth position, attached to the hard substrate provided by the bryozoans and coralline algae. In-situ articulated shells of

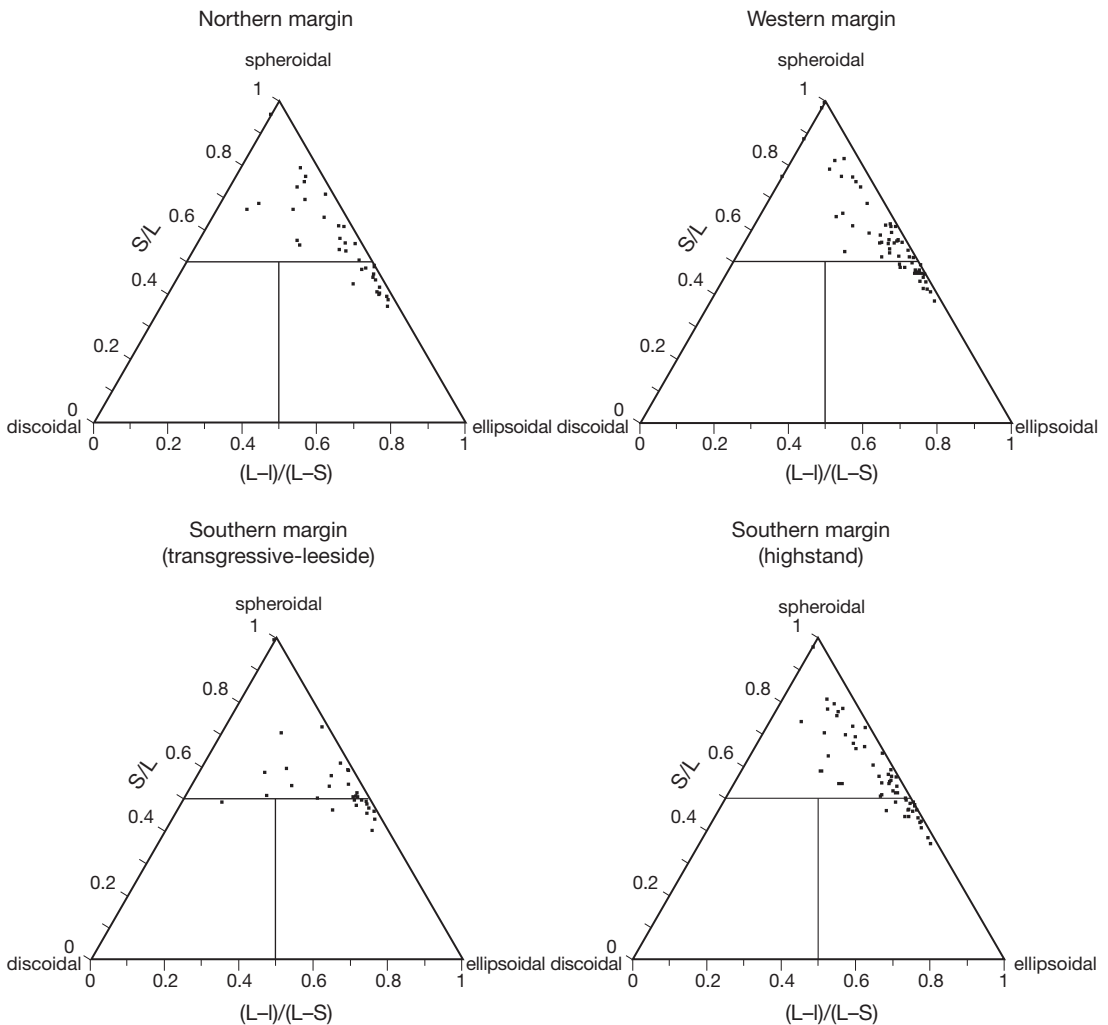


FIG. 6. — Ternary diagrams representing rhodolith morphology in the rhodolith beds.

Spondylus are also preserved in the surrounding sediment. Rare articulated brachiopods, fragments of echinoids, and complete isolated ahermatypic corals are minor components of the buildups.

The buildups developed either as vertically elongated pillars (up to 90 cm high and 40 cm wide) (Fig. 10A) or as patches (up to 2 m high and 7 m wide). The former are isolated, about half a metre apart from one another. The patches are flat or irregular in shape and are isolated or interconnected to form larger structures (Fig. 10B, C).

DISCUSSION

PALAEOENVIRONMENTAL INTERPRETATION *Rhodolith beds*

The different platform geometries along the palaeomargins of the Carboneras Basin during deposition of the transgressive systems tract of the Lower Pliocene sequence were controlled by local hydrodynamics and palaeotopography (Braga *et al.* 2003a; Martín *et al.* 2004) (Fig. 2A). The northern palaeomargin was influenced by strong

TABLE 2. — Coralline algal abundance (in percentages) in the rhodolith beds of the Carboneras Basin. Abbreviations: **R1**, northern margin; **R2**, western margin; **LS**, southern margin (leeside); **R3**, southern margin (highstand).

	R1	R2	LS	R3
<i>Lithothamnion corallioides</i> (P. & H. Crouan) P. & H. Crouan, 1867			7.8	
<i>Lithothamnion minervae</i> Basso, 1995	37.0	14.8	22.1	6.6
<i>Lithothamnion philippii</i> Foslie, 1909		20.8	5.1	5.5
<i>Lithothamnion ramosissimum</i> (Reuss) Piller, 1994	6.8	7.7		4.7
<i>Lithothamnion sonderi</i> Hauck, 1883		0.2		13.2
<i>Lithothamnion valens</i> Foslie, 1909		3.1		
<i>Mesophyllum alternans</i> (Foslie) Mendoza & Cabioch, 1998	2.1	13.8	14.1	11.8
<i>Mesophyllum lichenoides</i> (Ellis) Lemoine, 1928	3.8	10.2	5.8	4.1
<i>Mesophyllum macroblastum</i> (Foslie) Adey, 1970				7.8
<i>Mesophyllum</i> sp.		0.4	4.0	3.6
<i>Phymatolithon calcareum</i> (Pallas) Adey & McKibbin, 1970	11.2	0.4		5.5
<i>Phymatolithon lenormandii</i> (Areschoug) Adey, 1966				1.6
<i>Lithophyllum dentatum</i> (Kützing) Foslie, 1900		4.8	12.5	0.2
<i>L. incrustans</i> Philippi, 1837- <i>L. racemus</i> (Lamarck) Foslie, 1901	12.5	12.5	20.9	13.8
<i>Lithophyllum orbiculatum</i> (Foslie) Foslie, 1900				1.2
<i>Lithophyllum pustulatum</i> (Lamouroux) Foslie, 1904	2.1	1.0	1.0	1.5
<i>Lithophyllum</i> sp.	0.3	2.9		3.8
<i>Neogoniolithon brassica-florida</i> (Harvey) Setchell & Manon, 1943		1.9	5.1	1.4
<i>Spongites decipiens</i> (Foslie) Chamberlain, 1993	1.9			1.7
<i>Spongites fruticulosus</i> Kützing, 1841	5.0	1.4		1.6
<i>Sporolithon ptychoides</i> Heydrich, 1897		1.3		
unidentifiable	17.3	2.8	1.6	10.4

southeasterly storms (deflected western storms), which disrupted part of the southern-facing outer- and edge-platform settings, reworking the material into the slope to produce tempestite beds. The western palaeomargin was protected from major hydrodynamic disturbances and became the locus of development of a gently eastward-deepening ramp. During the transgressive stage, sediment transported by longshore drift accumulated behind the cape at the southeastern end of the basin to form a spit-platform (Fig. 2A). This spit-platform was subsequently affected by eastern storms and the sediment removed accumulated on its landward slope. During the highstand stage, a gentle ramp extended into the sea at the southern margin of the basin (Fig. 5).

Coralline algae were significant components throughout the Pliocene succession in the Carboneras Basin, mainly in the transgressive deposits, occurring as isolated branches or fragments dispersed in the sediment as well as forming rhodoliths and buildups of variable sizes. However, rhodolith concentrations occur in particular subenvironments (Martín *et al.* 2004): at the shelf edge at

the northern margin, in the mid-outer ramp at the western margin, and in the lee of the spit-platform at the southern margin, in the transgressive stage, and at the mid-to-outer ramp in the highstand stage (Figs 4; 5).

Analysis of the stratal geometries, post depositional tilting of the Pliocene rocks, and present-day differences in elevation between rhodolith beds and coeval shore deposits suggest that rhodolith growth and concentration took place at palaeodepths of several tens of metres, probably shallower than 50 m (Martín *et al.* 2004). The dominance of members of the subfamily Melobesioideae in the rhodolith algal assemblages is in accordance with this interpretation. The most abundant melobesoid species are *Lithothamnion minervae*, *L. philippii*, and *Mesophyllum alternans*, commonly found in fairly deep waters in the modern Mediterranean (Basso 1998; Bressan & Babini 2003; Toscano *et al.* 2006; Braga & Aguirre 2009). *Phymatolithon calcareum* (Pallas) Adey & McKibbin, 1970 and *Mesophyllum macroblastum* (Foslie) Adey, 1970 are relatively important taxa in the rhodolith beds of the northern and southern margins, respectively.

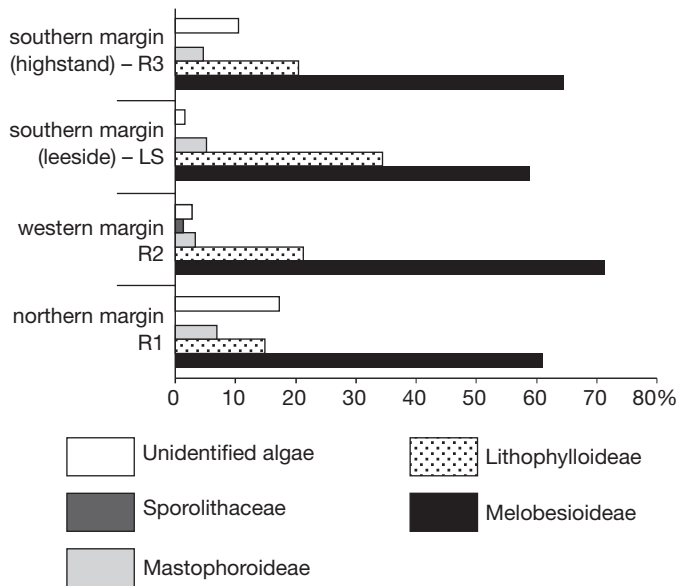


FIG. 7. — Abundance, in percentages, of family and subfamily constituents of the rhodoliths in the studied beds.

P. calcareum is one of the major components of the rhodolith-rich lithofacies in the southern Balearic platform at 35-100 m depth (Fornós & Ahr 2006), in the central Tyrrhenian Sea at 25-100 m (greatest abundance at 60-70 m) (Basso 1998), in the Gulf of Naples at 35-40 m (Toscano *et al.* 2006). Off the Cabo de Gata area, in the vicinity of the Carboneras Basin, *P. calcareum* occurs between 20 and 60 m, but flourishes below 40 m (Braga & Aguirre 2009). *Mesophyllum macroblastum* is recorded at the same depths (Braga & Aguirre 2009), similar to its depth range (30-40 m) in Corsica (Cabioch & Mendoza 2003).

Members of the subfamily Lithophylloideae have a wide range of water-depth distribution; however, the group peaks in shallow to intermediate depths off Cabo de Gata (Braga & Aguirre 2009). In the present study, lithophylloids are minor components of the algal assemblages except in the LS beds of the southern palaeomargin, where they are moderately represented (Fig. 7). A comparison of the elevation of the LS beds with the laterally equivalent trough cross-bedded calcarenites at the top of the spit-platform gives a depositional depth of rhodolith growth of about

20-25 m. This shallower, proximal position might account for the relative increase in the lithophylloid representation. The dominant lithophylloid species in the Pliocene deposits of the Carboneras Basin is *Lithophyllum incrustans*-*L. racemus* species complex. *Lithophyllum dentatum* (Kützing) Foslíe, 1900, which is a relatively shallow-water alga (Braga & Aguirre 2009), can also be locally important in the LS beds.

Mastophoroids are scarcely represented in these algal assemblages, in accordance with the characteristic scarcity of representatives of the subfamily in temperate carbonates from the Neogene basins in southern Spain (Braga & Aguirre 2001). *Neogoniolithon brassica-florida* (Harvey) Setchell & Mason, 1943, a shallow-water representative of the subfamily, reaches its maximum in the LS rhodolith beds (Fig. 8). As commented above, these beds were deposited in the shallowest and most proximal settings. It is also worth mentioning the presence of plants with features typical of *Spongites decipiens* (Foslíe) Chamberlain, 1993 (Fig. 9G), a species recorded in California, Mexico, India, south Argentina, the Malvinas Islands, and South Africa (e.g., Chamberlain 1993; Silva *et al.* 1996;

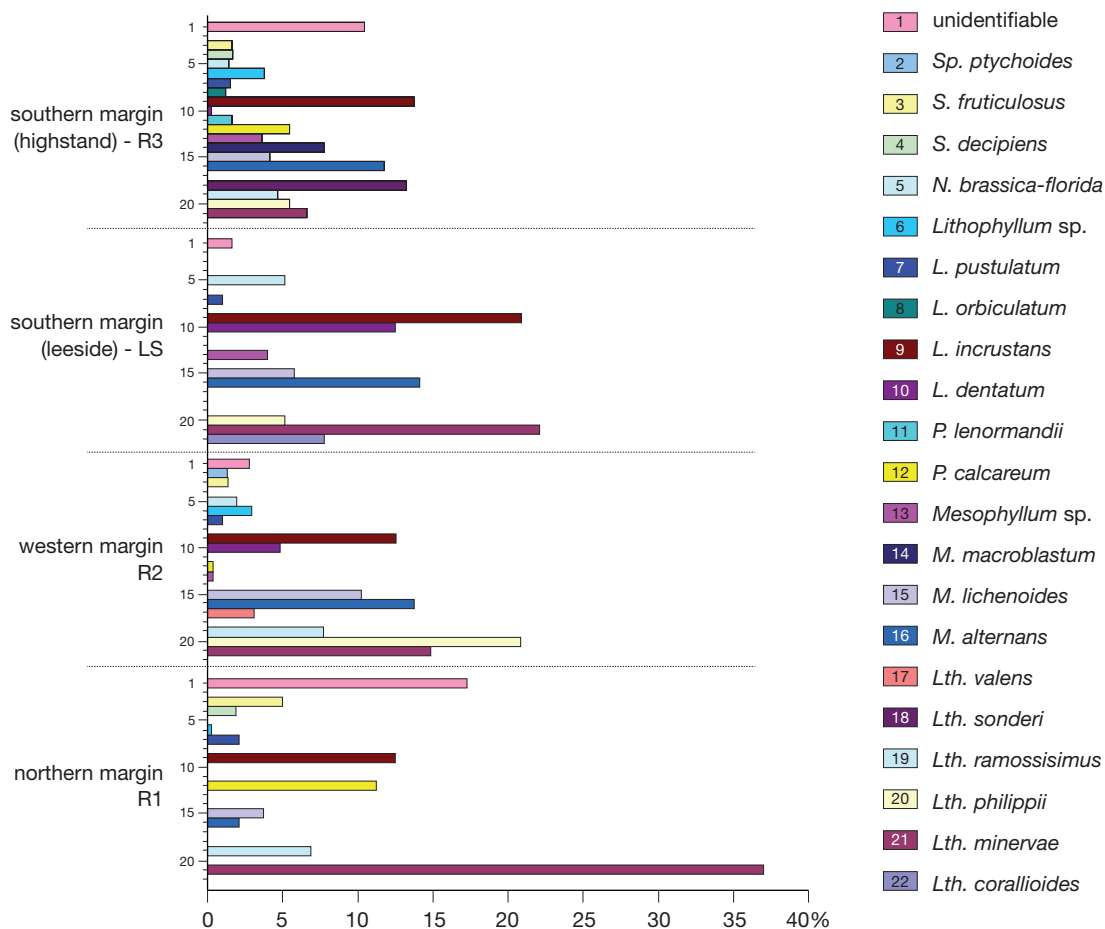


FIG. 8. — Abundance, in percentages, of constituent species of the rhodoliths in the studied beds. Abbreviations: L., *Lithophyllum*; Lth., *Lithothamnion*; M., *Mesophyllum*; N., *Neogoniolithon*; P., *Phymatolithon*; S., *Spongites*; Sp., *Sporolithon*.

Mateo-Cid et al. 2000; Frago & Rodríguez 2002), but never in the Mediterranean.

Sporolithon ptychoides is the only sporolithacean species identified in the Carboneras Basin (Fig. 9H); it is anecdotal in the rhodoliths of the western margin and a few fragments of this species have also been found dispersed in the carbonate matrix. The genus *Sporolithon* is mostly tropical and subtropical, but *S. ptychoides* occurs in the present-day Mediterranean (Hamel & Lemoine 1952; Alongi et al. 1996; Bressan & Babini 2003), as well as in fossil temperate carbonate deposits (Braga & Aguirre 2001; Bassi et al. 2006; Braga & Bassi 2007).

Coralline bioconstructions

Coralline algal-bryozoan-bivalve buildups developed in the distal ramp of the sheltered western margin (Fig. 4B). The major coralline algal builders are *Lithothamnion philippii* and *Mesophyllum lichenoides*. The distal isolated pillars show similarities with columnar structures, rising up to 1 m from the seafloor, described by Di Geronimo et al. (2001, 2002) at about 30 m depth off Marzamemi in SE Sicily. These bioconstructions are made up of an open framework of algae and invertebrates with pores filled by internal bioclastic sediment. In contrast to the pillars in Carboneras, the Sicilian buildups mainly comprise coralline algae with subordinate

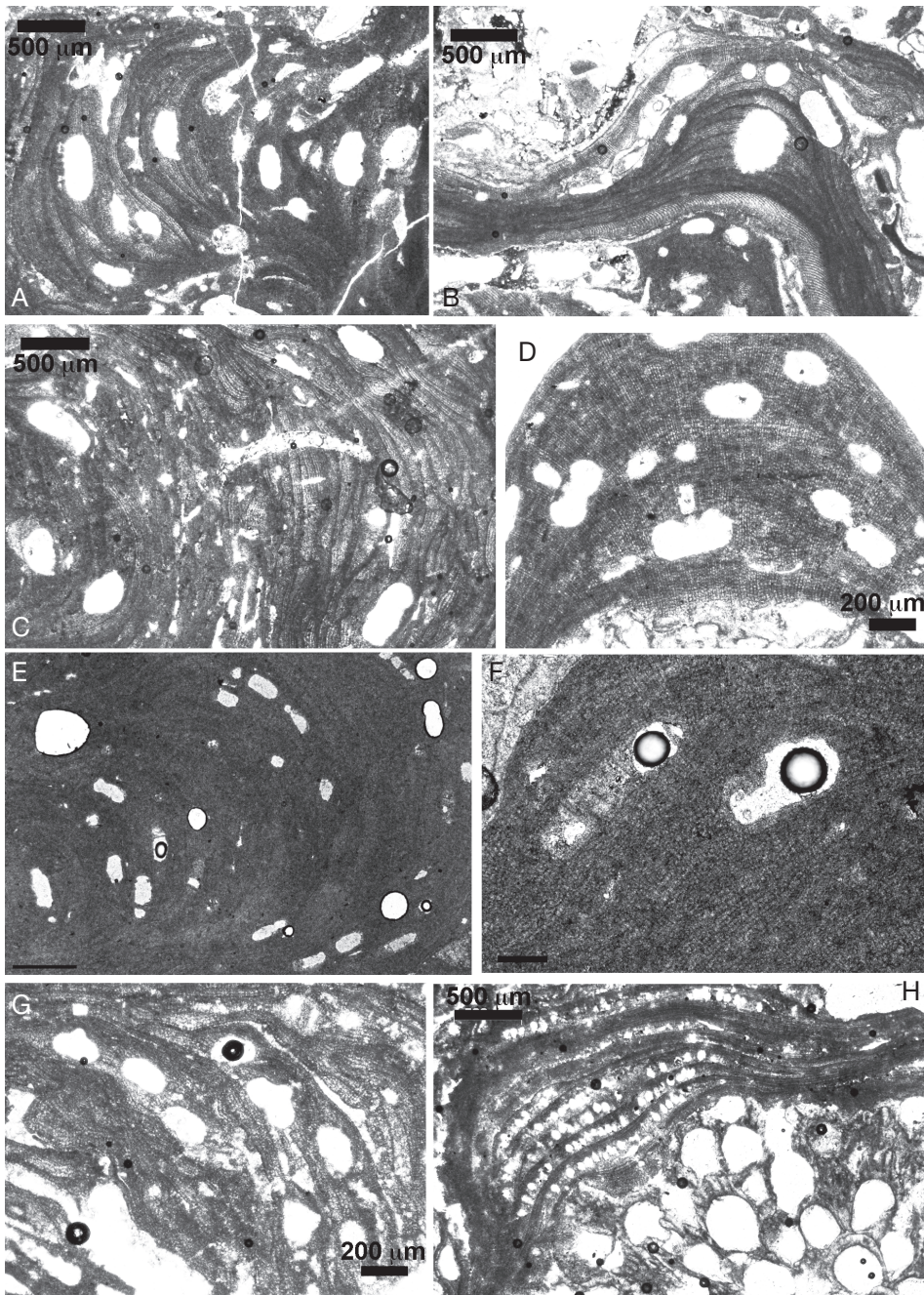


FIG. 9. — Thin section photographs in parallel light of some of the most abundant algal species: **A**, *Lithothamnion minervae* Basso, 1995 (R1 bed, northern margin); **B**, *Mesophyllum alternans* (Foslie) Mendoza & Cabioch, 1998 (LS bed, southern margin); **C**, *Lithothamnion philippii* Foslie, 1909 (R2 bed, western margin); **D**, *Lithophyllum incrustans* Philippi, 1837-*L. racemus* (Lamarck) Foslie, 1901 species complex (R3 bed, southern margin); **E**, *Lithothamnion ramosissimum* (Reuss) Piller, 1994 (R1 bed, northern margin); **F**, *Lithothamnion ramosissimum* (R1 bed, northern margin); **G**, *Spongites decipiens* (Foslie) Chamberlain, 1993 (LS bed, southern margin); **H**, *Sporolithon Ptychoides* Heydrich, 1897 (R2 bed, western margin). Scale bars: E, 500 μm ; F, 100 μm .

serpulids, vermetids, bryozoans, encrusting foraminifers, byssate bivalves, and brachiopods. The algal assemblage includes four species and a variety of growth forms, from foliose to fruticose. According to Di Geronimo *et al.* (2001, 2002), the columnar structures in Sicily locally coalesce to form ridges separated by channels. Coalescence of small pillars and irregular patches seems to be the origin of the largest coralline algal-bryozoan-bivalve buildups in Carboneras, but no recent or fossil analogue matches the features of these bioconstructions. The Mediterranean buildups referred to as “coralligènes de plateau” are also characterized by dominant lateral growth of low relief structures that extend for tens to hundreds of metres. In these bioconstructions, however, coralline algae are markedly the main components, with only subordinate invertebrates (Pères & Picard 1964; Bosence 1985b; Gili & Ros 1985; Ros *et al.* 1985; Nalin *et al.* 2006; Basso *et al.* 2007; Titschack *et al.* 2008).

Both the “coralligènes de plateau” and the Sicilian pillars form positive reliefs on the seafloor and are surrounded by coarse bioclastic sediment partially derived from the framework. In our study case, however, there are no indications suggesting that the bioconstructions created significant positive relief when they were growing. Instead, they seem to have grown at or close to the sediment-water interface. A positive relief would have caused the formation of steep or vertical walls. However, the laminar growths of the coralline algae and bryozoans are in horizontal continuity with the sediment. Furthermore, no debris derived from the framework is observed in the periphery of the buildups, which instead are surrounded by fine-grained sediment.

Even with a low relief hardly protruding from the seafloor, these bioconstructions offered a hard substrate amongst fine-grained loose sediment, attracting sessile organisms with rigid calcareous skeletons, which maintained the growth of buildups in pace with sediment accumulation.

SEQUENCE STRATIGRAPHIC CONTEXT OF THE RHODOLITH BEDS

Rhodolith beds are not randomly distributed in the Lower Pliocene successions of the Carboneras Basin, as most developed during the transgressive stage.

As in other Neogene Mediterranean-linked basins of southeastern Spain, most rhodolith factory facies occur seawards of shoal facies (Braga *et al.* 2006), in relatively low-energy areas with low sedimentation rates. Rhodolith growth is favoured by moderate hydrodynamic conditions, which guarantee relatively stable substrates for algal attachment and growth in the absence of continuous disturbances (Bosence 1983b; Steller & Foster 1995; Harvey & Bird 2008; Peña & Bárbara 2008, 2009; Steller *et al.* 2009). In such contexts, the activity of vagrant benthic organisms would promote the displacement and overturning of rhodoliths (Prager & Ginsburg 1989; Marrack 1999), favouring their growth in all directions. Furthermore, moderate water energy ensures that the fine-grained particles are washed out, promoting the development of healthy rhodolith beds (Steller *et al.* 2009). A low sedimentation rate enables rhodoliths to grow for long periods of time in clean waters. The negative effect of siliciclastics inhibiting the development of rhodolith beds has been shown in the eastern and western platforms of the Atlantic Ocean (Milliman 1977). Sediment input also muddies the water column, causing suspended particles to reduce light penetration and thereby further inhibiting rhodolith growth (Adey & MacIntyre 1973; Bosence 1983b; Steller *et al.* 2009). Experiments on the response of rhodoliths to burial have demonstrated that corallines are very sensitive to burial and are killed off very rapidly, within just months (Figueiredo *et al.* 2009).

During transgressions, the fair-weather wave-base migrates landwards and low-energy areas spread out on the platform, benefitting rhodolith growth and the net accumulation of rhodoliths. Progressive sea-level rising promoted an increase in accommodation space, enough to support rhodolith growth and accumulation for longer periods of time, the “catch-up” regimen of Pedley & Grasso (2006), favouring the development of thick rhodolith beds. The formation of thick rhodolith beds has been proposed as an indicative feature for transgressive deposits (Friebe 1993; Nalin *et al.* 2008).

The isolation of the Carboneras Basin from siliciclastic influx during the transgressive stage promoted rhodolith formation and accumulation. At the end of the transgression and during the highstand stage, the

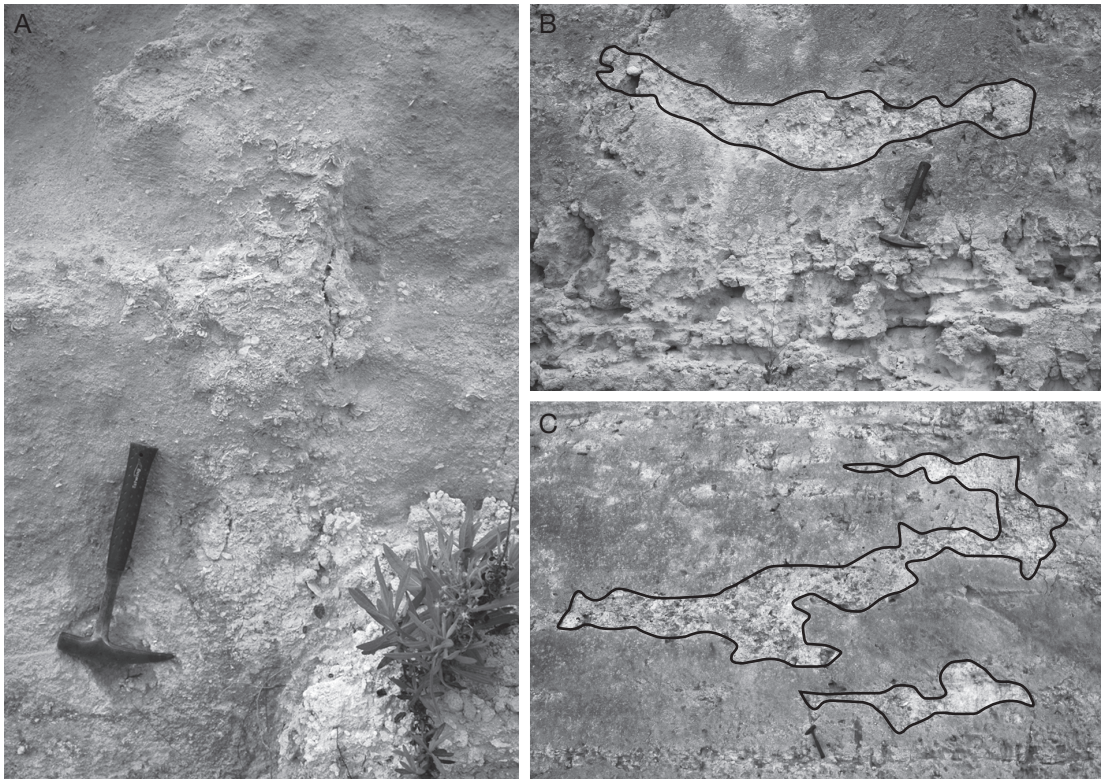


FIG. 10. — Field views of the bryozoan-coralline-bivalve builds of the western margin: **A**, pillar builds; **B**, irregular isolated patches (outlined); **C**, irregular interconnected patches (outlined). The whitish patches at the upper part of the photo are also irregular interconnected builds. Hammer for scale: 32.5 cm in length.

Carboneras Basin was connected with the neighbouring Almería-Níjar Basin, and terrigenous delta sediments entered the basin (Braga *et al.* 2003b; Martín *et al.* 2003, 2004; Aguirre *et al.* 2008). The initiation of terrigenous sedimentation switched off carbonate production as well as rhodolith accumulation except for the southeastern margin, the area most distant from the terrigenous source at the northwestern shore of the basin. As the required conditions for profuse rhodolith growth were maintained seawards of shoals in that particular area, a thick rhodolith bed accumulated during the highstand stage. Progradation of shallower deposits displaced the area of maximum production of rhodoliths basinwards to the north (Braga *et al.* 2003a), but their growth only stopped when the entire carbonate factory was shut down, probably by relative sea-level fall and emersion.

In summary, the conditions promoting rhodolith beds in the Pliocene of the Carboneras Basin were preferentially achieved during transgression as seems to be common in modern and fossil examples (Nalin *et al.* 2008), but environments favourable for their growth locally persisted in reduced areas of the basin during the subsequent highstand stage.

CONCLUSIONS

Coralline algae are major components of the lower Pliocene deposits of the Carboneras Basin (SE Spain). These deposits can be divided into three subunits, which have been interpreted as the lowstand, transgressive, and highstand systems tract deposits of a stratigraphic sequence (Martín *et al.* 2004).

Thick rhodolith concentrations (rhodolith beds) occur in the transgressive intermediate subunit in middle-to-outer ramp deposits at the northern and western margins, and at the base of the strata on the leeside of a spit-platform at the southern margin of the basin. A thick rhodolith bed also occurs in the highstand upper subunit at the southern margin.

The stratal geometries and relative elevation of rhodolith beds in relation to shore deposits indicate that rhodolith growth and concentration took place at water depths of several tens of metres. These depth estimates are consistent with the dominance in the coralline algal assemblages of the melobesiods *Lithothamnion minervae*, *L. philippii*, and *Mesophyllum alternans*, which are common in relatively deep platform settings in the modern Mediterranean. Subordinate species are *Phymatolithon calcareum* and *M. macroblastum* and the lithophylloids of the *Lithophyllum incrustans*-*L. racemus* species complex.

Moderate energy and low sedimentation rates favoured the widespread development of rhodolith beds in the transgressive intermediate subunit. However, rhodoliths continued to accumulate during the highstand in the mid-ramp setting at the southern margin of the basin. Here, similar conditions of moderate turbulence and sedimentation rate continued to prevail far from the terrigenous influx that hindered carbonate production in the rest of the basin. Therefore, the example of the Carboneras Basin shows how rhodolith beds can be common in but are not exclusive to transgressive systems tracts.

Coralline algal-bryozoan-bivalve bioconstructions occur in outer-shelf settings within the transgressive systems tract deposits. They are either isolated pillars (up to 90 cm high and 40 cm wide) or irregular patches (up to 2 m high and 7 m wide) locally interconnected to form larger structures. *Lithothamnion philippii* and *M. lichenoides* are the main corallines in these bioconstructions. These structures show morphological similarities to pillars and low-relief buildups constructed by coralline algae ("coralligène de plateau") reported from the present-day Mediterranean Sea. However, the Pliocene buildups in the Carboneras Basin differ from these known modern bioconstructions in the secondary role of corallines as builders and the ab-

sence of surrounding bioclastic debris derived from the buildups indicative of substantial positive relief on the seafloor.

All the identified corallines belong to species living today in the waters off the Carboneras Basin except for the extinct *Lithothamnion ramosissimum* and for plants attributable to *Spongites decipiens*, which has been recorded in the Indo-Pacific and the southern Atlantic but is unknown in the Mediterranean Sea.

Acknowledgements

We thank R. Nalin, D. Basso and V. Malécot for their helpful comments that have improved the manuscript. This manuscript is part of the research projects CGL2010-20857 and Topo-Iberia Consolidar Ingenio 2006 (CSD 2006-00041), both funded by Ministerio de Ciencia e Innovación (Spanish government), and the project RNM-190 of the Junta de Andalucía. We are grateful to Christine Laurin for correcting the English text.

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*Submitted on 9 May 2011;
accepted on 7 December 2011.*