Palaeoenvironmental analysis of the Miocene barnacle facies: case studies from Europe and South America

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Abstract: Acorn barnacles are sessile crustaceans common in shallow-water settings, both in modern oceans and in the Miocene geological record. Barnacle-rich facies occur from polar to equatorial latitudes, generally associated with shallow-water, high-energy, hard substrates. The aim of this work is to investigate this type of facies by analysing, from the palaeontological, sedimentological and petrographical points of view, early Miocene examples from Northern Italy, Southern France and South-western Peru. Our results are then compared with the existing information on both modern and fossil barnacle-rich deposits. The studied facies can be divided into two groups. The first one consists of very shallow, nearshore assemblages where barnacles are associated with an abundant hard-substrate biota (*e.g.*, barnamol). The second one includes a barnacle-coralline algae association, here named "barnalgal" (=barnacle/red algal dominated), related to a deeper setting. The same pattern occurs in the distribution of both fossil and recent barnacle facies. The majority of them are related to very shallow, high-energy, hard-substrate, a setting that represents the environmental optimum for the development of barnacle facies, but exceptions do occur. These atypical facies can be identified through a complete analysis of both the skeletal assemblage and the barnacle association, showing that barnacle palaeontology can be a powerful tool for palaeoenvironmental reconstruction.

Keywords: Carbonate Factories, Heterozoan, Barnamol, Barnalgal, Tertiary Piedmont Basin, Sommières Basin, Pisco Basin.

Introduction

Acorn barnacles (Cirripedia: Sessilia) are common carbonate producers in modern and fossil shallow-water shelf environments (Foster 1987; Foster & Buckeridge 1987; Doyle et al. 1997). Albeit often overlooked, this group of sessile, suspension-feeding crustaceans occur on any available surface in shallow seas, including "mobile surfaces" like turtles and whales (Ross & Newman 1967; Newman & Abbot 1980; Scarff 1986; Seilacher 2005; Bianucci et al. 2006; Dominici et al. 2011; Harzhauser et al. 2011; Collareta et al. 2016a,b). They are common at middle and high latitudes (Raymond & Stetson 1932; Hoskin & Nelson 1969; Milliman 1972; Müller & Milliman 1973; Farrow et al. 1978; Hottinger 1983; Domack 1988; Nelson et al. 1988; Scoffin 1988; Wilson 1988; Taviani et al. 1993; Henrich et al. 1995; Frank et al. 2014; Buckeridge 2015), but they can also thrive at low-latitudes, especially in nutrient-rich environments (Glynn & Wellington 1983; Carannante et al. 1988; Halfar et al. 2006; Westphal et al. 2010; Michel et al. 2011; Reijmer et al. 2012; Klicpera et al. 2013; Reymond et al. 2016). The fossil record of encrusting cirripedes starts in the Cretaceous (if primitive forms like *Archaeochionelasmus* Kočí, Newman & Buckeridge, 2017 in

Kočí et al. 2017 are included), but it is only during the Neogene that barnacles became really frequent in the shallow-water environments that they presently master (Darwin 1854; Newman et al. 1969; Foster & Buckeridge 1987; Doyle et al. 1997; Buckeridge 2015).

Worldwide, barnacle facies are particularly well represented in the sedimentary sequences of the Neogene and the Quaternary (Sakai 1987; Donovan 1988; Kamp et al 1988; Nebelsick 1989, 1992; Hayton et al. 1995; Doyle et al. 1997; Betzler et al. 2000; Nielsen & Funder 2003; Civitelli & Brandano 2005; Aguirre et al. 2008; Nomura & Maeda 2008; Radwańska & Radwański 2008; Massari & D'Alessandro 2012; Stanton & Alderson 2013; Brandano et al. 2015; Buckeridge 2015; Buckeridge et al. 2018). Based on the ecology of modern taxa, these facies are generally interpreted as shallow-water, high-energy, deposits. Although this interpretation is usually reasonable, considering the modern distribution of barnacle-rich sediments, barnacle facies clearly display a variability that reflects environmental differences. The aim of this work is to investigate the environmental factors that govern the development of barnacle facies, thus gaining further insights useful for palaeoenvironmental reconstructions. To achieve this goal, four Burdigalian (early Miocene) barnacle facies, from both

the Northern and Southern hemisphere, were analysed and compared by means of palaeontology, sedimentology and petrography, highlighting their differences and their similarities. The studied barnacle-rich skeletal assemblages are located in the well studied successions of the Pietra da Cantoni Basin in Italy, of the Sommières Basin in France, and of the East Pisco Basin in Peru (Fig. 1; Vannucci et al. 1996; Bicchi et al. 2006; Reynaud & James 2012; Coletti et al. 2015; Bianucci et al. 2018; DeVries & Jud 2018; Di Celma et al. 2018b). Previous research provides a firm basis for the interpretation of the barnacle facies of these basins, which has received limited attention until now. These facies, despite having in common abundant remains of barnacles, are characterized by different skeletal assemblages and different petrographic composition, thus suggesting different palaeoenvironmental settings. The results of this analysis are integrated with the existing information on both modern and fossil barnacle facies, to provide a general framework for this kind of sedimentary rock.

Geological setting

Pietra da Cantoni Basin, Northern Italy

The Pietra da Cantoni Group was deposited in the eastern Monferrato, a part of the Tertiary Piedmont Basin that evolved from the late Eocene to the late Miocene, over the inner part of the Alpine wedge (Novaretti et al. 1995; Rossi et al. 2009). During the Aquitanian, the deformation caused by the rotation of the orogenic wedge uplifted the eastern Monferrato and resulted in the deposition of the Burdigalian to early Langhian limestones of the Pietra da Cantoni (Clari et al. 1995; Novaretti et al. 1995; Maffione et al. 2008). The group is divided into two depositional sequences (Bicchi et al. 2006). The oldest ("Sequence 1" sensu Bicchi et al. 2006) is related to the first and localized marine transgression. The youngest ("Sequence 2" sensu Bicchi et al. 2006) accumulated at the beginning of a transgressive trend in the area that lasted for most of the Miocene. The second sequence is divided into two units. The Lower Unit of Sequence 2 is characterized by coralline-algal-nodule rudstones and floatstones interbedded with grainstones and rudstones rich either in large benthic foraminifera or in barnacles. Deposition occurred during the Burdigalian (Novaretti et al. 1995; Ruffini 1995; D'Atri et al. 1999, 2001). The Upper Unit of Sequence 2 is characterized by foraminiferal oozes, testifying hemipelagic sedimentation. A bed of condensed sediments, rich in glauconite and phosphates, separates the two units (Schüttenhelm 1976; Bicchi et al. 2006). This interval is related to a period of major sediment starvation, caused by the drowning of the carbonate factory (Coletti et al. 2015). Both units of Sequence 2 occur in the outcrop of Uviglie (Fig. 1; 45°04'42" N, 08°24'48" E), where the barnacle-rich facies has been investigated.

Sommières Basin, Southern France

The Alpine Molasse Basin was a seaway during the early Miocene; it was about 100 km wide and 1000 km long and connected the Western Mediterranean with the Western
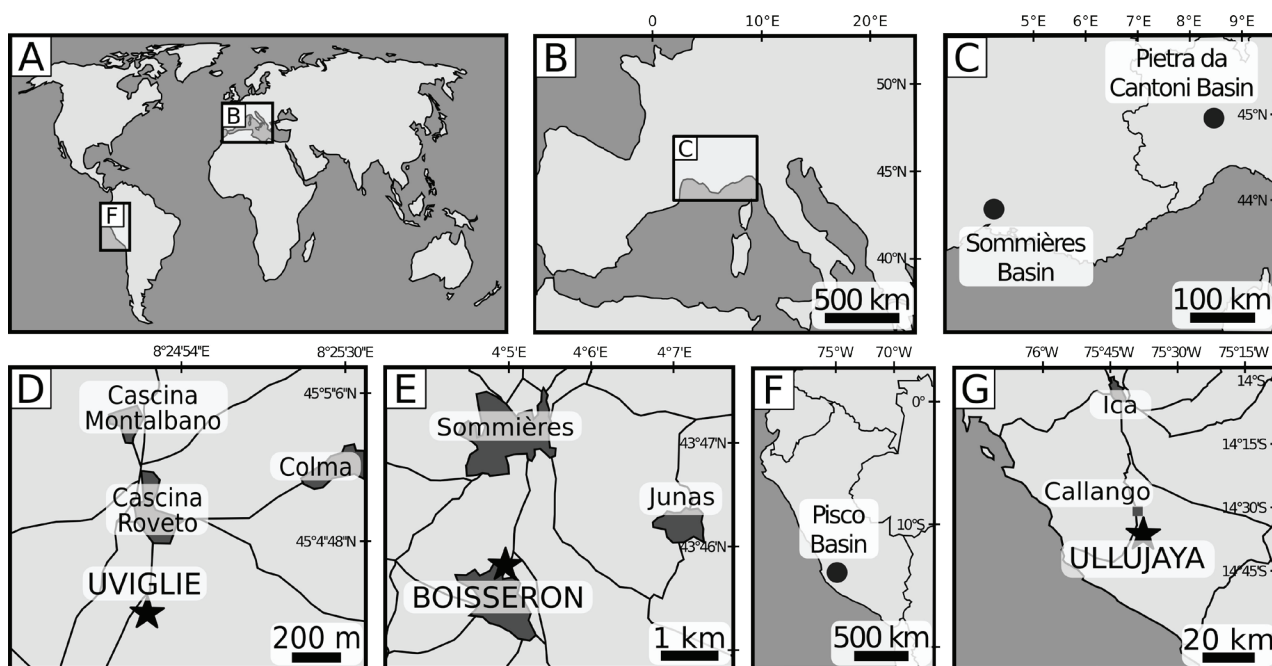

Fig. 1. Location of the studied facies. **A** — World map including the location of the studied areas highlighted in the panels. **B** — Western Europe, magnification of panel B included in panel A. **C** — Location of the Sommières Basin (France) and of the Pietra da Cantoni Basin (Italy). **D** — Location of the outcrop of Uviglie (Italy). **E** — Location of the Boisseron outcrop (France). **F** — North-western South America, magnification of panel F included in panel A. **G** — Location of the Ullujaya outcrop (Peru).

Paratethys (Allen et al. 1985; Rögl 1998; Dercourt et al. 2000; Reynaud & James 2012). This narrow sea was dominated by strong tidal currents created by the amplification of the Atlantic tide entering the basin from the south-west (Allen et al. 1985; Harzhauser & Piller 2007). The Sommières Basin was a small embayment within the Alpine Molasse Basin, located near the junction of the seaway with the Mediterranean and connected with the former through a flooded valley (Reynaud & James 2012). Within the Sommières Basin, three main units are recognized: the Sandy Molasse, the Sandy Marls and the Calcareous Molasse (Demarcq 1970; Reynaud & James 2012). These units represent two different Burdigalian depositional sequences (Berger 1974; Reynaud & James 2012). The first sequence records the marine transgression in the Sommières Basin: in particular, the Sandy Molasse Unit represents the transgressive system tract, while the Sandy Marls Unit is the highstand system tract (Reynaud & James 2012). The end of the deposition of the Sandy Marls Unit is followed by an abrupt fall in sea level. The subsequent transgression is represented by the Calcareous Molasse Unit, which is included in the second sequence (Reynaud & James 2012). The Sandy Molasse Unit, which deposited during the early Burdigalian, is characterized by limestones composed mainly of bryozoans, molluscs, barnacles, echinoids and coralline algae (Berger 1974; Reynaud & James 2012). The barnacle-rich assemblages occur in the lowermost bed of the unit that onlaps the basement of the basin ("Sub-facies A1" *sensu* Reynaud & James 2012). The architecture of these deposits is especially clear in the outcrop of Boisseron (Fig. 1; 43°45'42" N, 04°04'54" E), investigated in the present paper.

East Pisco Basin, South-western Peru

The East Pisco Basin was a Cenozoic semi-enclosed forearc-embayment, protected by an archipelago of islands, located on the southern coast of Peru (DeVries & Jud 2018; Di Celma et al. 2018b). It has been mainly investigated for its diverse and exceptionally-preserved Neogene fossil vertebrates (including pinnipeds, sharks, crocodiles, seabirds, turtles and bony fish) that characterize several outcrops west of the Ica River (*e.g.*, Bianucci et al. 2015, 2016a,b, and previous references therein; Lambert et al. 2014, 2015, 2017a,b; Landini et al. 2017a,b, 2018; Marx et al. 2017; Gioncada et al. 2018). The sedimentary successions were first described in the 1990s by Dunbar et al. (1990) and DeVries (1998). Within the Palaeogene succession, these authors recognized the Caballas (middle Eocene), Paracas (middle to late Eocene age) and Otuma (late Eocene to early Oligocene age) formations. These are followed by the Neogene Chilcatay and Pisco formations. The lower Miocene Chilcatay Formation (investigated over the years by Wright et al. 1988; DeVries & Schrader 1997; León et al. 2008; DeVries & Jud 2018) is a focus of this paper. Recent surveys in the Western side of the Ica River Valley have recognized within the Chilcatay Formation distinct depositional sequences, separated by basin-wide unconformities (Di Celma et al. 2017, 2018a). Based on

that, the Chilcatay Formation has been divided into the Ct1 and Ct2 allomembers (Di Celma et al. 2018b). Ct1 is further subdivided into two facies associations: Ct1a, composed of sandstones and conglomerates (less common than sandstones) alternating with siltstones, and Ct1b, including clinobedded coarse-grained mixed siliciclastic/bioclastic arenites. Both facies associations are characterized by abundant barnacle remains. The overlaying Ct2 deposits include massive and intensely bioturbated sandstones, changing upwards into massive siltstones with dolomitized mudstone layers. A tephra layer near the top of this sequence locates the Chilcatay Formation in the Burdigalian — which agrees with diatom and silicoflagellate biostratigraphy (Di Celma et al. 2017, 2018b). These allomembers are well exposed at Ullujaya (Fig. 1; 14°35'06" S, 75°38'30" W), and are investigated in the present work.

Material and methods

For the purposes of the present work, skeletal assemblages where barnacle remains dominate or codominate the bioclastic fraction of the rock are regarded as barnacle facies (with codominance meaning the situation in which barnacles, within reasonable confidence limits, are equally abundant to another group of skeletal grains). Barnacle facies were studied in the outcrops of Uviglie, Boisseron and Ullujaya in order to describe their macroscopic texture and sedimentary structures (Fig. 1). Special attention was given to the observation of fossil barnacle assemblages, focusing on their first-order taxonomic composition. Barnacle preservation and distribution were investigated following the methods of Doyle et al. (1997), Nomura & Maeda (2008) and Nielsen & Funder (2003), which are based on the fragmentation of shells and whether or not the specimens are in life position. Representative rock samples from each facies were collected for petrographic, palaeontological and mineralogical analyses. A large number of barnacle specimens were also collected in the studied outcrops (including isolated opercula, shell fragments, complete shells and multi-individual aggregates; Fig. 2). In most cases, cirripede palaeontology relies on an analysis of shell fragments as the co-embedding of adjacent valves and, even more, the occurrence of complete shells is uncommon (Foster & Buckeridge 1987). For this reason, barnacle taxa were studied by integrating information from both complete specimens (where available) and plates retrieved from the embedding rock. From each facies, about 500 g of rock sample was disaggregated through freezing-thawing cycles and then wet-sieved to isolate barnacle opercula and wall plates (following Aguirre et al. 2008). After studying them under a stereomicroscope, some selected specimens (67, including compartment fragments, isolated wall plates and complete shells) were prepared as thin sections to observe the internal microstructure of the shells (Fig. 2), which can be useful for taxonomic identification (Cornwall 1956, 1958, 1959, 1960, 1962; Davadie 1963; Newman et al. 1969; Newman & Ross 1971; Buckeridge 1983).
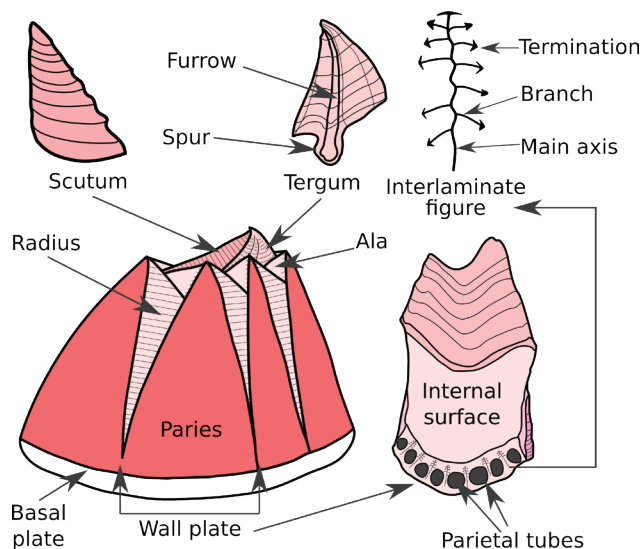
Fig. 2. Generalized structure of a balanomorph barnacle shell. Lower left corner present a model of a complete shell, partially modified after Buckeridge (1983); upper left includes details of the opercular plates; lower right includes details of a carinal plate and its internal structure revealed by a transverse section above the basal margin showing the interlaminate figures, one being enlarged in the upper right.

In particular, attention was paid to interlaminate figures (*i.e.*, "lames épithéliales" *sensu* Davadie 1963) that are observable in thin sections of the wall plates of the encrusting barnacles with a calcareous basis. These interlaminate figures (*e.g.*, Fig. 2) reflect the patterns made by the organic matrix during the formation of the calcareous denticles at the basal ends of the longitudinal septa of the wall plates that interdigitate with the corresponding radial septa of the calcareous basis (Newman et al. 1967). As a result of the uncertainties inherent in fossil barnacle taxonomy, it was decided to simply differentiate the different taxa occurring in the investigated facies. When enough information for a reliable diagnosis was available an identification is proposed; otherwise only a provisional identification is attempted. The systematic taxonomy used for the classification mostly follows Buckeridge (1983), Zullo (1992) and Newman (1996).

The petrographic characteristics of the rocks and their skeletal assemblages were analysed on 35 polished thin sections. The different components were identified and quantified using point-counting method with a minimum of 400 points per section (Flügel 2010). X-ray powder diffraction analysis (XRD) method was used to estimate the carbonate and siliciclastic fractions of the whole rock. Samples were first ground in an agate mortar, and then mounted on zero-background silicon plates. The measurements were made with a Philips PW1140 diffractometer equipped with CoKα radiation (Kα1 wavelength 1.789 Å) operating at 40 kV and 20 mA. Each sample was scanned between 3° and 70° 2θ with a step size of 0.02° 2θ and an acquisition time of 1 s per step. X-ray pattern treatment was carried out with Panalytical X'pert HighScore Plus to identify the mineralogical phases and

a semiquantitative analysis was carried out using the Reference Intensity Ratio (RIR) method (Chung 1974).

Results

Barnalgal, Pietra da Cantoni Group

Skeletal assemblage and mineralogical composition

The barnacle facies of the Pietra da Cantoni Group consists of a massive rudstone with a slight yellowish to pinkish colour (Fig. 3A–E). This peculiar colour of the rock is partly due to the large number of barnacle plates that still retains their pinkish pigmentation. The rock is very porous, poorly lithified and, except for some rare burrows (Fig. 3C), does not present macroscopically evident sedimentary structures; only locally flat skeletal elements exhibit a preferential orientation (Fig. 3F). Besides barnacle plates, coralline-algal nodules (rhodoliths) are abundant, especially towards the top of the interval. Most of them are encrusted by barnacles (Fig. 3D). Sectioned rhodoliths show that barnacles are also present within the nodules, alternating with layers of coralline algae. Thin section analysis shows that the skeletal assemblage is dominated by barnacles and coralline algae (mainly Hapalidiales; Table 1; Fig. 3F–G). For this assemblage, the new term "barnalgal" is here proposed, complementing the assemblages introduced by Hayton et al. (1995). Bryozoans are relatively common (Table 1); their association includes branched colonies, globular colonies and disarticulated elements of the articulated bryozoan *Bifissurinella lindenbergi* Keij, 1969. Benthic foraminifera are present but less abundant (Table 1; Fig. 3F–H), the most common genera being *Amphistegina* d'Orbigny, 1826, *Elphidium* Montfort, 1808, and *Cibicides* Montfort, 1808. *Sphaerogypsina* Galloway, 1933, *Miogypsina* Sacco, 1893, *Operculina* d'Orbigny, 1826, *Nephrolepidina* Douvillé, 1911, *Eponides* Montfort, 1808, and *Neoconorbina* Hofker, 1951 are less common; *Stomatorbina* Dorreen, 1948, textulariids and miliolids are rare. Echinoids are uncommon in the skeletal assemblage and mostly occur as loose spines (Table 1). Molluscs are rare, those present being mainly pectinids; serpulids and ostracods are very rare (Table 1). The siliciclastic fraction is almost non-existent, except for some rare pebbles and some quartz grains (Table 1). XRD results support this observation, indicating >> 95 % of carbonate minerals (Table 1).

Barnacle preservation

Cirripede shells are evenly distributed in the horizon; they are generally disarticulated and the plates are slightly abraded (Fig. 3E; grade 0 of Nielsen & Funder 2003). Complete shells occur on the surface of rhodoliths, together with stubs (*i.e.*, broken shells of which almost only the base is preserved) and partially broken specimens (Figs. 3D; 4A–B). These specimens have randomly-oriented openings, suggesting that they are no longer in life position (Type B preservation of Nomura
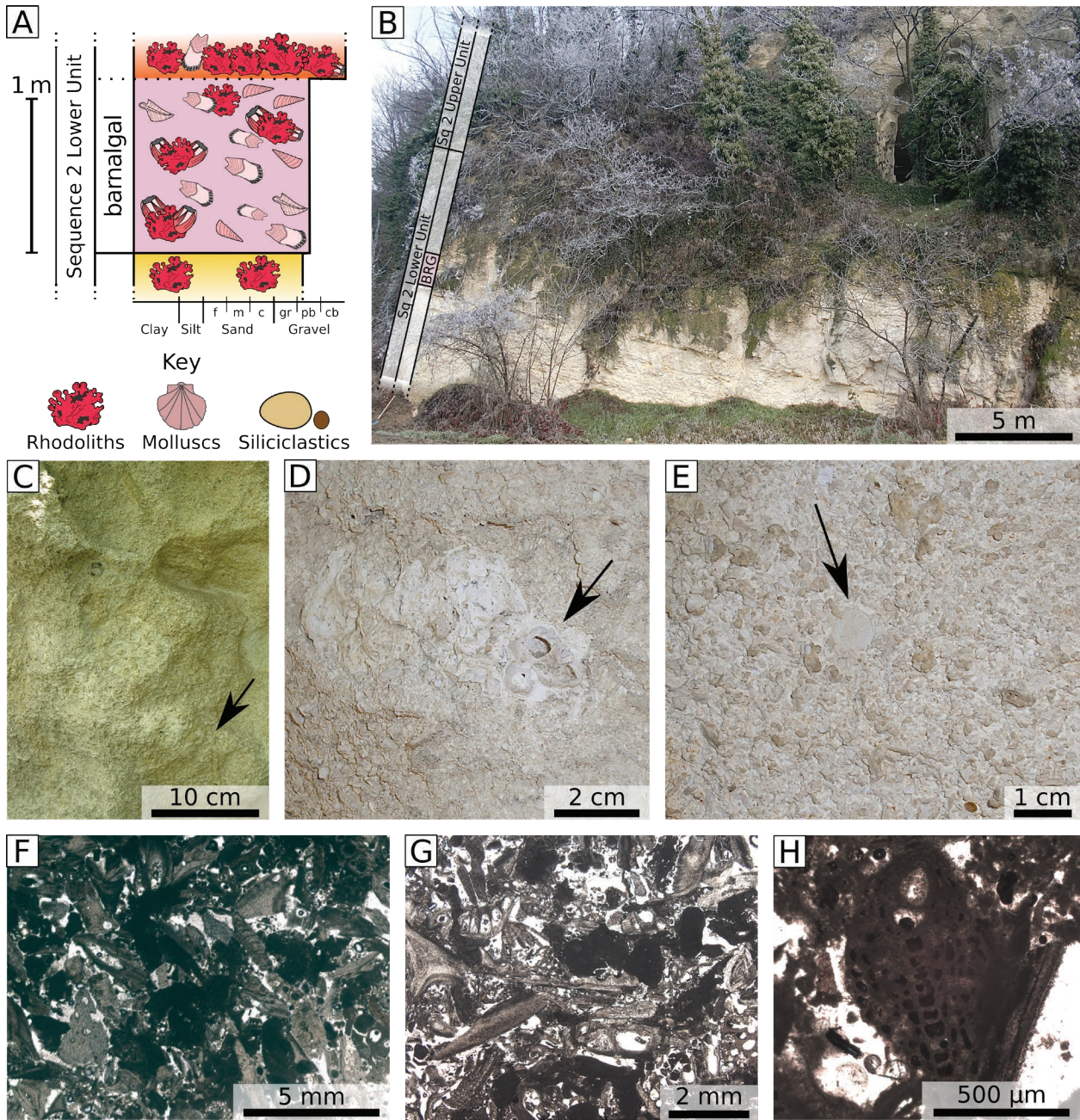
Fig. 3. Barnacle coralline assemblage (barnalgal) of the Lower Unit of Sequence 2 of Pietra da Cantoni Group (Uviglie, Italy). **A** — Simplified stratigraphic column of the barnalgal of the Pietra da Cantoni Group. **B** — Overview of the Uviglie outcrop including a simple stratigraphic column highlighting the different units and the barnalgal facies, BRG=barnalgal assemblage, Sq=sequence. **C** — Detail of a burrowing trace, black arrow=trace. **D** — Barnacle-encrusted rhodolith, black arrow=barnacles. **E** — Detail of the texture of the facies, black arrow=*Operculina*. **F** — Thin section of a sample of lower part of the barnalgal facies. **G** — Thin section of a sample of the upper part of the barnalgal facies. **H** — Axial section of a *Miogypsina* specimen.

& Maeda 2008; displaced clusters of Doyle et al. 1997). The specimens are moderately well-preserved, retain their colour and only lack the loose and tiny opercula (Fig. 4B). The latter are quite abundant in the rock, commonly slightly abraded, even though some of them still preserve a pinkish colour; sometimes they present gastropod predation holes. Scuta and terga do not occur in equal abundance, the scuta being much more common than the terga (Fig. 4C–D).

Barnacle identification

The shells are generally small, with the basal diameter in adult specimens ranging from slightly under 0.5 cm to a little over 1 cm (Fig. 4B). They are comprised of six mural plates plus a calcareous, tubiferous basis. Externally the parietes possess strong longitudinal ribs. Where the colour is preserved, the plates are light pink with white spots organized in

Table 1: Petrographic composition, skeletal assemblage and mineralogical content of the examined barnacle facies.

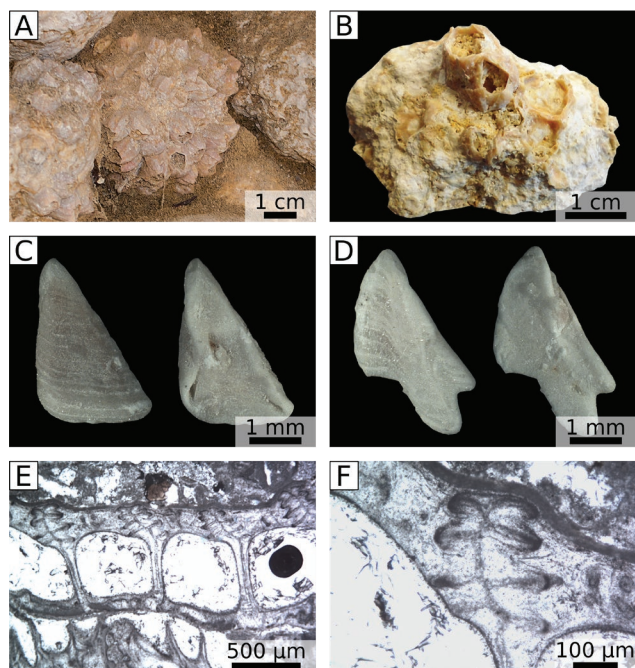|	Pietra da Cantoni Group	Sandy Molasse Unit	Chilcatay Formation	
	Barnalgal	Barnamol	Ct1a barnacle facies	Ct1b barnacle facies
Petrographic composition [Point counting]				
Bioclastic components	95.0 %	68.5 %	22.0 %	24.0 %
Terrigenous components	0.5 %	16.5 %	65.0 %	30.5 %
Sparite	4.0 %	8.0 %	10.0 %	41.0 %
Micrite	0.5 %	7.0 %	3.0 %	4.5 %
Detail of the bioclastic fraction [Point counting]				
Barnacles	41.5 %	34.5 %	71.5 %	80.0 %
Molluscs	0.5 %	40.5 %	8.5 %	7.5 %
Echinoids	1.0 %	16.5 %	18.5 %	8.0 %
Bryozoans	6.5 %	8.0 %	<0.5 %	///
Coralline algae	47.0 %	<0.5 %	///	///
Benthic foraminifera	3.5 %	<0.5 %	1.0 %	4.0 %
Serpulids	<0.5 %	<0.5 %	<0.5 %	<0.5 %
Ostracods	<0.5 %	///	///	///
Mineralogical composition [XRD]				
Carbonates	97.0 %	72.0 %	16.0 %	31.0 %
Silicates	3.0 %	28.0 %	71 %	64.0 %
Salts	0.0 %	0.0 %	13.0 %	5 %

Fig. 4. Barnacles of the barnalgal of Uviglie (Italy). **A** — A rhodolith completely encrusted by barnacles (cf. *Amphibalanus* sp.), upper part of the Lower Unit of Pietra da Cantoni Sequence 2 (Colma, Fig. 1). **B** — Barnacle shells (cf. *Amphibalanus* sp.) growing on a rhodolith. **C** — Internal and external surfaces of the same scutal plate. **D** — Internal and external surfaces of the same tergal plate. **E** — Interlaminate figures of a wall plate of cf. *Amphibalanus* sp. **F** — Detail of the interlaminate figures of the plate depicted in panel E.

longitudinal rows. Interlaminate figures are present; they have short and almost straight main axes with few transverse branches (Fig. 4E–F). The terminations of the branches are crescent-moon to arrow-shaped. The scuta are thick and triangular in shape, with the outer surface characterized by transverse growth lines (Fig. 4C). The terga are much thinner, with a spur as long as one third of the total length of the plate, removed from the basiscutal angle by less than half its width, and with a very shallow furrow (Fig. 4D). The size and the morphology of the recovered opercula indicates that they all belong to a single species. This consistency is also reflected in the wall plates and their interlaminate figures, leading us to conclude that only one barnacle species is present in this facies. The morphology of the opercula, wall plates and interlaminate figures (Fig. 4E–F) conforms to a taxon of Balanidae closely allied to the amphibalanine *Amphibalanus amphitrite* (Darwin 1854).

Barnamol, Sandy Molasse Unit

Skeletal assemblage and mineralogical composition

This facies consists of rudstone organized in low-angle cross-bed sets (Fig. 5A–C). The rock is porous, especially at the base of the succession, and exhibits a clear fabric due to the common orientation of flat skeletal elements (Fig. 5D–F). Barnacle plates and fragments of molluscs are very common. Granule-sized bryozoan colonies are also visible on the rock surface. According to point-counting analysis the skeletal assemblage is dominated by barnacles and molluscs (consequently the assemblage was classified as barnamol *sensu* Hayton et al. 1995; Table 1; Fig. 5 D–I). Barnacles are especially important at the base of the interval, where they account for most of the skeletal grains. Molluscs are more important upwards, where they are locally more abundant than barnacles; they are mainly represented by ostreids and subordinated pectinids. Echinoids are abundant, occurring as spines and test fragments (Table 1). Bryozoans are common (both branching and globular colonies are present; Table 1). Coralline algae and benthic foraminifera are very rare, the latter being mostly represented by *Cibicides*, *Amphistegina* and *Miogypsina* (Table 1). The siliciclastic fraction is important and accounts for 16.5 % of the detected elements (Table 1; Fig 5D–L). It includes quartz grains and fragments of sedimentary rocks (mainly limestones and sandstones). XRD results highlight the presence of about 30 % of silicate minerals and 70 % of carbonates (Table 1).

Barnacle preservation

Wall plates are invariantly disarticulated and evenly distributed within the rock (Type D of Nomura & Maeda 2008; comminuted shell bed of Doyle et al. 1997). They are fragmented, disarticulated and heavily abraded, often exposing

their internal structure (Grade 1 and 2 of Nielsen & Funder 2003). None of the observed plate fragments preserve their original colour. Very rare scuta, but no terga, were recovered from the disaggregated rock sample. They are fragmented, abraded and exhibit pitted surfaces probably due to incipient pressure solution.

Barnacle identification

The preservation state of the cirripede remains greatly hinders identification based on their macroscopic features. The inner structure of the plates and the interlaminate figures indicates that three different taxa are probably present: Concavinae? indet., Balaninae gen. et sp. indet. 1, and Balaninae gen. et sp. indet. 2 (Fig. 6). The presence of more than one barnacle taxon is also supported by the scutal plates, which exhibit at least two different morphologies: one characterized by transverse growth lines only and another exhibiting both transverse growth lines and longitudinal (*i.e.*, radial) striae (Fig. 6F–G, respectively). The specimens identified as Concavinae? indet. have small parietal-tubes, sometimes divided by septa and characterized by interlaminate figures with a straight axis and few transverse branches with crescent-moon- to arrow-shaped terminations (Fig. 6A). The presence
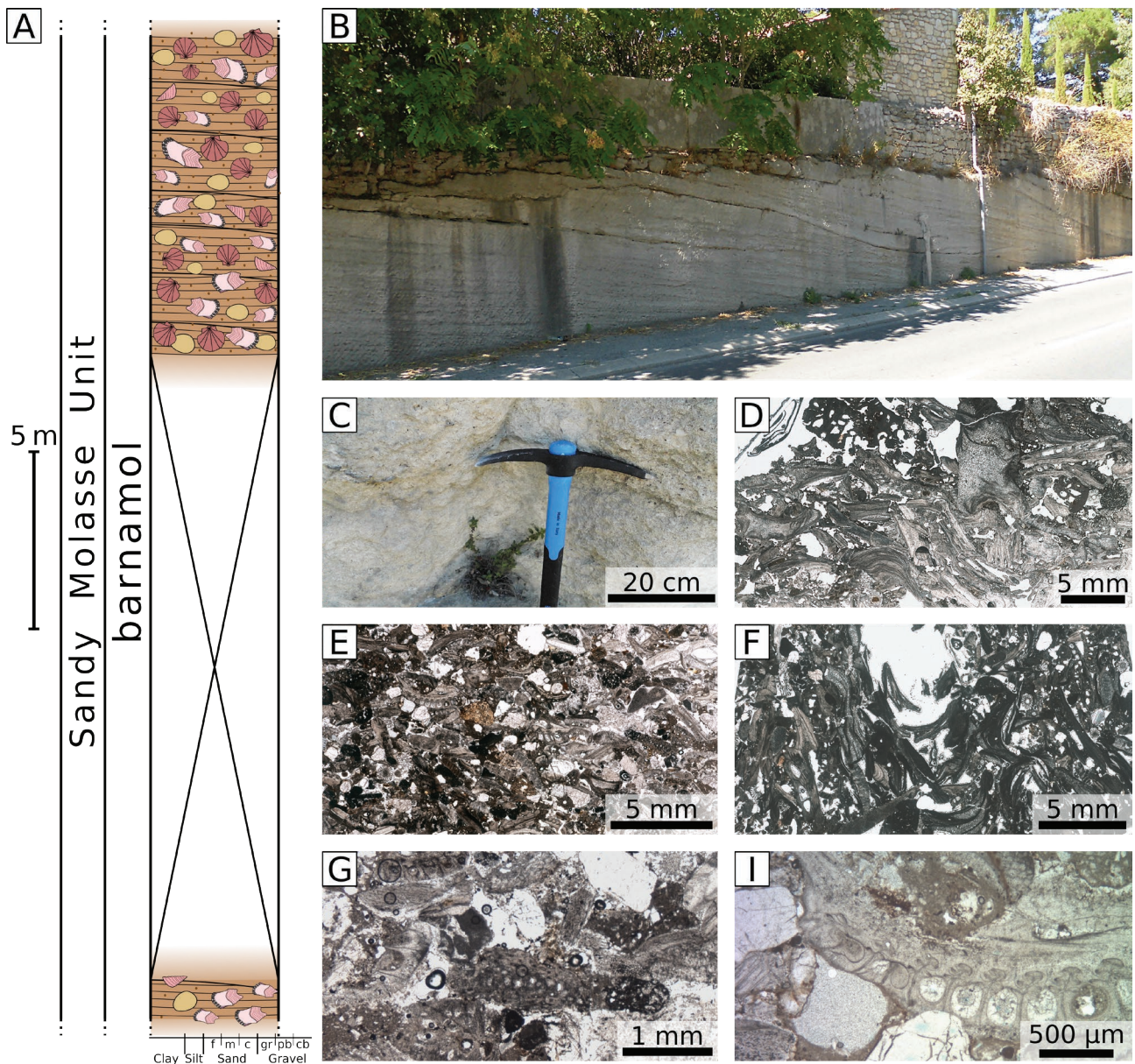

Fig. 5. Barnacle-mollusc assemblage (barnamol) of the Sandy Molasse Unit of the Sommières Basin (Boisseron, France). **A** — Simplified stratigraphic column of the barnamol facies of the Sandy Molasse Unit. **B** — Overview of the Boisseron outcrop. **C** — Macroscopic texture of the facies. **D** — Thin section of a sample from the barnamol facies with common orientation of the bioclasts. **E** — Thin section of a barnacle-rich sample of the barnamol facies. **F** — Thin section of a mollusc-rich sample of the barnamol facies. **G** — Detail of a *Miogypsina* specimen. **H** — Detail of a cross-section of a tubiferous barnacle wall plate exhibiting interlaminate figures.

of representatives of the subfamily Concavinae is as also suggested by the occurrence of scuta with both longitudinal striae and transverse growth lines; however, it must be stressed that the latter feature is also observed in the extant amphibalanine *Amphibalanus eburneus* (Gould, 1841). Concavine barnacles are known to occur in the Neogene deposits of the Alpine Molasse Basin. De Alessandri (1906) pointed out the presence of "*Balanus*" *concavus* Bronn, 1831 (=*Concavus concavus*) in lower Miocene strata of the Upper Marine Molasse of Switzerland, but under this specific name several taxa of specific and generic rank are lumped (Newman 1982; Zullo 1992; Carriol 2000). More recently, concavine barnacles (belonging to the genus *Chesaconcavus* Zullo, 1992) have been reported by Carriol & Schneider (2008) and Carriol & Menkveld-Gfeller (2010) from Burdigalian beds of the Upper Marine Molasse of Bavaria and Switzerland, respectively. The specimens referred to Balaninae gen. et sp. indet. 1 have larger parietal tubes and interlaminate figures with a long axis and numerous transverse branches with club-shaped terminations (Fig. 6B–C). Similar interlaminate figures have been figured by Nebelsick (1989: pl. 4, figs. 2–3) for Burdigalian barnacles of the Zogelsdorf Formation of Austria (Alpine Molasse

Basin) and by Davadie (1963; pl. XIV) for recent specimens of the subfamily Balaninae. The specimens belonging to Balaninae gen. et sp. indet. 2 have large tubes and interlaminate figures with a bent axis and numerous transverse branches with club-shaped terminations; differing from the other groups, these branches present complex ramifications (Fig. 6D–E).

Barnacle facies, Chilcatay Formation

Skeletal assemblage and mineralogical composition

Two slightly different barnacle facies can be recognized in Ct1a and Ct1b facies associations, respectively (Fig. 7A–B).

The barnacle facies of Ct1a consists of poorly-sorted coarse-sandstones to conglomerates with siliciclastic and bioclastic elements (Fig. 7A, C–E); the barnacle-bearing horizons alternate with medium- to fine-grained sandstones, almost devoid of bioclasts (Fig. 7A).The rock is massive, porous and poorly cemented. Barnacles are very common, occurring as clusters of shells, isolated individuals and large shell fragments (Fig. 7D–E).According to thin section analysis, barnacles dominate the skeletal assemblage (Table 1; Fig. 7F–G). Echinoids are also very common; molluscs are less abundant and mainly represented by ostreids and pectinids (Table 1). Benthic foraminifera are very rare (mainly *Cibicides*, *Peneroplis* Montfort, 1808 and *Nonion* Montfort, 1808; Table 1). Serpulids are uncommon in the skeletal assemblage, but occasionally they occur in large clusters. Bryozoans are very rare (Table 1). The siliciclastic fraction is important and accounts for more than half of the components (Table 1; Fig. 7F–G). It consists of fragments of igneous rocks from the basement and ash-flow tuffs. XRD results indicate > 70 % of silicate minerals and only lesser amounts of carbonates and salts (mainly gypsum; Table 1).

The barnacle facies of Ct1b is organized into clinobeds of well-sorted, coarse-grained mixed siliciclastic-bioclastic deposits, which are more cemented and less porous than those of the lower facies (Fig. 7A). On a macro-scale at the outcrop, barnacles dominate the bioclastic fraction (occurring as clusters, isolated individuals and shell fragments), but bivalves also occur (Fig. 7 H–J). In thin section, barnacle remains are the most abundant group of skeletal grains; however, the common presence of sparite-filled molds suggests that molluscs were also important (Table 1; Fig. 7 K–L). Among the few preserved bivalve specimens, ostreids and pectinids are dominant. Echinoids are also abundant (Table 1). Benthic foraminifera are less common (mainly *Cibicides* and *Peneroplis*; Table 1). Rare calcareous tubes also occur (Table 1). Based on point-counting analyses, siliciclastic components are slightly more important than bioclasts and they mainly consist of pebbles and granules of igneous basement rocks (Table 1; Fig. 7F–G, K–L). XRD results suggest that silicate minerals account for > 60% of the rock, whereas carbonates only represent 30 % (Table 1). Minor amounts of gypsum are also present (Table. 1).
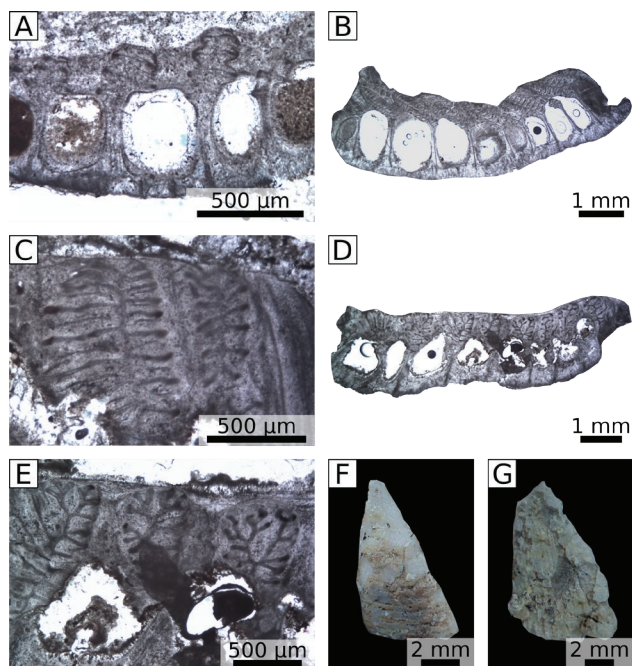

Fig. 6. Barnacles of the barnamol of Boisseron (France). **A** — Concavinae? indet., interlaminate figures; note the straight axis, few branches and crescent-moon to arrow-shaped terminations. **B** — Balaninae gen. et sp. indet. 1, interlaminate figures; note the long axis and numerous branches with club-shaped terminations. **C** — Balaninae gen. et sp. indet. 1, detail of the interlaminate figures. **D** — Balaninae gen. et sp. indet. 2, interlaminate figures; note the bent axis and numerous, ramified branches with club-shaped terminations. **E** — Balaninae gen. et sp. indet. 2, detail of the interlaminate figures. **F** — External surface of a scutal plate exhibiting transverse growth lines only. **G** — External surface of a scutal plate exhibiting both longitudinal striae and transverse growth lines.
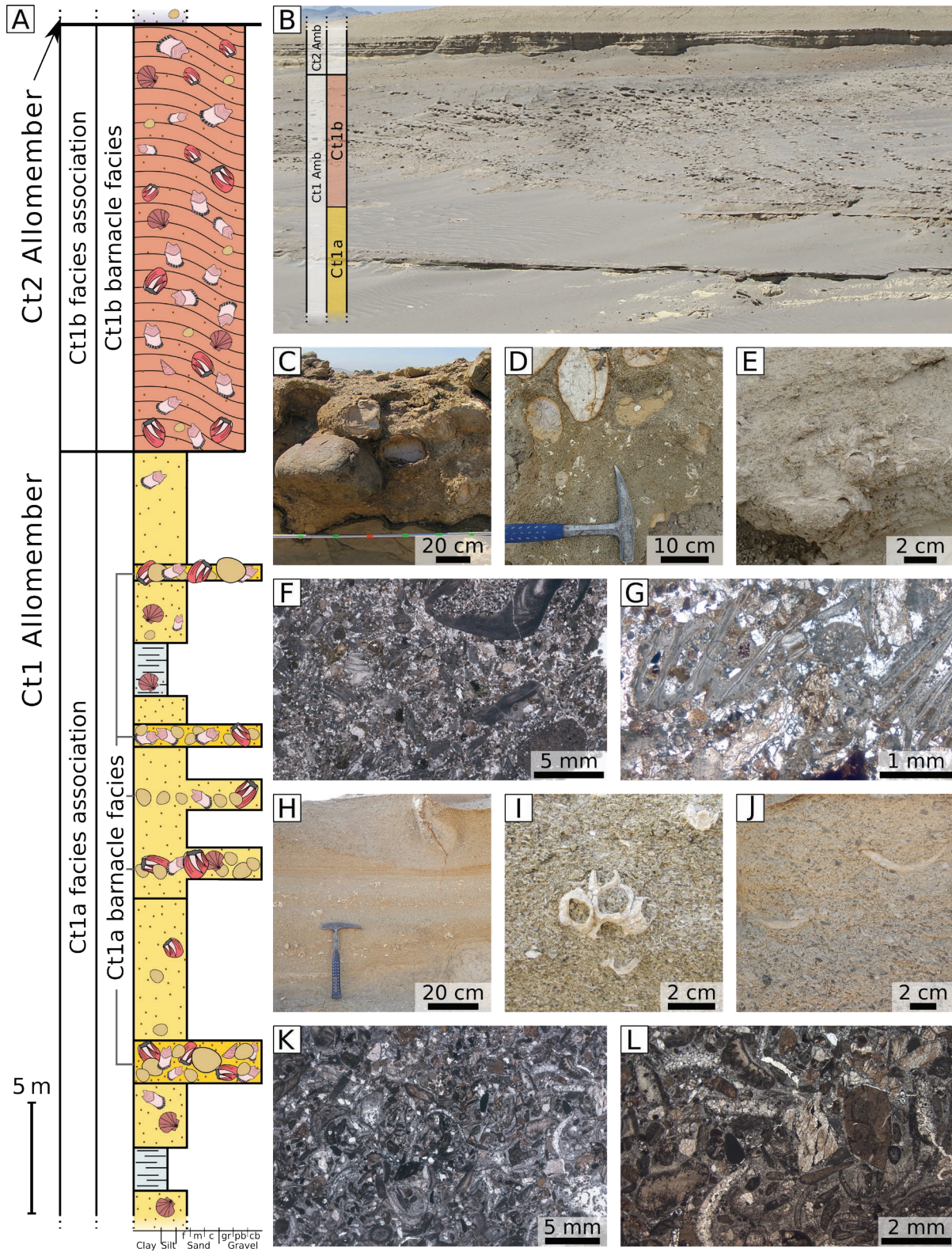
Fig. 7. Barnacle facies of the Chilcatay Formation (Ullujaya, Peru). **A** — Simplified stratigraphic column of the barnacle facies of the Chilcatay Formation. **B** — Overview of the Ullujaya outcrop including a simple stratigraphic column highlighting the different facies. **C** — Macroscopic texture of the barnacle facies of Ct1a. **D** — Detail of the texture and clast composition of the Ct1a barnacle facies. **E** — Detail of the texture and composition of the Ct1a barnacle facies. **F** — Thin section of a sample of the Ct1a barnacle facies. **G** — Detail of sample of the Ct1a barnacle facies with barnacles and foraminifera. **H** — Macroscopic texture of the Ct1b barnacle facies. **I** — Detail of the texture and bioclastic composition of the Ct1b barnacle facies. **J** — Detail of the texture and composition of the Ct1b barnacle facies. **K** — Thin section of a sample of the Ct1b barnacle facies. **L** — Detail of the abundant sparite-filled molds in the Ct1b barnacle facies.

Barnacle preservation

In both facies, the cirripede remains occur as displaced clusters, displaced complete shells and wall plate fragments (Fig. 8). Unlike the barnacle-coralline facies, the clusters are generally detached from their original substrate (Type C of Nomura & Maeda 2008; displaced clusters of Doyle et al. 1997).

Complete specimens are generally moderately well-preserved, but display evidence of abrasion and lack the opercula (Fig. 8). The best preserved specimens retain their pigmentation (Fig. 8A, D). The shells are often filled by sand. In the barnacle facies of Ct1a, this filling is remarkably rich in bioclastic fragments and has less abundant mineral grains than the rock embedding the specimens. Disarticulated plates are often abraded (Grade 1 of Nielsen & Funder 2003). Opercula

are rare — only a couple of abraded and fragmented scuta have been recovered.

Barnacle identification

Based on macroscopic features of the wall plates and on their internal microscopic structure, three barnacle taxa have been recognized: cf. *Austromegabalanus* sp., Balanidae indet., and Concavinae indet. (Fig. 8). The specimens identified as cf. *Austromegabalanus* sp. have a shell diameter approaching 4 cm (Fig. 8A–C); they are comprised of six wall plates with broad, well-developed radii plus a calcareous, tubiferous, basis (Fig. 8A). The best preserved specimens are longitudinally striped, with pink-purple bands alternating with white (Fig. 8A). In thin section, the radii are tubiferous and their sutural edges bear transversely oriented septa with secondary
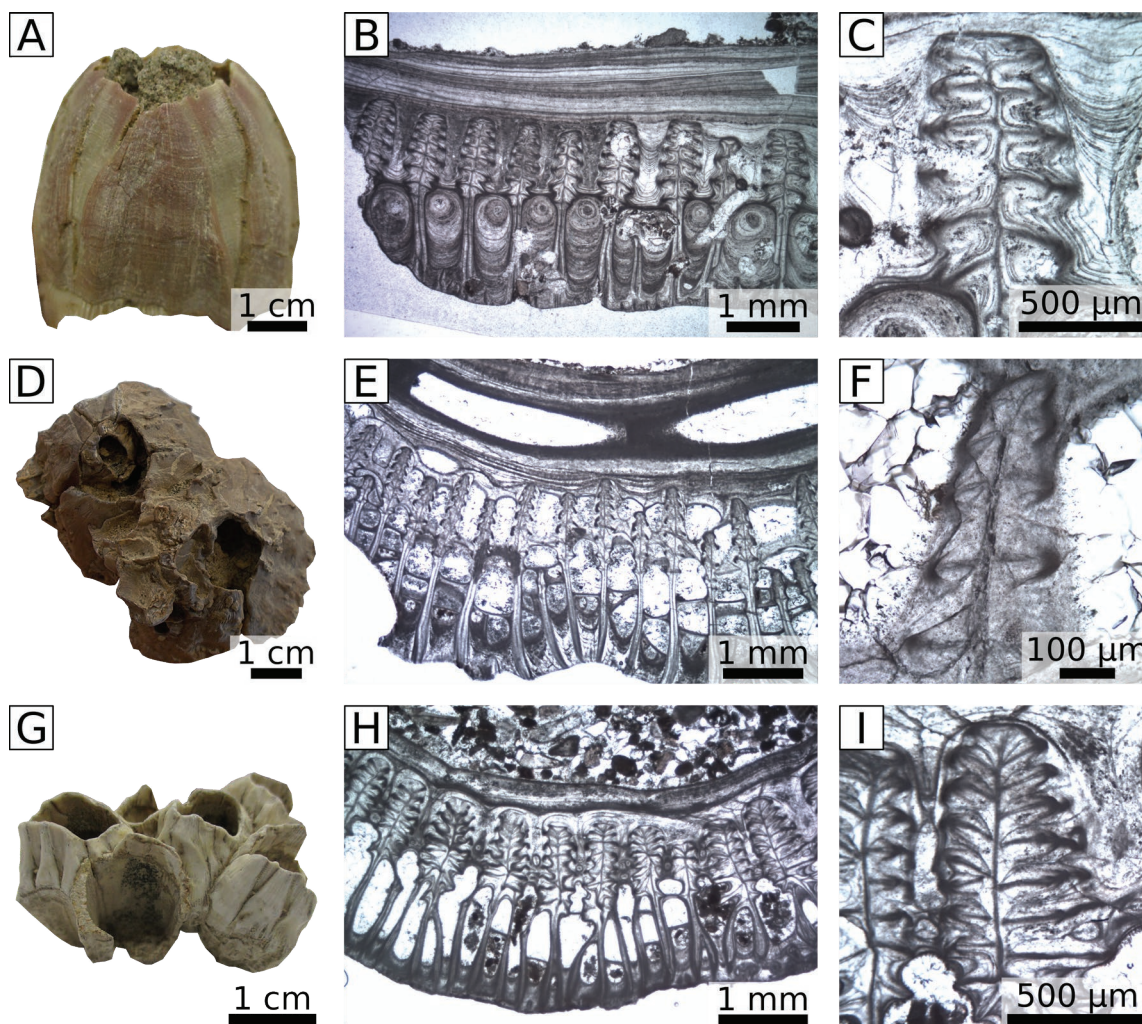

Fig. 8. Barnacles of the barnacle facies of Ullujaya (Peru). **A** — cf. *Austromegabalanus* sp., complete shell (from Ct1a). **B** — cf. *Austromegabalanus* sp., interlaminate figures (from Ct1a). **C** — cf. *Austromegabalanus* sp., detail of the interlaminate figures (from Ct1a). **D** — Balanidae indet., cluster of shells (from Ct1a). **E** — Balanidae indet., interlaminate figures (from Ct1a). **F** — Balanidae indet., detail of the interlaminate figures (from Ct1a). **G** — Concavinae? indet.,cluster of shells (from Ct1b). **H** — Concavinae? indet., interlaminate figures (from Ct1a). **I** — Concavinae? indet., detail of the interlaminate figures (from Ct1a).

denticles on the lower side only (a diagnostic character of the megabalanine genera included in the tribe Austromegabalanini; Newman 1979; Buckeridge 2015). The interlaminate figures present an almost straight main axis with many transverse branches characterized by multiple arrow-shaped terminations (Fig. 8B–C). *Austromegabalanus* Newman, 1979 is known to occur along the coasts of southern Peru and in the Miocene sediments of the Pisco Basin (*e.g.*, Newman 1991; Carriol et al. 1987). The specimens referred to Balanidae indet. are medium- to large-sized shells, comprised of six wall plates and characterized by a longitudinally striated outer wall with spiny-bulging protuberances creating a rough and irregular external surface (Fig. 8D–F). Some individuals display a pink colour on the plates (Fig. 8D). In the lowermost portion of the shell the basal edges of the wall plates become inflected, and grow horizontally inwards, thus producing an inward-tapering calcareous membrane. This feature is often incomplete (*i.e.*, a hole is present at the centre of the basal calcareous membrane). In juvenile individuals that were overgrown by adults the basal calcareous membrane is not developed. The parietes of the wall plates are porous and multiple rows of tubes are present (Fig. 8E). Large pores occur also in the sheath (Fig. 8E). The radii are solid. Interlaminate figures are arborescent, with a long straight axis and short transverse branches with crescent-moon to kidney-shaped terminations (Fig. 8F). Based on the general architecture of the six-plated shell and the presence of complex interlaminate figures, these specimens are provisionally identified as indeterminate balanids. Among Balanidae, a porous sheath characterizes *Titobustillobalanus tubutubulus* Carriol & Álvarez-Fernández, 2015 from the latest Pleistocene of Spain and various species of the amphibalanine genus *Fistulobalanus* Zullo, 1984. The specimens identified as Concavinae indet. are medium- to small-sized, six-plated shells with a basal diameter ranging between 1 and 2 cm (Fig. 8G–I). They appear to have been strictly cluster-forming organisms, since even displaced single individuals show an elongated, tubiferous, basal plate tapering downwards (a morphology that is typically associated with a gregarious growth habit, *e.g.*, Newman & Ross 1976). Some specimens display a faint pink to purple pigmentation. The wall plates are porous and display a single row of tubes divided by frequent transverse septa (Fig. 8H). Interlaminate figures have a long and straight axis with numerous, closely-spaced transverse branches characterized by arrow-shaped terminations (Fig. 8I). These branches are often organized in pairs, stemming from the same point of the main axis (Fig. 8I). The very rare opercula retrieved in the sieved material may be attributed to this group of specimens due to their size. They consist of triangular scuta characterized by transverse growth lines.

A further, currently unidentified, barnacle taxon was observed only once in the Ct1a facies association. It is represented by small-sized individuals (around 0.5 cm in basal diameter) forming a cluster which partially encrusts a pectinid shell. These small-sized barnacles could also represent juveniles of one of the afore-mentioned taxa. The common

occurrence of pectinids with small barnacle attachment scars (*Anellusichnus circularis* Santos, Mayoral & Muñiz, 2005) on the outer surface could indicate that this type was less uncommon than suggested by body fossils alone.

Discussion

Facies interpretation

Previous works based on coralline-algal and foraminiferal assemblages suggest that both the Pietra da Cantoni and the Sommières Basin barnacle facies developed in a tropical setting (Vannucci et al. 1996; Coletti et al. 2015, 2017, 2018). Vertebrate and mollusc assemblages indicate warm-temperate conditions for the East Pisco Basin during the deposition of the Ct1 beds of the Chilcatay formation (DeVries & Frassinetti 2003; Bianucci et al. 2018). The observation of the foraminiferal genus *Peneroplis*, which is typical of warm and warm-temperate water (Murray 2006), supports this hypothesis. The skeletal assemblages observed in all the sites, characterized by the abundance of filter feeding organisms and the scarcity of symbiont-bearing taxa, in warm water points to a nutrient-rich setting (Brasier 1995 a, b). This is also in agreement with other works on the studied successions (Dunbar et al. 1990; Reynaud & James 2012; Coletti et al. 2015, 2017; Bianucci et al. 2018).

Both barnacle facies of the Chilcatay Formation have a "low diversity" skeletal assemblage, with barnacle and molluscs (mainly epifaunal bivalves like ostreids and pectinids) accounting for >75 % of the skeletal fragments (Table 1). It should be noticed that mollusc abundance was probably reduced by selective dissolution during diagenesis; this particularly applies to the barnacle facies of Ct1b, where mollusc-shaped, sparite-filled molds are common. The abundance of barnacles and epifaunal bivalves points toward an exposed setting since both groups are favoured by high water energy (Farrow et al. 1978; Nebelsick 1992). A setting favourable for barnacles is also supported by the diverse barnacle assemblage with at least three common taxa. The preservation of barnacles in both facies is similar. Whole individuals are present (either as displaced clusters or single shells) and always separated from their substrate. Some specimens still preserve their pigmentation but the majority of them do not. Opercula are extremely rare. These characteristics suggest significant reworking, compatible with a setting above fair-weather wave-base. This hypothesis is in agreement with Bianucci et al. (2018) and Di Celma et al. (2018b), which interpreted Ct1b as a shoreface deposit, probably formed at a water depth of less than 15–20 m (assuming a storm-wave base around 15–20 m in accordance with the models of Hernández-Molina et al. 2000; Massari & Chiocci 2006). The same authors interpreted Ct1a as an offshore deposit resulting from the downslope transport of shoreface material (below 30–40 m of water depth since the height of the clinoforms is about 15–20 m). Since both facies have the same signature, it is likely that most of

reworking occurred in the shoreface environment, with the downslope movement only mildly affecting the association. This is also supported by the sediment preserved within the shells of the Ct1a barnacles, which is similar in composition to that of Ct1b (more bioclasts and less siliciclastic particles).

The skeletal assemblage of the barnamol facies of the Sandy Molasse Unit is also overwhelmingly dominated by barnacles and epifaunal bivalves, suggesting a high-energy setting (Table 1; Farrow et al. 1978; Nebelsick 1992). Extensive evidence of dissolution was not observed in this facies, suggesting that the mollusc abundance was not significantly reduced. Suitable conditions for barnacles are suggested by the presence of a diverse cirripede assemblage. There are no complete shells and well-preserved specimens in general are missing; opercula are also extremely rare. The poor state of preservation of the barnacle remains and the cross-bedded structure of this facies are consistent with a very shallow and proximal marine environment (nearshore zone, less than 15 m of water depth). This interpretation is in agreement with previous sedimentological studies on the Boisseron outcrop of the Sandy Molasse Unit (Reynaud & James 2012). The environment was probably characterized by higher hydrodynamic energy than that of the Chilcatay Formation.

The barnalgal of the Pietra da Cantoni significantly diverge from the other barnacle facies. Siliciclastic elements are much rarer (Table 1), ruling out the presence of nearby rocky cliffs. Its skeletal assemblage is more diverse, coralline algae are codominant, benthic foraminifera are more diverse, and there are fewer molluscs and echinoids than in the other facies (Table 1). There is no extensive evidence of dissolution suggesting that the low abundance of molluscs is not a result of diagenetic processes (although leaching of aragonite might have occurred since gastropods are absent even thought gastropods predation holes are present on barnacles). Unlike the other facies only a single taxon of barnacle was recognized. Differing from the other facies, most of the shells are well preserved, retain their original colour and are associated with their substrate (*i.e.*, the rhodoliths). Opercula are abundant and only limited reworking can be inferred by the unequal ratio of terga and scuta (the heavier scuta being more common than the lighter terga). These features suggest a less exposed environment, below the fair-weather wave base (probably between 20 and 40 m of water depth). This is in agreement with previous studies that interpreted this material as a short-distance mass-transport of inner-middle ramp material deposited in a slightly deeper middle-ramp setting (below 50–60 m of water depth; Schüttenhelm 1976; Coletti et al. 2015). Short-distance transport and rapid burial, without further reworking, are strongly supported by the preservation of colour in barnacles (Hollingworth & Barker 1991; Aguirre et al. 2008).

The detailed comparison of skeletal assemblages, petrographic characteristics and barnacle preservation and diversity clearly separates the barnalgal facies from the remaining three facies. The latter have a diverse barnacle assemblage mainly associated with epifaunal bivalves and echinoids, and

comprise an important siliciclastic fraction. The barnalgal do not. The French and Peruvian facies are related to a very shallow, nearshore carbonate factory, developed along a high-energy rocky coast. This is the ideal setting for encrusting barnacles; they are perfectly adapted to systems where hard surfaces are abundant. The environment of the barnalgal facies deviates substantially from this optimum. There are less available surfaces and most of them are coralline algae, which directly compete with barnacles for space (as suggested by the presence of alternating layers of barnacles and coralline algae in the rhodoliths). This might explain why various different species of barnacles are found in the first group of facies and only a single species characterizes the barnalgal facies.

Environmental controls on barnacle facies

Modern barnacle facies occur from the Poles to the Equator and, notwithstanding this large latitudinal variation, they show clear similarities (see Table 2 for the complete references list and Fig. 9 for the locations). Barnacle facies usually contain abundant molluscs (Table 2; Hoskin & Nelson 1969; Milliman 1972; Müller & Milliman 1973; Farrow et al. 1978; Scoffin 1988; Wilson 1988; Halfar et al. 2006; Westphal et al. 2010; Michel et al. 2011; Reijmer et al. 2012; Reymond et al. 2016). Echinoids are important contributors in most of the occurrences (Table 2; Hoskin & Nelson 1969; Farrow et al. 1978; Scoffin 1988; Wilson 1988; Michel et al. 2011). At low latitudes, the association with hermatypic corals is also possible (Table 2; Glynn & Wellington 1983; Halfar et al. 2006; Reymond et al. 2016). Coralline algae and benthic foraminifera are practically absent (Table 2; Hoskin & Nelson 1969; Farrow et al. 1978; Scoffin 1988; Wilson 1988; Halfar et al. 2006; Westphal et al. 2010; Michel et al. 2011; Reijmer et al. 2012; Reymond et al. 2016). Barnacle facies have an important siliciclastic fraction, which accounts for at least 10 % of the grains, although it is typically much higher (Table 2; Hoskin & Nelson 1969; Milliman 1972; Müller & Milliman 1973; Farrow et al. 1978; Scoffin 1988; Scoffin and Bowes 1988; Wilson 1988; Halfar et al. 2006; Westphal et al. 2010; Michel et al. 2011; Reijmer et al. 2012; Frank et al. 2014; Reymond et al. 2016). As far as the depositional environment is concerned, most modern barnacle facies are related to shallow-water (less than 50 m and generally less than 20 m), high-energy environments with nearby rocky outcrops (Table 2; Hoskin & Nelson 1969; Farrow et al. 1978; Scoffin 1988; Wilson 1988; Henrich et al. 1995; Halfar et al. 2006; Westphal et al. 2010; Michel et al. 2011; Reijmer et al. 2012; Reymond et al. 2016). Most barnacle facies are also related to plankton-rich water (Table 2; Müller& Milliman 1973; Taviani et al. 1993; Henrich et al. 1995; Westphal et al. 2010; Michael et al. 2011; Reijmer et al. 2012; Klicpera et al. 2013; Frank et al. 2014; Reymond et al. 2016).

Those occurrences that significantly deviate from this general model are located at polar latitudes and in bathyal settings (Table 2). The barnacle facies of the Barents Sea are characterized by almost pure carbonates, composed of barnacles and

Table 2: Sub-recent and recent barnacle facies, including information on the position, barnacle assemblage, skeletal assemblage, texture, clastic fraction and available environmental information.

Location	Age	Key references	Barnacle taxa	Associated bioclasts	Texture	Clastic particles	Environmental information
Antartica, Ross Sea Shelf	Pleistocene–Recent	Frank et al. 2014; Taviani et al. 1993	*Bathylasma corolliforme* (Hoek, 1883)	Locally only composed by barnacles; minor local contributions from stylasterine hydrocorals, bryozoans and benthic foraminifera; rare bivalves and serpulids. According to Taviani et al. (1993) barnacles are mainly associated with foraminifera	Coarse to very coarse	0 to 40 %	Polar; more than 350 m of water depth; high energy; plankton-rich water
South Pacific Ocean, South Tasman Rise	Holocene–Recent	Buckeridge 1999	*Tetrachaelasma tasmanicum* Buckeridge, 1999	Mainly solitary deep-water scleractinian corals, but also planktonic foraminifera	Very fine to coarse	Present, both rocks and mud	Bathyal environment, 2100-3600 m of water depth
South Madagascar; Indian Ocean	Recent	Newman & Ross 1976	*Tetrachaelasma* Newman & Ross, 1971	///	Coarse	///	Bathyal environment, 2000 m of water depth
Barents Sea, Spitsbergenbank	Recent	Henrich et al. 1995	*Balanus crenatus* Bruguière, 1789	Mainly benthic foraminifera	Coarse	Pure carbonate	Polar; between 6 and 20 m of water depth; high energy; plankton-rich water
Alaska, Alexander Archipelago	Recent	Hoskin & Nelson 1969	///	Major contributions from molluscs and echinoids; minor contributions from benthic foraminifera; rare ahermatypic corals, coralline algae and bryozoans	Fine to coarse	15 % to 60 %	Cold sub-polar; macrotidal setting
Canada, Newfoundland	Recent/Sub-recent	Müller and Milliman 1973	///	Major contribution from molluscs	Coarse	50 % to 80 %	Cold sub-polar; 60 to 80 m of water depth; plankton-rich water
USA, locally along Carolina and Florida Atlantic shelves	Recent/Sub-recent	MacIntyre & Milliman 1970; Milliman 1972	*Balanus calidus* Pilsbry, 1916 (temptative)	Mainly coralline algae (locally codominant)	///	3 % to 74 %, 39 % on average	Barnacles growing on a relict algal ridge that borders the upper slope and the outer shelf edge (50-150m); strong currents.
USA, locally along Carolina and Florida Atlantic shelves	Recent/Sub-recent	Milliman 1972	*Balanus calidus* (temptative)	Mainly molluscs (locally codominant)	///	3 % to 94 %, 45 % on average	Barnacles growing on submerged rocky outcrops
U.K., western Scotland	Recent	Farrow et al. 1978; Scoffin 1988; Wilson 1988	*Semibalanus balanoides* (Linnaeus, 1767)	Codominance with molluscs; important contributions from echinoids; minor contributions from serpulids and coralline algae; rare bryozoans and benthic foraminifera. According to Wilson (1988) the contributions from serpulids can be very important	Coarse	0 % to 50 %, with most of the values around 20 %	Cool-temperate; less than 50 m of water depth; hard substrate; high energy
Mexico, Bahía de Los Angeles	Recent	Halfar et al. 2006	///	Major contributions from molluscs and hermatypic corals; minor contributions from bryozoans and echinoids; rare serpulids; very rare coralline algae and barnacles	Fine to coarse	30 % to 70 %	Warm-temperate; upwelling currents; high nutrient concentration (eutrophic); less than 20 m of water depth; hard substrate; high energy
Pacific side of Panama, Gulf of Panama	Recent	Reijmer et al. 2012	///	Mainly bivalves; common gastropods; minor contributions from echinoids, serpulids, benthic foraminifera and coralline algae	Coarse	At least 10 %	Tropical; upwelling currents; high nutrient concentration (eutrophic); less than 50m of water depth
Mauritania, Banc D'Arguin	Recent	Westphal et al. 2010; Michel et al 2011; Klicpera et al. 2013	*Balanus* Costa, 1778	Codominance with bivalves; significant contributions from echinoids; rare gastropods and benthic foraminifera; very rare bryozoans	Medium	30 % to 50 %	Tropical; upwelling currents; high nutrient concentration (eutrophic); sub-tidal, less than 20 m of water depth; high energy
Chile, Galápagos Archipelago	Recent	Glynn & Wellington 1983; Westphal et al. 2010; Reymond et al. 2016	*Megabalanus tintinnabulum* (Linnaeus, 1758)	["barnamol"] Important gastropods and serpulids; minor contributions from bryozoans, bivalves, echinoids and coralline algae	Fine to coarse	10 % to 70 %	Equatorial; strong upwelling; less than 15 m of water depth; mesotrophic
				["barnamolcor"] Codominance with gastropods; important contributions from coralline algae and corals; minor contributions from echinoids, serpulids, bryozoans and bivalves		10 % to 50 %	Equatorial; moderate upwelling; less than 15 m of water depth; oligotrophic

benthic foraminifera (Henrich et al. 1995). Unlike the examples discussed in detail herein, carbonate production is localized far away from the coast, on shallow submerged rocky shoals colonized by kelp forests (Henrich et al. 1995). The Ross Sea barnacle facies develop on hard substrates under high energy conditions; however, they are dominated by *Bathylasma corolliforme* (Hoek, 1883) that lives in deeper water than most other encrusting barnacles (Taviani et al. 1993; Frank et al. 2014). Bathylasmatidae-dominated facies occur also in even deeper, bathyal, settings (Table 2; Newman & Ross 1976; Buckeridge 1999). They are found close to seamounts and, unlike their shallow-water counterparts, they are associated with fine grained sediments and deep-sea fauna (deep-water corals, bryozoans and planktonic foraminifera;
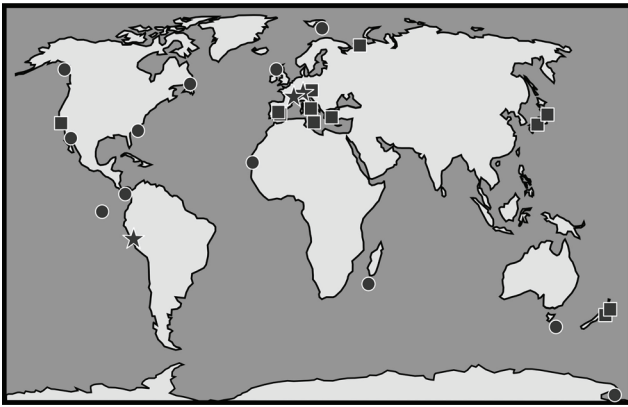
Fig. 9. World map including the location of the fossil (Neogene and Quaternary) and recent/sub-recent barnacle facies. Circles represent recent/sub-recent facies; squares indicates fossil facies; stars identify the early Miocene facies investigated in this study.

Newman & Ross 1976; Buckeridge 1999). The barnalgal association described by Milliman (1972) along the South-eastern Coast of the United States is also peculiar and differs from most of the other barnacle facies. It is related to the recent barnacle colonization of a relict algal ridge growing during the last glacial period that now borders the outer shelf edge.

Neogene and Quaternary barnacle facies follow the same pattern as their modern counterparts (Table 3; Fig. 9). The skeletal assemblage is mainly characterized by barnacles and molluscs, with common bryozoans and echinoids, rare benthic foraminifera and coralline algae; the siliciclastic fraction is also important (Table 3; Sakai 1987; Kamp et al. 1988; Nebelsick 1989, 1992; Doyle et al. 1997; Betzler et al. 2000; Nielsen & Funder 2003; Aguirre et al. 2008; Nomura & Maeda 2008; Stanton & Alderson 2013; Brandano et al. 2015; Buckeridge et al. 2018). They are generally interpreted as high-energy shallow-water deposits related to non-oligotrophic conditions (Table 3; Buckeridge 1983; Sakai 1987; Kamp et al. 1988; Nebelsick 1989, 1992; Doyle et al. 1997; Nielsen & Funder 2003; Civitelli & Brandano 2005; Aguirre et al. 2008; Nomura & Maeda 2008; Stanton & Alderson 2013; Brandano et al. 2015).

When considering the distribution of both modern and fossil barnacle concentrations, the major factors controlling the development of a barnacle-dominated carbonate factory seem to be the presence of suitable hard substrates, hydrodynamic energy and nutrient availability. Although barnacle accumulations are more common in the cool-temperate and cold realms, it seems that the lack of nutrients is the main factor that limits their distribution in the tropical zone. Therefore, an inshore rocky substrate characterized by high-energy conditions and abundant nutrient-supply is very favourable to the development of a barnacle-dominated carbonate factory. This setting represents an environmental optimum for barnacles (Sanford & Menge 2001) and other hard-substrate organisms (*e.g.*, ostreids and pectinids), and can lead to the formation of classical barnamol facies carbonates (*sensu* Hayton et al.

1995). Coralline algae might occur in this environment, but mostly as thin adherent crusts, with a poor preservation potential. Foraminifera can also occur, but they prone to be swept away by currents and deposited elsewhere (Farrow et al. 1978; Nebelsick 1992). The barnacle-rich facies investigated in this study comply with this model, except for the barnalgal facies. The latter represents a more atypical setting, located in slightly deeper water and where the surface available for barnacle colonization is more limited. Facies similar to those of the Pietra da Cantoni Group, with barnacle and coralline algae growing together, occur in the lower Miocene Latium-Abruzzi carbonate platform, where they have been interpreted as inner ramp deposits (Civitelli & Brandano 2005). Barnalgal assemblages are also reported in modern oceans, well below the fair weather wave base (Table 2; Macintyre & Milliman 1970; Milliman 1972). However, they do not represent an example of barnacles and coralline algae growing together but rather a case of barnacles colonizing a hard substrate provided by relict coralline algal bioconstructions (Milliman 1972). Although atypical barnacle facies are uncommon, they occur in both modern oceans and in the sedimentary record, thus indicating that dismissal of all barnacle concentrations as the result of nearshore carbonate factories might lead to erroneous palaeoenvironmental reconstructions. A perfect example includes Bathylasmatidae-rich facies, which are dominated by barnacles while being related to bathyal settings (Buckeridge 1975, 1999; Newman & Ross 1976). The study of the barnacle assemblage, as demonstrated herein, can help in identifying these atypical situations. Furthermore, while the hard substrate where barnacle carbonate factories normally develop is a major site of skeletal production, due to the high hydraulic energy, few bioclasts are preserved there (Scoffin 1988; Henrich et al. 1995). Most of the material is swept away and deposited in the closest sheltered areas (Scoffin 1988; Henrich et al. 1995). Remarkable transport processes are also reported in fossil barnacle facies, and can lead to significant displacement of the fossils (*e.g.*, Buckeridge et al. 2018). Therefore, before making palaeoenvironmental assumptions based on barnacles, their preservation should be carefully evaluated in order to determine how far the material has been reworked and transported prior to burial.

Conclusions

Four barnacle facies from three different Burdigalian successions have been analysed and divided into two groups on the basis of skeletal assemblages and barnacle preservation and diversity. The first group includes the barnamol facies of the Sandy Molasse Unit of the Sommières Basin (France) and the two barnacle facies of the Chilcatay Formation of the East Pisco Basin (Peru). These facies are overwhelmingly dominated by shallow-water hard-substrate biota, including different species of barnacles, molluscs (mainly ostreids and pectinids) and echinoids; they are also characterized by an important siliciclastic fraction. Skeletal assemblages,

Table 3: Neogene and Quaternary fossil barnacle facies, including information on the position, age, barnacle assemblage, skeletal assemblage, texture, clastic fraction and palaeo-environmental interpretation.

Location	Age	Key references	Barnacle taxa	Associated bioclasts	Texture	Clastic particles	Palaeoenvironmental interpretation
Southeastern Japan, Shikoku	Oligocene to Miocene	Sakai 1987	///	Very minor contributions from molluscs, bryozoans, echinoids, sponges and foraminifera	Coarse	Highly impure limestone	Shallow-water; high-energy
Austria, Bohemian Massif	Early Miocene	Nebelsick 1989, 1992	///	Codominance with bivalves (pectinids and ostreids), important contribution from bryozoans and serpulids	Very coarse	50 %	Shallow-water; near-shore; high-energy
Central Italy (several sites)	Early Miocene	Civitelli & Brandano 2005	///	Molluscs, coralline algae, echinoids, bryozoans, serpulids, ostracods and benthic foraminifera (both large- and small-sized forms)	Very coarse	Almost pure limestone	Tropical; shallow-water inner ramp; hard substrate; high energy; high nutrient concentration
Motutapu Island, New Zealand	Early Miocene	Buckeridge 1975	*Hexelasma aucklandicum* (Hector, 1888)	Bryozoans, molluscs, corals	Fine	Abundant	Deep-water; low-energy
Japan, Sendai	Early to middle Miocene	Nomura & Maeda 2008	*Arossia sendaica* (Hatai et al., 1976) (frequent); *Balanus sulcatus* Bruguière, 1789 (frequent); *B. crenatus* Bruguière, 1789; *B. rostratus* (Hoek, 1883)	Minor contributions from molluscs, serpulids and bryozoans; rare brachiopods, foraminifera, echinoids and corals	Very coarse	>>50 %	Very shallow-water; high-energy
California, Santa Monica Mountains	Early–middle Miocene	Stanton & Alderson 2013	///	Codominance with bivalves; minor contributions from echinoids, serpulids, bryozoans; rare gastropods and brachiopods; very rare coralline algae	Fine to coarse	Impure limestone	Warm-temperate; inner shelf; moderate-energy; hard substrate; high productivity
Italy, Liguria	Middle Miocene	Brandano et al. 2015	///	Bryozoans, serpulids, echinoids, benthic foraminifera (including symbiont-bearing *Amphistegina* d'Orbigny, 1826), bivalves; minor contributions from *Halimeda* Lamouroux, 1812	Very coarse	From more than 50 % to around 20 %	Humid tropical; high terrigenous input; near-shore shallow-water, above fair-weather wave base; high energy; high nutrient supply
Spain, Almeria	Late Miocene	Doyle et al. 1997	*Megabalanus* cf. *tintinnabulum* (Linnaeus, 1758)	Minor contributions from bivalves, echinoids and bryozoans	Very coarse	>50 %	Very shallow-water
Spain, Almeria	Late Miocene	Betzler et al. 2000	///	Minor contributions from bivalves, bryozoans; coralline algae, echinoderms, gastropods; rare ostracods	Very coarse	///	More than 15m of water depth; moderate energy
Spain, Almeria	Pliocene	Aguirre et al. 2008	*Concavus concavus* (Bronn, 1831) (dominant); *Perforatus perforatus* (Bruguière, 1789); *Megabalanus* Hoek, 1913	Mainly bivalves but also bryozoans	Coarse to very coarse	Up to 50 %	High energy; near-shore shallow-water; high nutrient supply
Greece, Rafina	Pliocene	Radwańska & Radwański 2008	*Concavus concavus*	///	///	///	///
New Zealand, North Island (several sites)	Pliocene–Pleistocene	Hayton et al. 1995; Kamp et al. 1988; Buckeridge 1983; Buckeridge 2015; Buckeridge et al. 2018	*Notobalanus* Newman & Ross, 1976; *Austromegabalanus* Newman 1979; *Balanus* Costa, 1778; *Fosterella* Buckeridge, 1983	Mainly bivalves, but also bryozoans; minor contributions from echinoids and small benthic foraminifera; rare coralline algae; brachiopods and solitary corals	Coarse to very coarse	10 %–20 % for most of the samples	Cold- to warm-temperate; high nutrient concentration; sub-tidal, less than 50–30 m of water depth; hard or coarse-grained substrate; high-energy seaway; locally important downslope transport of sediment

barnacle preservation and sedimentary structures suggest that the bioclasts originated in a high-energy rocky shoreface environment (less than 15–20 m of water depth), where reworking of bioclasts was significant. The second group includes the barnacle and coralline algae facies of the Pietra da Cantoni Group of the Tertiary Piedmont Basin (Italy). For this peculiar skeletal assemblage, rarely reported from the fossil record, the new name "barnalgal" is proposed. The barnalgal is characterized by a single barnacle species, abundant coralline algae, benthic foraminifera and almost no siliciclastic elements. Compared to the other facies, barnacle shells are also

better preserved. The related carbonate factory probably developed in slightly deeper conditions (20–40 m of water depth) than those responsible for the first group of barnacle facies. In this setting, the only hard substrate available for barnacles were rhodoliths, leading to the formation of this atypical association. Reworking was also less important, reducing the abrasion of the specimens and leading to the conservation of abundant barnacle opercula in the sediment.

The analysis of both modern and fossil barnacle facies suggests that the major factors controlling the development of a barnacle-dominated carbonate factory are the availability of

hard substrate, hydrodynamic energy and nutrient availability. Consequently, the most favourable setting for a barnacle-dominated carbonate factory is probably an inshore rocky substrate characterized by high-energy conditions and abundant nutrient supply. This situation can lead to the formation of the typical barnacle-rich deposit, where abundant barnacles are associated with other hard substrate organisms (*e.g.*, the barnamol assemblage). The first group of facies recognized in this paper, embracing the French and Peruvian case studies, can be easily included in this category. The Italian barnalgal facies, on the other hand, represents an atypical barnacle facies related to situations that deviate from the aforementioned environmental optimum. Similar atypical situations can be identified throughout careful analyses of both the skeletal assemblage and the barnacle association, highlighting the importance of barnacle palaeontology for palaeoenvironmental reconstructions in shallow-water settings.

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