BIVALVES IN THE UPPER MIOCENE REEF COMPLEX OF MALLORCA, SPAIN

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ABSTRACT

Bivalves are common components in all the palaeoenvironments recognised in the Llucmajor Platform, the best-known outcrop of the Upper Miocene Mallorca Reef Complex. Shell concentrations of autochthonous elements with a low degree of taphonomical modification accumulated on the deep, quiet water bottoms from the basin to proximal reef slope. Low sedimentation presumably enhanced shell concentration as well as the development of clusters of superimposed slow-growing organisms, such as *Neopycnodonte* oysters that are typical of the basin and distal slope settings. Debris-flow beds of mostly disarticulated, fragmented and reoriented moulds of valves intercalate with the autochthonous shell concentrations in the basin and slope deposits as the result of downslope transport of bioclasts from shallower reef areas. Bivalve assemblages in the shallower-water reef palaeonvironments mainly consist of moulds of reworked fragments of disarticulated valves. Some crevice-dwellers, cemented and epibyssate forms were preserved in life position in the shelters created by coral colonies and blocks. The percentage of unbroken and articulated shallow endosedimentary bivalves is higher towards the protected inner-lagoon settings, in which *Tellina* specimens are the most characteristic components. We have identified 52 bivalve species belonging to 38 genera and recorded 19 additional species only identifiable at the generic level in all the sampled reef palaeonvironments. This species number is greater than in other western Mediterranean Upper Miocene reefs studied in detail but is relatively low with respect to common figures in modern reefs, probably as the result of the marginal location of the western Mediterranean reefs in relation to the Upper Miocene reef belt. Most of the recorded species are still extant in the eastern Atlantic and Mediterranean while only a few are restricted to modern tropics or became extinct at the end of the Miocene when coral reefs disappeared from the Mediterranean.

Keywords: Bivalves, reef, Upper Miocene, Mallorca, Mediterranean.

RESUMEN

Los restos de bivalvos son comunes en todos los ambientes sedimentarios de la Plataforma de Llucmajor, el afloramiento mejor conocido del Complejo Arrecifal Mioceno de Mallorca. En los fondos profundos y sin turbulencia de la cuenca al talud proximal se acumularon conchas autóctonas con un grado bajo de modificación tafonómica. La baja tasa de sedimentación facilitó la concentración de conchas y el desarrollo de agregados de organismos de crecimiento lento, como los ostreidos del género *Neopycnodonte*, que son típicos de medios de talud distal y cuenca. Capas de flujos de derrubios de valvas, actualmente conservadas como moldes, mayoritariamente desarticuladas, fragmentadas y reorientadas, se intercalan entre las concentraciones autóctonas en los depósitos de cuenca y talud, como resultado del transporte pendiente abajo de bioclastos procedentes de áreas más someras del arrecife. Las asociaciones de bivalvos en los paleoambientes someros del arrecife consisten fundamentalmente en moldes de fragmentos resedimentados de valvas desarticuladas. Algunos bivalvos que vivían en ranuras, o cementados, o epibisados se han conservado en posición de vida en los recovecos de las colonias o los bloques de coral. El porcentaje de conchas intactas y articuladas de formas infáunicas someras crece hacia los ambientes protegidos de lagoon interno, donde *Tellina* es el género más característico. Entre todos los paleoambientes arrecifales hemos identificado 52 especies de bivalvos, pertenecientes a 38 géneros, y registrado 19 especies más que sólo hemos podido determinar a nivel genérico.

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Este número de especies es mayor que el de otros arrecifes del Mioceno Superior del Mediterráneo Occidental estudiados en detalle, pero es relativamente pequeño si se compara con la riqueza de especies en arrecifes de coral actuales, probablemente como resultado de la situación marginal de los arrecifes mediterráneos con respecto al cinturón tropical del Mioceno Superior. La mayor parte de las especies de bivalvos identificadas siguen viviendo en el Atlántico oriental y en el Mediterráneo, mientras que sólo unas pocas están restringidas a los trópicos o se extinguieron al final del Mioceno, cuando los arrecifes de coral desaparecieron del Mediterráneo y este mar alcanzó su carácter templado actual.

Palabras clave: Bivalvos, arrecifes, Mioceno Superior, Mallorca, Mediterráneo.

INTRODUCTION

The Reef Complex is an upper Tortonian-lower Messinian sedimentary unit which crops out on most Balearic islands (Mallorca, Menorca, Ibiza, and Formentera) (Pomar *et al.,* 1996). In Mallorca, this unit overlies the Tortonian Heterostegina Calcisiltites Unit and is itself unconformably capped by different deposits, probably Messinian in age: the Bonanova Marls, Santanyí Limestones (Fornós and Pomar, 1984), and Gypsum and Grey Marls of the Palma Basin (Pomar *et al.,* 1996). Depositional facies of the Reef Complex on Mallorca have been described in detail (Pomar, 1988, 1991) and their distribution (Figs. 1 and 2) is known both from sea-cliff exposures and borehole data (Pomar and Ward, 1995). Bivalves are conspicuous components in all lithofacies and their occurrence has been reported in previous papers dealing with the stratigraphical and sedimentological features of the reef system. This paper describes in detail the bivalve assemblages and their distribution in the already well-characterised palaeoenvironments of the Llucmajor Platform reef, the best exposed and known portion of the Mallorca Reef Complex.

STRATIGRAPHIC ARCHITECTURE OF THE LLUCMAJOR PLATFORM REEF COMPLEX

The Reef Complex consists of several lithofacies characteristic of depositional environments associated with the reef growth: off-reef basin, forereef slope, reef, and back-reef lagoon (Fig. 3). These lithofacies units are defined based on lithology, components, and geometric relationships.

In the Llucmajor Platform reef, about 100 m thick, there is a general vertical succession from basin to reef-slope to reef-core to lagoonal lithofacies (Fig. 2). Within this simple vertical succession, however, there is a complicated stratigraphy, reflecting high-frequency oscillations in relative sea level (Fig. 2) (Pomar, 1988, 1991; Pomar and Ward, 1994, 1995). The oscillations in sea level produced the most characteristic facies relationship within the Llucmajor platform: progradation with upward and downward shifts of the reef-core and associated lithofacies. The basic building block of this carbonate complex is the "sigmoid" (Fig. 3), interpreted as the result of accretion and erosion during the highest-frequency relative sea-level cycle. This basic accretional unit fractally stacks in larger-scale accretional units: "sets", "cosets, and "megasets" of sigmoids, which reflect lower frequencies of sea-level oscillations with amplitudes on the order of less than 15 m, 20-30 m, 60-70 m, and about 100 m (Pomar, 1991). Preservation of the lagoon and upper reef-core facies depends on the amount of erosional truncation, controlled by the magnitude of the sea-level falls.

The reef progradation across 20 km of the Llucmajor Platform (Figs. 1 and 2) reflects a post-tectonic depositional setting characterised by a broad shallow carbonate platform, low terrigenous influx, and low rates of subsidence (Pomar, 1991).

Despite the good exposures of the Reef Complex on the sea-cliffs, it has not been possible to sample bivalve fossil assemblages in coeval lithofacies of a single sigmoid from basinal to reef-slope to reef-core to lagoon facies. In fact, accessibility of sampling sites and lithofacies outcrops in the successive reef progradation phases have limited the number of study localities. In the Vallgornera-Els Bancals area (Figs. 1 and 2), where the first phases of reef progradation crop out, we have sampled bivalve assemblages from pinnacle-reef, reef-crest and lagoon lithofacies. In the Ses Olles-Cala Carril area (Figs. 1 and 2), where later phases of the Reef Complex occur, we have studied assemblages from basin, slope and reef-core lithofacies. The Llucmjor Platform probably grew over a long period during the late Miocene (Pomar, 1991; Pomar *et al.,* 1996); thus, bivalve assemblages from the two areas might well be of significantly different ages in the late Tortonian-early Messinian interval.

METHODS

In most study localities bivalve remains, especially those from originally aragonitic shells, are preserved as coupled inner and outer moulds of articulated or disarticulated valves (Fig. 4). Even if the original valves are preserved, extraction is difficult due to strong cementation of the rock. This situation led us to sample by casting the moulds or valves with silicone-based impression material (PROVIL) directly on the outcrop. In addition, we have counted valve fragments and measured their size and orientation in 2 to 5 sample quadrats of 30 x 30 cm in each locality. The cementation of the remains prevents measuring their absolute size in many cases but the measurements can be used to estimate some taphonomical attributes of the bivalve assemblages: degree of disarticulation, fragmentation, sorting and reorientation.

REEF LITHOFACIES AND THEIR BIVALVE FOSSIL ASSEMBLAGES

VALLGORNERA - ELS BANCALS AREA

Pinnacle reefs: *Vallgornera*.- The oldest outcropping part of the reef complex, exposed between Torrent de Vallgornera and Cala Pi consists of pinnacles 10-12 m across and spaced several metres apart. Observable thickness above sea level is up to 8 m. They comprise massive and columnar colonies of *Tarbellastraea* and *Porites* up to 3 m in diameter and 1.5 m high, with minor *Siderastrea* heads. In some pinnacles, coral skeletons are encrusted with red algae and micritic microbial encrustations that are thicker at the top of the reef. Coarse grainstone between the coral colonies contains molluscs (bivalves and *Haliotis* gastropods are characteristic), red algae fragments, and crabs such as *Daira speciosa* (Reuss) (Pomar *et al.,* 1996). The inter-mound grainstone, locally channelised, is rich in mollusc fragments, red algae, crab shells and corals. Most of the reef rock in this area is calcitic, with only small dolomitised patches (Pomar *et al.,* 1996).

Bivalve shells are abundant in the crevices inside and between coral colonies with steeply oblique orientations predominanting. Up to 20% of shells are articulated and fragmentation is low (30%). Aragonitic shells have been completely dissolved and are fossilised as coupled inner and outer moulds. Calcitic shells suffered only partial dissolution. Cemented and epibyssate bivalves predominate in these sites: *Ostrea lamellosa* Brocchi, *Hyotissa hyotis* (Linné), *Chama gryphoides* Linné, *Spondylus* sp., *Lima lima* (Linné), *Chlamys linguafelis* (Almera and Bofill), *Chlamys pusio* (Linné), and *Barbatia barbata* (Linné).

Loosely packed, disarticulated and fragmented (60 to 100%) valves of these taxa concentrate together with coral and coralline algal fragments in discontinuous, channelized beds in the rudstones and grainstones overlying and surrounding the coral colonies and pinnacles. Valve orientation tends to be concordant (subparallel to bedding) or bipolar (subvertical and subparallel). Some endosedimentary forms such as *Lutraria* sp., *Clausinella* sp., and *Modiolus* sp. also occur in these rudstones and grainstones, together with the gastropods *Strombus* sp., *Oliva* sp., and *Cypraea* sp., and the sand dollar echinoid *Encope* sp. Articulated specimens of the oysters *Hyotissa hyotis* and *Ostrea lamellosa* appear in certain horizons cemented on coral fragments.

Taphonomical attributes and type of occurrence indicate that bivalve assemblages in this lithofacies consist of autochthonous elements preserved in life position on or between the coral colonies and of parautochthonous components accumulated in the sediment surrounding the colonies and reworked.

Reef Crest: *Els Bancals*.- The reef crest is well preserved at Els Bancals. It is composed of large colonies of *Porites* and *Tarbellastraea*, up to 1 m high and 2 m across, and small *Siderastrea* heads. Inter-coral bioclastic deposits are mostly dolomitised grainstones to wackestones rich in red algal fragments and rhodoliths, coral debris, molluscs, benthic foraminifers, and echinoids, sometimes filling 2-3 m wide channels perpendicular to the reef tract. Near the middle of the Els Bancals coast there is a 1-m-thick sheet of densely stacked large rhodoliths, up to 20 cm in diameter, deposited on a back-reef flat or in a broad reef-crest channel (Pomar *et al.,* 1996).

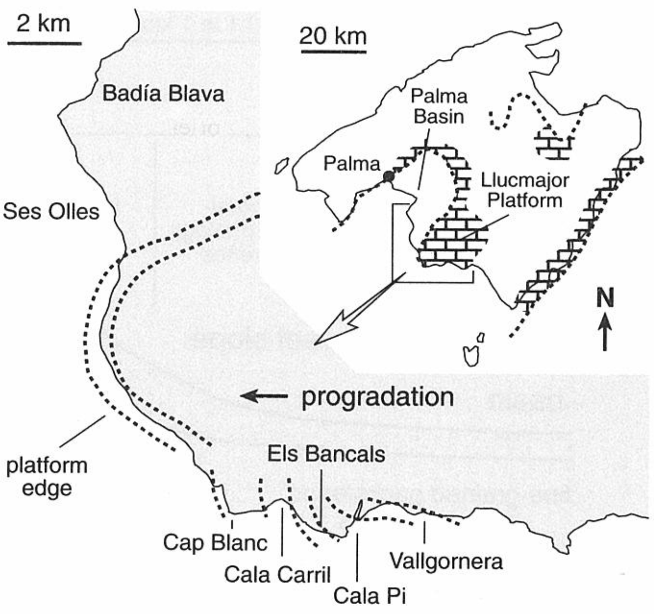

Figure 1. Distribution of the Llucmajor Platform (Upper Miocene Reef Complex Unit) in Mallorca and location of sampling localities. Successive positions of platform edge advanced westwards in the study area as the platform prograded in this direction (after Pomar *et al.,* 1996).

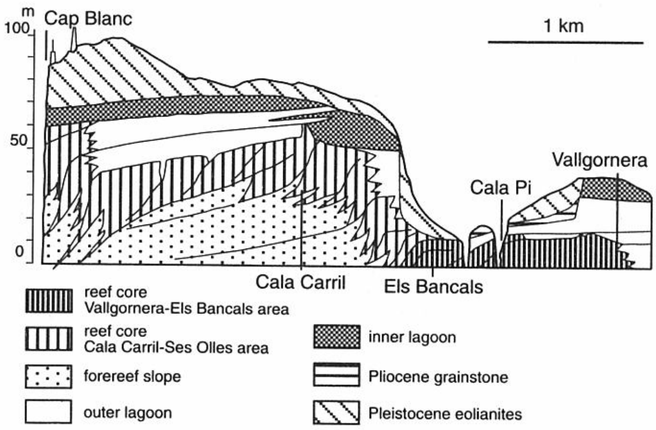

Figure 2. Study localities in a simplified composite section of the Reef Complex Unit from Vallgornera to Cap Blanc (projection lines approximately N225E). The stratigraphic architecture of the reef unit is made up of sigmoids (see Fig. 3) that stack in larger-scale accretional units. Oscillations in sea level produced progradation with upwards and downwards shifts of the reef-core and associated lithofacies (after Pomar *et al.,* 1996).

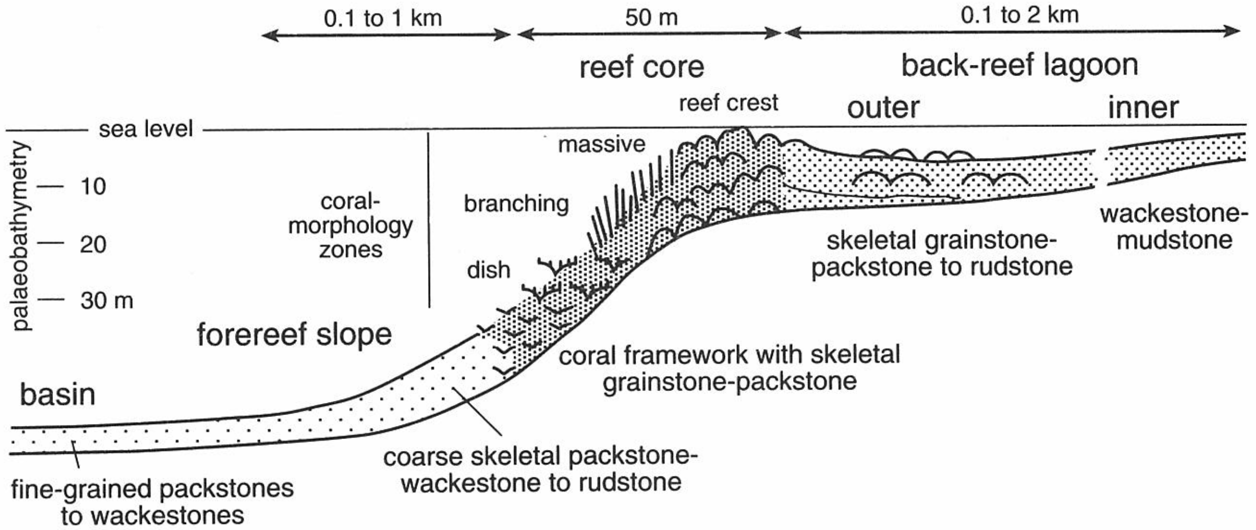

Figure 3. The basic accretional unit of the upper Miocene Mallorca reef (sigmoid) consists of several lithofacies characteristic of depositional palaeoenvironments: basin, forereef slope, reef, and back-reef lagoon (modified from Pomar *et al.*, 1996).

At this site, we have sampled in four beds separated by erosion surfaces. The lowest bed (1.5 m thick) consists of coral colonies embedded in calcirudites. Moulds of small fragments together with scarce whole valves concentrate in pockets around corals. Identifiable remains belong to *Barbatia barbata*, *Modiolus intermedius* (Foresti), *Chlamys linguafelis*, *Lima lima*, *Chama* sp. and cypreid and olivid gastropods.

The overlying bed is the above-mentioned sheet of large, densely stacked rhodoliths. Scarce moulds of whole and locally articulated valves, smaller than 30 mm, of *Dosinia lupinus* (Linné), *Glycymeris insubrica* (Brocchi), *Venus multilamella* (Lamarck) and *Strombus* sp. are dispersed among the algal nodules.

Scattered fragments of *Ostrea lamellosa*, *C. linguafelis*, *L. lima* and *Spondylus* sp., together with *Clypeaster* sp., occur in the bioclastic calcarenites and calcirudites in the third bed.

The upper bed is made up of *Tarbellastraea* colonies surrounded by bioclastic sediment with small (less than 45 mm), dispersed, disarticulated and fragmented valves *of C. linguafelis*, *C. pusio*, *L. lima*, *Acar clathrata* (Defrance), *Arca noae* Linné, *Cardita aculeata* (Poli), *Spondylus gaederopus* Linné, *Chama gryphoides* and *Dosinia* sp., together with moulds of *Haliotis* and conid gastropods and fragments of *Schizaster* and cidarids. This latter bed is overlain by rhodolith-bearing calcarenites with no identifiable bivalve remains.

The bivalve assemblages in this lithofacies consist of reworked valves of epibyssates, cemented and crevice-dwellers concentrated in the bioclastic sediment around the coral colonies, and some endosedimentary forms sometimes preserved *in situ*.

Lagoon: The reef rocks are overlain by and interfinger landwards with flat-lying lagoon lithofacies. The thickness and extent of the lagoon units are unequal, depending on the relative sea-level changes that controlled each reef-building episode. Lagoons were wide during sea-level rises and reef aggradation, but narrow or non-existent during falling sea level and reef offlapping. Maximum thickness of lagoonal lithofacies in the sea-cliff exposures is about 30 m (Pomar *et al.*, 1996). These lagoonal rocks can be differentiated into "outer-lagoon" and "inner-lagoon" lithofacies. Some units contain a mixture of components and can be considered "middle lagoon" lithofacies (Pomar *et al.*, 1996). The lagoon units are composed of centimetre- to metre-scale depositional sequences, mostly shallowing-upward cycles.

Outer lagoon: Outer-lagoon rocks behind the reef crest are characterized by horizontal layers of extensively burrowed skeletal grainstone and packstone with coral-patch reefs, rhodoliths, molluscs, bryozoans, benthic and planktonic foraminifers, serpulid worm tubes, and *Halimeda*. In some places these rocks are partly to completely dolomitised. Most of the beds are bounded by erosional discontinuities and locally bored hardgrounds (Pomar *et al.*, 1996). We have sampled bivalve assemblages from the outer lagoon at two localities.

Vallgornera.- Bivalve shells concentrate mainly on the leeward side of *Tarbellastraea* colonies. Aragonitic bivalves are preserved as coupled inner and outer moulds while calcitic shells are only partially dissolved. Bivalve assemblages consist of loosely packed, mostly disarticulated and fragmented (more than 90%) valves with bipolar orientation. Identifiable samples belong to the epibyssates *Chlamys linguafelis*, *C. pusio*, *Lima lima* and to *Ostrea lamellosa*, *Chama gryphoides*, *Pseudochama gryphina* (Lamarck), and *Spondylus* sp. Articulated specimens of *Hyotissa hyotis* appear cemented to bioclasts. Endosedimentary forms such as *Dosinia orbicularis* (Agassiz), *Codakia (Ctena) decussata* (Costa) and *Linga columbella* (Lamarck) occur only slightly fragmented in the upper part of the outer lagoon deposits at this locality. Many of these shells are articulated and subparallel to bedding.

Cala Pi.- Except for some fragments of *Ostrea*, bivalve remains occur as coupled inner and outer moulds of mostly disarticulated (>80%) and fragmented (80-100%) valves (Fig. 4). They are loosely packed with no preferred orientation in the rudstones to grainstones surrounding *Porites* and *Tarbellastraea* colonies densely bored by *Entobia* and *Gastrochaenolites* (Perry, 1996). The bivalve assemblages are dominated by cemented forms, such as *O. lamellosa*, *C. gryphoides*, *P. gryphina*, and epibyssate shells such as *L. lima*, *C. linguafelis*, and *Acar clathrata*, which inhabited between coral colonies and coral fragments.

Shallow endosedimentary bivalves, represented by *Plagiocardium papillosum* (Poli), *Dosinia exoleta* (Linné), and *Codakia (Ctena) decussata*, appear together with deeper infaunal forms, such as *Venus excentrica* Agassiz (Fig. 4), *V.* cf. *verrucosa* Linné and *Tellina tenuis* Costa. Samples of *Barbatia subhelbingi* (D'Orbigny) concentrate in the upper part of the lagoon lithofacies.

In summary, assemblages are made up of reworked fragments of epibyssate and cemented bivalves accumulated around corals and from both autochthonous and displaced remains of endosedimentary forms.

Inner lagoon: *Vallgornera*.- In the fine-grained grainstones and packstones of this lithofacies the bivalve assemblages consist of loosely packed inner moulds, with a high proportion of articulated and whole valves (up to 20%), subparallel to the bedding and preferentially oriented concave up. The identifiable samples belong to the endosedimentary *Tellina planata* Linné, *T. incarnata* Linné, *Macoma* sp., *Donax* sp., and *C. (Ct.) decussata*. Some fragments of *Ostrea lamellosa* occur dispersed in the sediment together with inner moulds of gastropods. Calcite constitutes most of the rocks from this facies but minor patches of dolomite are associated with subaerial-exposure surfaces (Pomar *et al*., 1996).

The inner-lagoon assemblage is therefore made up of autochthonous and parautochthonous endosedimentary forms with a relatively low degree of reworking and displaced cemented forms.

CALA CARRIL-SES OLLES AREA

Basin: *Ses Olles*.- The fine-grained basin lithofacies is characterized by flat-lying, extensively burrowed beds of packstone and wackestone several decimetres thick. The predominant components in finer-grained portions of this lithofacies are planktonic foraminifers, ostracods, and fragments of oysters, other bivalves, echinoids, red algae, scaphopods, and scarce sclerosponges. Irregular echinoids are conspicuous in this section. Thickness of this lithofacies is poorly constrained, but in the sea-cliff exposures it is at least 25 m thick (Pomar *et al*., 1996).

Beds with fossil concentrations, several decimetres thick, alternate with barren layers and densely burrowed layers. Two types of bivalve-shell concentration occur in this facies. The first type consists of clusters of mostly articulated shells, in life position, of *Neopycnodonte navicularis* (Brocchi). The low disarticulation and fragmentation are probably due to biogenic activity. The embedding micritic sediments clearly indicate absence of hydraulic reworking.

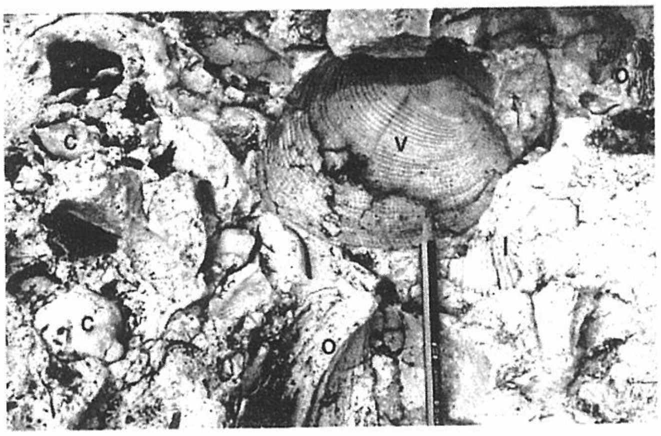

Figure 4. Bivalve fossil assemblage in the outer-lagoon lithofacies at Cala Pi. Bivalves are mostly preserved as coupled inner and outer moulds of valves as the original shells were dissolved. v: *Venus excentrica*, c: *Chama gryphoides*, o: *Ostrea lamellosa*, l: *Lima lima*.

The other, less frequent type is made up of disarticulated small, flat (right) valves of *N. navicularis* together with disarticulated valves of *Chlamys pusio*, *C. seniensis* (Lamarck), *Pecten benedictus* Lamarck, and moulds, sometimes of articulated shells, of *Anadara diluvii* (Lamarck), *Cardita aculeata*, *Thracia pubescens* (Pulteney), *Acar clathrata*, *Linga columbella*, *Diplodonta rotundata* (Montagu), *Modiolus adriaticus* (Lamarck) and *Acanthocardia* sp. Moulds of valves, some articulated, of *A. diluvii* dominate in the uppermost shell concentration, which is overlain by accumulations of *Halimeda* algal plates. These beds were formed by downslope displacement of valves, presumably as debris flows of concentrated valve fragments. The articulated and unbroken components may represent either autochthonous endosedimentary inhabitants of the bottoms resulting from the debris flows or elements transported with no breaking by the dense, fine-matrix flows.

Forereef slope: Overlying and interfingering with the finer-grained basin lithofacies are dolomitised skeletal grainstone, packstone, and wackestone characterized by basinward-dipping clinobeds. Thickness and lateral extent of the slope deposits are highly variable, depending on configuration of the forereef platform and rate of sediment production. Maximum thickness of slope beds measured on outcrop and in cores is about 70 m (Pomar *et al*., 1996).

Distal slope: The more basinward reef-slope deposits are gently inclined (less than 10°) layers of poorly stratified, extensively burrowed fine-grained red algae-mollusc dolopackstone and dolograinstone. Small-scale depositional units can be defined by textural changes. These units are about 3 m thick, and are composed of 0.5-3-m coarsening-upwards sequences bounded by less-distinct discontinuities (Pomar *et al*., 1996).

Badía Blava.- We sampled 4 beds of loosely packed bivalve shell concentrations intercalated between almost barren fine-grained calcarenites at this locality. The two lower beds contain clusters or isolated shells of *Neopycnodonte navicularis* mostly preserved in life position and articulated. Moulds of mostly fragmented valves (76%), sometimes articulated (8%), of *Chlamys opercularis* (Linné), *Cardita aculeata*, *Lucina orbicularis* Deshayes, and *Loripes lacteus* (Lamarck), *Corbula gibba* (Olivi), *Timoclea ovata* (Pennant), *Acar clathrata*, *Anadara diluvii*, occur together with *Neopycnodonte* in the upper two beds, which have sharp, channelized bottoms.

Moulds of mostly articulated valves of *C. aculeata* and *Linga columbella* appear dispersed in the fine-grained calcarenitic interbeds. In the upper part of the section, *Halimeda* beds include moulds of dissolved *Neopycnodonte*, *Chlamys* and *Venus* shells.

In this lithofacies two different types of bivalve assemblages occur. *Neopycnodonte* clusters or isolated shells represent autochthonous elements preserved with no or little displacement from life position. The slight displacement and disarticulation are probably caused by biogenic activity as no signs of hydraulic reworking after their deposition can be observed in the surrounding fine-grained calcarenites. On the other hand, the concentrations of fragmented valves consist of allochthonous to parautochthonous components, probably displaced downslope from higher slope sites and/or the framework. Debris flows caused valve concentrations but the dense fine-grained matrix prevented the fragmentation and even the disarticulation of some shells.

Proximal slope: Proximal-reef-slope deposits on this platform are steeply dipping (10°-30°) layers of dolomitised skeletal and intraclastic grainstone, packstone, rudstone, and floatstone that interfinger landwards with coral reefs. Lenticular layers of coral rubble and skeletal debris-flow deposits are common. Blocks of reef rock up to 80 cm in diameter occur in the upper layers. Skeletal fragments belong to red algae and rhodoliths, corals, bivalves, gastropods (including vermetids), echinoids, bryozoans, and the green alga *Halimeda*, which is a principal component in the forereef slopes of the youngest reef tracts (Pomar *et al.*, 1996).

Cala Carril.- At this site bivalve shells occur densely packed in many beds interlayerd with calcirudites with only dispersed bivalves. Calcitic shells are partially dissolved while the aragonitic ones have been completely dissolved and are preserved as moulds.

Episedimentary bivalves from the reef framework or living on the coral breccias, such as *Chlamys pusio*, *Ostrea lamellosa*, *Hyotissa hyotis*, *Spondylus* sp., *C. linguafelis*, *Lima lima*, and *Arca noae*, occur as dispersed fragments in the calcirudites together with rhodoliths.

Epi and endosedimentary species are found together in the densely packed shell concentrations, consisting of fragments with no preferred orientation of *Chama gryphoides*, *C. pusio*, *Barbatia barbata*, *A. noae*, *Acar clathrata*, *L. lima*, *Limaria tuberculata* (Olivi), *Codakia (Ctena) decussata*, *Irus irus* (Linné), *Cardita calyculata* (Linné), *Leporimetis papiracea* (Gmelin) and *Venus casina* Linné. These densely packed concentrations are most likely the result of debris flows of bioclasts originating in the uppermost part of the slope or in the transition from the framework to the lagoon.

Cap Blanc.- There are 5 beds of shell concentrations in the proximal-slope deposits at this locality.

The lowest bed, 5 m above present-day sea level, consists of shell fragments, mostly subparallel to bedding, of *Chlamys* sp., *A. noae*, *Anadara* sp., *Gonimyrtea meneghinii* (De Stefani and Pantanelli) and *Loripes lacteus* . Some of these shells were colonised by serpulids, indicating long preburial exposures at sea bottom. Some articulated examples of *Panopea* sp., *Cardita aculeata, Pecten* sp. and *Linga columbella* occur in life position among the reoriented shell fragments.

The second bed is made up predominantly of articulated shells of *L. columbella* mostly in life position.

The third shell concentration, 10 m above sea level, consists at its bottom of randomly oriented shell fragments of *Acanthocardia echinata* (Linné), *Acanthocardia tuberculata* (Linné), *A. noae*, *Chlamys opercularis*, *Chama gryphoides*, *Tapes (Ruditapes) basteroti* (Mayer in Cossmann and Peyrot) and *Diplodonta rotundata* together with some examples of *Laevicardium oblongum* (Gmelin) preserved in life position or slightly tilted. The upper part of the bed contains abundant articulated shells of *L. columbella*, *D. rotundata*, and *Thracia pubescens* fossilized in life position.

The fourth bed, 14 m above sea level, consists once again of mostly articulated shells of *L. columbella* in life position, embedded in a bioclastic sediment in which a few isolated valves of *Tellina incarnata*, *C. gryphoides*, *Cerastoderma edule* (Linné) and *Spisula* sp. can be identified.

The last bed, 22 m above sea level, contains abundant articulated, whole shells of *L. columbella, A. echinata, Dosinia* sp. and *Pinna* sp.

In summary, the proximal slope facies of Cap Blanc contain two types of bivalve assemblages: autochthonous assemblages mostly composed of *L. columbella* alternate with assemblages made up of allochthonous to parautochthonous components from higher positions on the slope and probably transported downslope by debris-flows. These assemblages also include a small proportion of endosedimentary forms installed after the deposition of the bioclastic bed.

Reef framework: *Cap Blanc*.- From Els Bancals to Cap Blanc, reefs are constructed mainly of *Porites* with minor amounts of *Tarbellastraea* and *Siderastrea*. This change in the reef builder is sharp and occurs across a minor stratigraphic boundary with no change in coral morphologies. Most of the reef rock from Els Bancals to Cap Blanc is pervasively dolomitised (Pomar *et al.*, 1996). The most complete vertical sequence of this reef type crops out on the high Cap Blanc sea cliff, where three zones of coral morphology have been recognised: (1) a lower zone of "dish coral", developed at palaeodepths between 20 and 30 m, (2) a middle zone of

Pinnacles Vallgornera	**Reef Crest Els Bancals**	**Outer Lagoon Vallgornera**	**Outer Lagoon Cala Pi**	**Inner Lagoon Vallgornera**
	Arca noae			
Barbatia barbata	*B. barbata*	*B. barbata*		
			B. subhelbingi	
	Acar clathrata		*A. clathrata*	
	Glycymeris insubrica			
Modiolus sp.	*M. intermedius*			
C. linguafelis	*C. linguafelis*	*C. linguafelis*		
Chlamys pusio	*C. pusio*	*C. pusio*	*C. linguafelis*	
			C. varia	
Spondylus sp.	*S. gaederopus*	*Spondylus* sp.		
Lima lima	*L. lima*	*L. lima*	*L. lima*	
		Codakia (Ct.) decussata	*C. (Ct.) decussata*	*C. (Ct.) decussata*
		Linga columbella		
Ostrea lamellosa	*O. lamellosa*	*O. lamellosa*	*O. lamellosa*	*O. lamellosa*
Hyotisa hyotis		*H. hyotis*		
Chama gryphoides	*Ch. gryphoides*	*Ch. gryphoides*	*Ch. gryphoides*	
		Pseudochama gryphina	*P. gryphina*	
	Cardita aculeata			
			Plagiocardium papillosum	
Lutraria sp.				
			Tellina tenuis	
				T. incarnata
				T. planata
				Macoma sp.
				Donax sp.
			Venus excentrica	
			V. verrucosa	
	V. multilamella			
			Dosinia exoleta	
	D. lupinus			
		D. orbicularis		
Clausinella sp.				

Table 1. Bivalve species recorded in the different palaeoenvironments from the Vallgornera-Els Bancals area.

"branching coral" that grew between 10 and 20 m, and (3) an upper zone of "massive coral" formed at depths shallower than 10 m (Esteban, 1979; Pomar *et al.,* 1983; Pomar *et al.,* 1985; Pomar, 1991).

Dish-coral zone.- The dish-coral zone is about 10 m thick. Wavy plate coral colonies up to 30 cm in diameter give way upwards to platy forms with finger-like vertical protuberances, and finger corals up to 0.5 m long become dominant in the upper part. Intra-coral cavities are filled with dolowackestone and dolopackstone containing fine detritus of echinoids, red algae, foraminifers, molluscs, and ostracodes. No identifiable bivalves have been found in this zone.

Branching-coral zone.- Transitionally overlying the dish and finger *Porites* is a zone characterised by stick coral colonies, up to 7 m in thickness. *Porites* colonies form pinnacles 2-3 m across and up to 4 m high. The coral skeletons are bored by sponges and encrusted by red algae, bryozoans, worms, foraminifers, and cyanobacteria. Bioclastic channel deposits interfingered with laminar corals occur between some pinnacles. Identifiable remains of bivalves consist of moulds of disarticulated and fragmented valves of epibyssate and crevice-dwellers, displaced from the coral colonies and reworked into the surrounding sediments: *Chlamys pusio*, *Lima lima*, *Cardita calyculata*, *Plagiocardium papillosum*, *Spondylus* sp. and *Anadara* sp. Some *Cardita* examples occur articulated in life position. *Chlamys* fragments predominate at the top of the zone. *Haliotis* moulds and regular echinoids (*Arbacia*/*Arbaciella*) are also common.

Massive-coral zone.- The upper zone is characterised by massive *Porites* heads, up to 1.5 m in diameter, with *Tarbellastraea* and *Siderastrea* as minor constituents. *Porites* colonies are thickly encrusted by red algae foraminifers, cyanobacteria, worms, bryozoans, and vermetid gastropods, and bored by *Gastrochaenolites* and *Entobia* (Perry, 1996). Coral heads are surrounded by bioclastic sediment.

This coral zone is about 8 m thick and overlies an erosional surface truncating the branching coral zone.

Basin **Ses Olles**	**Distal Slope** **Badía Blava**	**Proximal Slope** **Cala Carril**	**Proximal Slope** **Cap Blanc**	**Framework** **Cap Blanc**
		Arca noae	*A. noae*	*Arca* sp.
Anadara diluvii	*A. diluvii*		*Anadara* sp.	*Anadara* sp.
		Barbatia barbata		
Acar clathrata	*A. clathrata*	*A. clathrata*		
			Pinna sp.	
Modiolus adriaticus				
		Chlamys linguafelis		
	C. opercularis		*C. opercularis*	
C. pusio		*C. pusio*		*C. pusio*
C. seniensis				
Pecten benedictus			*Pecten* sp.	
				Flabellipecten sp.
		Spondylus sp.		*Spondylus* sp.
		Lima lima		*L. lima*
		Limaria tuberculata		
		Ostrea lamellosa		
		Hyotissa hyotis		
Neopyc. navicularis	*N. navicularis*			
		Codakia (Ct.) decussata		*C. (Ct.) decussata*
Linga columbella	*L. columbella*		*L. columbella*	*L. columbella*
Diplodonta rotundata			*D. rotundata*	*D. rotundata*
		Chama gryphoides	*C. gryphoides*	*C. gryphoides*
	Lucina orbicularis			
	Loripes lacteus		*L. lacteus*	
			Gonimyrtea meneghinii	
Cardita aculeata	*C. aculeata*		*C. aculeata*	
		C. calyculata		*C. calyculata*
Acanthocardia sp.			*A. echinata*	
			A. tuberculata	
				Plagiocardium papillosum
			Laevicardium oblongum	
			Cerastoderma edule	
			Spisula sp.	
			Tellina incarnata	
		Leporimetis papiracea		
		Venus casina		
				V. verrucosa
				Dosinia sp.
		Irus irus		*I. irus*
	Timoclea ovata			
	Corbula gibba			
			Tapes (R.) basteroti	
			Panopea sp.	
Thracia pubescens		*T. pubescens*		

Table 2. Bivalve species recorded in the different palaeoenvironments from the Cala Carril-Ses Olles area.

The upper boundary is also an erosional surface, overlain by 6 m of dolomitised small massive and laminar *Porites*, scarce spherical heads of *Siderastrea*, and penecontemporaneously lithified sediment, which have been interpreted as reef-crest deposits (Pomar, 1991; Pomar *et al.*, 1983; Pomar *et al.*, 1985).

Moulds of articulated examples of *Venus verrucosa* and *C. calyculata* appear in life position in the bioclastic sediment, which also includes moulds of disarticulated and fragmented valves of *Codakia (Ctena) decussata*, *Linga columbella*, *Diplodonta rotundata*, *Chama gryphoides*, *Irus irus*, *Lima lima*, *Chlamys pusio*, *Flabellipecten* sp., *Spondylus* sp., *Arca* sp. and *Dosinia* sp. This assemblage is a mixture of displaced cemented, epibyssate, and crevice-dwellers, and both autochthonous and displaced endosedimentary forms.

Fragments of *C. pusio* and *L. lima* occur together with coral fragments in a thin bioclastic breccia overlying the coral colonies.

DISCUSSION

In the sampled lithofacies of the Reef Complex unit from the Llucmajor Platform we have identified 52 bivalve species belonging to 38 genera and recorded 19 additional species only identifiable at the generic level (Tables 1 and 2). All the recognised species have been previously reported in the Mediterranean Upper Miocene and show temporal ranges longer than the upper Tortonian-early Messinian interval that probably encompasses the Mallorca Reef Complex. Therefore, the differences in species occurrences between the older phases of reef development (Vallgornera-Els Bancals area, Table 1) and the younger ones of the Cala Carril-Ses Olles area (Table 2) are undoubtedly due only to different palaeoenvironmental features in the respective sampling sites.

The deeper-water environments from the basin to proximal slope are characterised by shell concentrations composed of autochthonous components with a low degree of taphonomical modification (*sensu* Kidwell and Bosence, 1991), which is mainly related to biogenic activity and later dissolution of shells. The low degree of fragmentation and the high proportion of articulated valves together with sedimentary features indicate the absence of background or episodic hydraulic energy (Speyer and Brett, 1988, 1991). The processes leading to such shell concentrations in some beds are still unclear. Low sedimentation rate could have promoted shell concentration by diminishing shell dilution in the sediment (Kidwell and Jablonski, 1983) as well as the development of clusters of superimposed slow-growing organisms (Kidwell *et al.*, 1986) such as *Neopycnodonte* oysters. Pomar and Ward (1994, 1995) suggest that net sedimentation on the slope and the basin of the Mallorca Reef Complex is significantly lower during high stillstand, descending and low sea-level phases. If sedimentation rate is the main factor controlling shell concentrations these would have developed preferentially in the above-mentioned sea-level phases while shells dispersed in the sediment would be characteristic of rising sea levels.

Beds composed of mostly disarticulated, fragmented and reoriented moulds of valves co-occur with the autochthonous shell concentrations in the basin and slope deposits. As in the slope deposits of the Messinian Níjar reef in southeastern Spain (Taphofacies 3 in Jiménez and Braga, 1993), these beds are the result of bioclastic debris flows that transported downslope valves from shallower reef environments and incorporated them into finer-grained sediments. The occurrence of *Neopycnodonte navicularis* is typical for fine-grained sediments of the basin and distal slope. This species is almost the only component of the deep-water assemblages in Níjar (Taphofacies 4 in Jiménez and Braga, 1993). *Corbula gibba*, *Timoclea ovata* and *Lucina orbicularis* have only been recorded in the distal slope deposits together with some other taxa that also occur in shallower settings.

Moulds of reworked fragments of disarticulated valves are the main components of bivalve assemblages in the shallower-water reef palaeonvironments, such as the reef framework of Cap Blanc, and the pinnacles, reef crest and outer-lagoon of the Vallgornera-Cala Carril area. However, some crevice-dwellers, cemented and epibyssate forms have been preserved in life position in the sheltered microenvironments offered by the big coral colonies or coral blocks. These episedimentary bivalves, together with endosedimentary forms, fed the bioclastic gravels that characteristically made up the sediment surrounding corals in the shallow-water reef settings. Some dispersed endosedimentary individuals are also preserved in life position. They probably represent late inhabitants of the bioclastic gravels which settled in them before their final stabilization and lithification and, in a few cases, deep endosedimentary forms that lived below the reworking zone. The proportion of shallow endosedimentary specimens preserved unbroken and articulated increases towards the inner-lagoon as a result of lower hydraulic energy in this protected palaeoenvironment. *Tellina* species are the most characteristic components in the inner-laggon assemblages.

The moldic preservation of bivalves, and the necessary sampling method by casting moulds, probably led to an underestimation of the species richness in the Mallorca Reef Complex, as uncommon species have probably escaped sampling. However, the bivalve species number recorded in the Llucmajor Platform is greater than in other western Mediterranean Upper Miocene reefs studied in detail. It is 2.6 times greater than the recorded species richness in the Messinian Níjar reef in SE Spain (Jiménez and Braga, 1993). The time span of the Mallorca reef is most likely longer (Pomar *et al.,* 1996), but even comparing only similar palaeoenvironments (basin to framework) in the late phases of the Llucmajor Platform the species number is still significantly higher than in Níjar (47 vs. 26). It is also greater than the reported species number from the Messinian reef environments in Orany (28 species, Saint-Martin *et al.,* 1985) and similar figures are reached only when considering the taxa recorded in all the Messinian palaeoenvironments in Orany (Algeria) (Freneix *et al.,* 1988) or Morocco (Ben Moussa, 1994).

Nevertheless, the species number is relatively low with respect to common figures in modern reefs (38 to 224, Taylor, 1971; Morton, 1983), probably the result of the marginal location of the western Mediterranean reefs in relation to the upper Miocene reef belt (Jiménez and Braga, 1993), which also causes low scleractinian diversity (Chevalier, 1977, Martín and Braga, 1994). In addition, most of the recorded species are still extant in the eastern Atlantic and Mediterranean (Table 3) while only a few are restricted to present-day tropical settings

Extant eastern Atlantic and Mediterranean[1]	
Arca noae	Southern Portugal
Barbatia barbata	Mediterranean
Acar clathrata	Northern Spain
Glycymeris insubrica	Portugal
Modiolus adriaticus	
Lithophaga lithophaga	Mediterranean
Chlamys pusio	
C. opercularis	
Spondylus gaederopus	Mediterranean
Lima lima	Portugal
Limaria tuberculata	Portugal
Codakia (Ctena) decussata	
Diplodonta rotundata	
Chama gryphoides	Mediterranean
Pseudochama gryphina	Portugal
Cardita calyculata	Northern Spain
C. acualeata	Southern Portugal
Acanthocardia echinata	
A. tuberculata	
Plagiocardium papillosum	
Laevicardium oblongum	Northern Spain
Cerastoderma edule	
Spisula subtruncata	
Tellina tenuis	
T. incarnata	
T. planata	Mediterranean
Venus verrucosa	
V. multilamella	
V. casina	
Dosinia lupinus	
D. exoleta	
Irus irus	
Timoclea ovata	
Corbula gibba	
Thracia pubescens	

Extant tropical[2]	
Hyotissa hyotis	Indo-Pacific
Leporimetis papiracea	Tropical Eastern Atlantic

Extinct eastern Atlantic and Mediterranean[3]	
Anadara diluvii	Pleistocene
Modiolus intermedius	Pliocene
Chlamys linguafelis	Miocene
C. seniensis	Pleistocene
Ostrea lamellosa	Pleistocene
Lucina orbicularis	Pliocene
Linga columbella	Pliocene
Loripes lacteus	Miocene
Gonimyrtea meneghinii	Pliocene
Venus excentrica	Pliocene

Extinct Paratethyan and/or Mediterranean[3]	
Barbatia subhelbingi	Pliocene
Pecten benedictus	Pleistocene
Neopycnodonte navicularis	Pliocene
Dosinia orbicularis	Pliocene
Tapes (Ruditapes) basteroti	Miocene

Table 3. (Palaeo)biogeographic character of the species recorded in the Llucmajor Platform. 1) When the northern limit of the species is mid-latitude (Iberian Peninsula and the Mediterranean) it is indicated in the right-hand column. 2) Present-day dispersal area is indicated in the right-hand column. 3) Species extinction age is indicated in the right column (Data from Parenzan, 1976; Tebble, 1976; Gómez-Alba, 1988 and Poppe and Goto, 1993).

or were extinct at the end of the Miocene (Table 3) when the last coral reefs disappeared from the Mediterranean and this sea acquired its modern temperate character.

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