LOWER PLIOCENE BARNACLE FACIES OF WESTERN LIGURIA (NW ITALY): A PEEK INTO A WARM PAST AND A GLIMPSE OF OUR INCOMING FUTURE

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Abstract. The lower Pliocene deposits of Pairola (Liguria, Italy) display the otherwise rare occurrence of rock-forming amounts of barnacles (mostly belonging to the extinct Euromediterranean species *Concavus concavus*). Three main facies are recognised in the investigated succession: a barnacle-dominated facies, which formed along a shallow (<15 m deep) nearshore environment, a foraminifera-dominated facies from relatively deeper waters (40-100 m), and an intermediate facies forming at the boundary of the other two. These facies and their relationships suggest deposition in a flooded valley – a kind of setting that was common in the Mediterranean after the Messinian Salinity Crisis. Differing from other rias, the Pairola basin was exposed to strong waves, resulting in conditions favourable to barnacles. Sedimentological and stratigraphic observations indicate that the Pairola succession formed within a timespan covering both cold and warm phases. This is relevant because the sub-tropical foraminifer *Amphistegina* is ubiquitous throughout the succession. *Amphistegina* occurs in the Pliocene and lower Pleistocene (Gelasian) of Northern Italy, but not in the remainder of the Pleistocene, not even its warm portions. This genus is currently recolonizing the Mediterranean and is projected to reach the northern coast of the basin soon, foretelling that Anthropocene temperatures are going to overcome those of the late Pleistocene warm periods and reach those of the Pliocene.

INTRODUCTION

Upper Neogene exposures of marine deposits are a common occurrence along the Italian Peninsula and have been investigated since the dawn of Italian geology, thus resulting in several stratotypes being located in Italy (e.g. Stoppani 1880; Issel 1910; Cita & Castradori 1995; Castradori et al. 1998; Van Couvering et al. 2000; Cantalamessa & Di Celma 2004; Cita et al. 2006, 2008; Violanti 2012; Amorosi et al. 2014; Nalin et al. 2016; Coletti et al. 2018a; Cau et al. 2019; Dominici & Scarponi 2020). These successions record the relatively recent past of the Mediterranean area and provide one of the best available models for understanding how the ongoing climate change will impact the Mediterranean realm in the near future. They formed within a geographic and climatic context that, with respect to previous epochs, is relatively similar to the present one and is characterised by

faunal and floral assemblages that include a large number of extant species, making the comparison with recent environments quite easy. Overall, the Mediterranean Pliocene palaeoenvironments, with their mostly warm climatic signature, comprise a very realistic example of what the Mediterranean Sea might become in a not-so-far future (e.g. Conti et al. 1983; Di Bella et al. 2005; Triantaphyllou et al. 2009; Langer et al. 2012; Prista et al. 2015). Among these Pliocene deposits, the shallow-water coastal successions have a special importance. Present-day Italian coasts are urbanised, heavily populated and, at the same time, extremely vulnerable to environmental variations connected to climate change. Therefore, by providing a glimpse of what the future holds for us, these Pliocene coastal deposits provide opportunities for useful research. Pliocene deposits occur along most of the Ligurian coast (Giammarino 1984; Marini 1984), an area that currently is heavily threatened by extreme climatic events (e.g. Meroni et al. 2018). With the aim of studying the palaeoenvironment of the Ligurian coast during the early Pliocene, the present paper investigates in detail the outcrop of Pairola (Diano Marina, Imperia Province, Western Liguria), thus providing the first quantitative analysis of the skeletal assemblage of these shallow-water mixed siliciclastic-bioclastic deposits, as well as a comprehensive model for facies distribution and sedimentary dynamics. While most of the coarse-grained units of the Ligurian Pliocene consist of siliciclastic conglomerates that deposited in submarine fan settings (e.g. Marini 2000, 2001; Breda et al. 2007), the Pairola outcrop is characterised by an abundant biogenic fraction dominated by barnacles and molluscs, a skeletal assemblage that indicates a shallow-water origin (Coletti et al. 2018b). Biogenic-rich deposits, related to very shallow coastal settings, are quite uncommon in the Pliocene of Liguria and of Northern Italy in general, being much rarer than their siliciclastic counterparts (Boni & Peloso 1973; Boni et al. 1976; Giammarino 1984; Gnaccolini 1998; Marini 2000, 2001; Breda et al. 2007; Nalin et al. 2016; Cau et al. 2019). The Pairola outcrop, with its barnacle-dominated, coarse-grained deposits, thus represents a uniquely informative lower Pliocene shallow-marine succession, and as such, it offers a great opportunity for investigating the coastal palaeoenvironment of Western Liguria during the early Pliocene.

GEOLOGICAL SETTING

During the Messinian Salinity Crisis, the Mediterranean Basin saw a remarkable sea-level drop, likely inducing an intense erosive phase resulting in the formation of deep and long canyons (Hsü et al. 1973; Adams et al. 1977; Ryan & Cita 1978; Clauzon et al. 1995; Krijgsman et al. 1999; Roveri et al., 2014; Madof et al. 2019; Meilijson et al. 2019). During the ensuing Zanclean transgression, the Messinian canyons were rapidly flooded by the sea and became rias (flooded valleys), thus providing the Western Ligurian coastline with a physiography somewhat similar to that of the modern Scandinavian region (Boni 1984; Breda et al. 2007, 2009). The Western Ligurian Pliocene coast was bounded to the north by the rising Alpine massif and to the south by the subsiding Ligurian–Provençal Basin (Giammarino 1984; Chaumillon et al. 1994; Clauzon et al. 1995; Breda et al. 2007, 2009) (Fig. 1A, B). The uplift started in the late Miocene, with a major phase around 3.5 Ma (Bigot-Cormier et al. 2000; Foeken et al. 2003). It was more intense in the West, close to the External Massifs, causing the Pliocene deposits to be currently located at higher altitudes in Western Liguria (i.e. close to the border with France) and at progressively lower altitudes moving eastwards (Boni et al. 1976; Boni 1984; Giammarino 1984; Giammarino & Piazza 2000) (Fig. 1B). Both hinterland uplift and basin subsidence contributed to increase coastal steepness, leading to a physiography similar to the current one, characterised by an extremely narrow continental shelf and a steep slope (Rehault et al. 1984, 1985). Along the coast, these movements were accommodated by reactivated Oligocene-Miocene normal faults originally related to the opening of the Ligurian–Provençal Basin (Biju-Duval et al. 1978; Speranza et al. 2002; Chaumillon et al. 1994; Breda et al. 2007, 2009). These faults exerted a strong control over Pliocene sediment deposition, as testified by the fault-bounded nature of most Pliocene basins (Giammarino 1984; Fanucci et al. 1978, 1980; Marini 1984, 2000). Such an interaction between tectonics and erosion resulted in the creation of several, only partially connected basins and sub-basins that differed from each other in terms of depositional histories and dynamics (Boni et al. 1976; Boni 1984) (Fig. 1D).

Three main formations (hereinafter: fms) can be recognised in the Pliocene succession of

Fig. 1 - Study area. A) General location of the study area within the Mediterranean region. B) The Western Ligurian coast showing the main outcrops of Pliocene rocks (dark gray) and the major towns. C) Simplified stratigraphic log representing a hypothetical, roughly 100 m high, cross section of the Pliocene successions of Western Liguria. D) Detail of the study area between the headlands of Capo Berta and Capo Mimosa showing the main outcrops of Pliocene deposits (dark gray). E) Detail of the Pairola outcrop and of the nearby Poiolo outcrop.
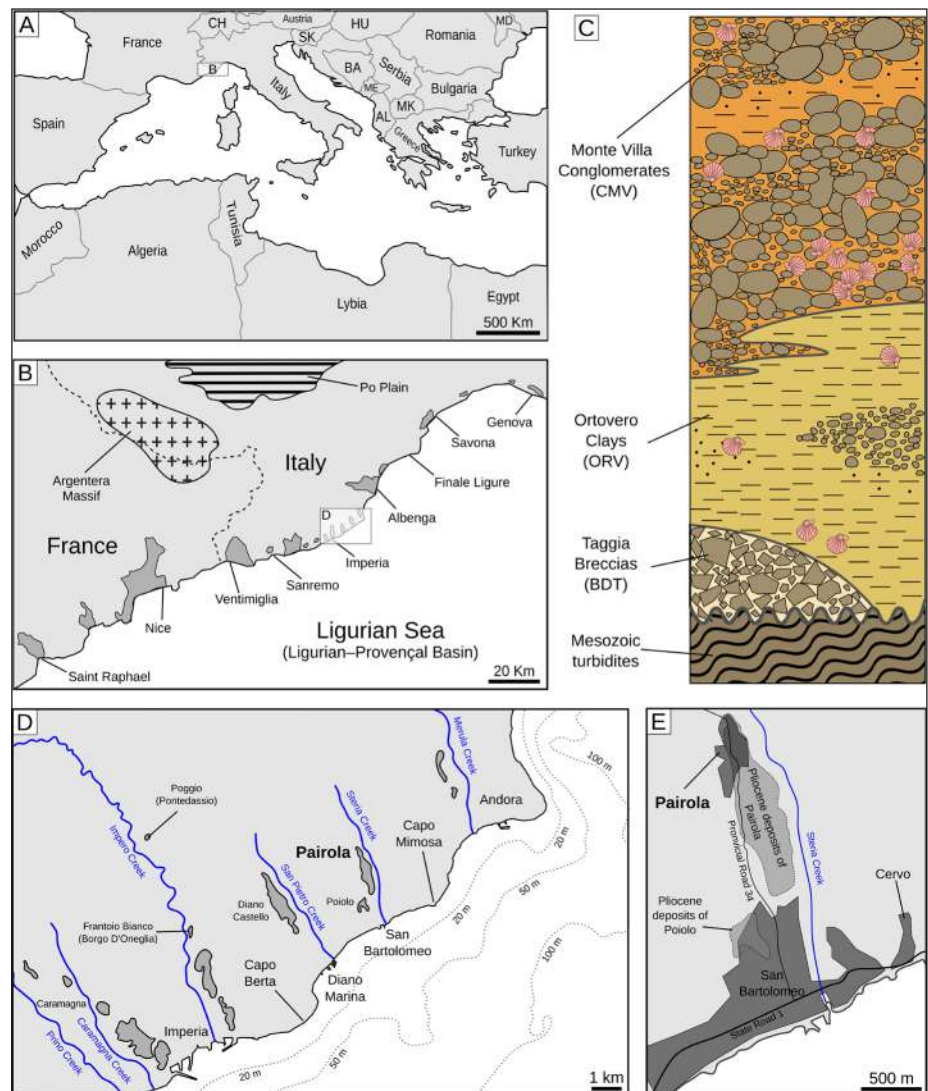
Western Liguria: the Taggia Breccias (Breccie di Taggia; BDT), the Ortovero Clays (Argille di Ortovero; ORV) and the Monte Villa Conglomerates (Conglomerati di Monte Villa; CMV) (Giammarino et al. 2010; Dalla Giovanna et al. 2016) (Fig. 1C). The BDT Fm represents the lowermost unit of the succession (Fig. 1C). It generally consists of small outcrops that are more common in the westernmost part of the region (close to the border with France) (Giammarino et al. 2010; Dalla Giovanna et al. 2016). The BDT Fm is comprised of poorly sorted, grain-supported breccias that completely lack any internal organization and display a silty-sandy matrix. Clasts are generally angular, with no evidence of rounding, and they clearly result form the erosion of the underlying substrate rocks (i.e. the Mesozoic flysch units) (Breda et al. 2007, 2009; Giammarino et al. 2010; Dalla Giovanna et al. 2016). The BDT Fm is interpreted as resulting from

the Messinian sub-aerial alteration and erosion of the pre-Pliocene substrate, whose constituting materials possibly re-sedimented as colluvial deposits, rock falls, rock slides and rock avalanches during the initial stages of the evolution of dry alluvial valleys (Boni et al. 1986; Marini 2000; Breda et al. 2007, 2009).

The ORV Fm is the most conspicuous Pliocene unit in the region. It occurs in most of the outcrops and often represents the sole evidence of Pliocene deposition; in most exposures, it directly overlies the pre-Pliocene substrate rather than the BDT Fm (Fig. 1C). The ORV Fm consists of clays and silty-sandy clays with local layers and lenses of coarse-grained material (usually siliciclastic conglomerates, but bioclastic intervals also occur) (Giammarino & Tedeschi 1983; Giammarino et al. 2010; Dalla Giovanna et al. 2016). The ORV Fm is generally characterised by a molluscan and
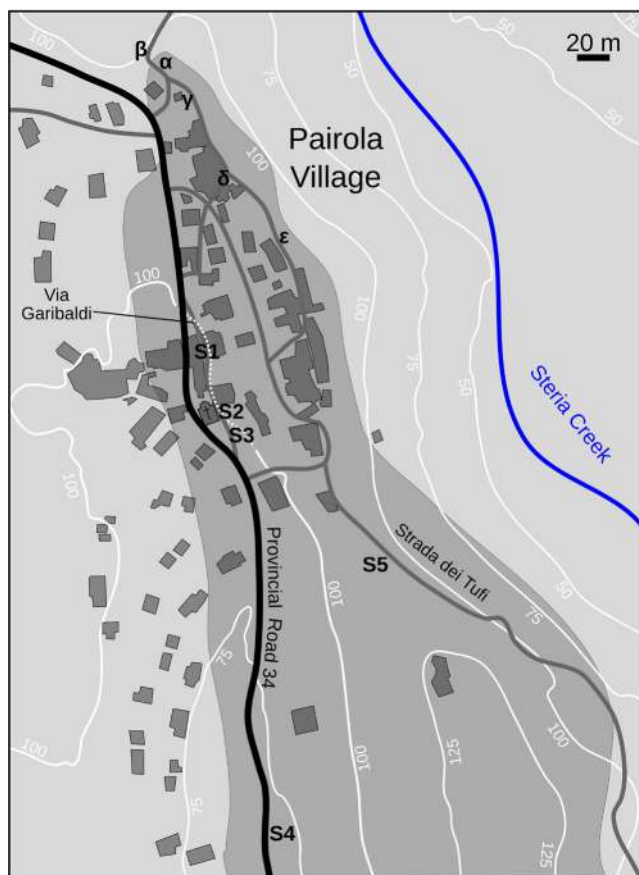
Fig. 2 - Detailed map of the investigated barnacle-rich deposits of Pairola. The map indicates all the observed outcrops and the five measured sections. The main buildings and alleys of the Pairola village are also indicated.

foraminiferal assemblage suggesting deposition in circalittoral to bathyal settings, at a few hundreds of meters of water depth (Giammarino & Tedeschi 1976, 1982, 1983; Robba 1981; Giammarino et al. 1984; Bernasconi 1989), but relevant differences exist between various outcrops (Boni et al. 1976; Marini 2000).

The CMV Fm is comprised of grain-supported, poorly organised, and generally poorly sorted conglomerates with a sandy-silty matrix and silty-marly lenses (Boni et al. 1984; Gnaccolini 1998; Giammarino et al. 2010; Dalla Giovanna et al. 2016) (Fig. 1C). Clasts are generally well rounded to sub-rounded, with rare platy elements, and are generally issued from the erosion of the Mesozoic flysch units that constitute most of the substrate of the Pliocene basins of Western Liguria (Boni & Peloso 1973; Boni et al. 1984; Gnaccolini 1998; Marini 2000). Westwards, along the Roia river valley near Ventimiglia (Fig. 1B), magmatic and metamorphic clasts also occur, originating from the erosion of

the External Massifs (e.g. the Argentera massif) and indicating longer and more developed drainage systems (Boni & Peloso 1973). Although generally treated as a single formation, the CMV Fm should rather be regarded a series of coarse-grained sedimentary bodies deposited in Gilbert-type deltas at variable water depths (Gnaccolini 1998; Marini 2000, 2001; Breda et al. 2007, 2009; Giammarino et al. 2010; Dalla Giovanna et al. 2016). Indeed, within the CMV Fm, it is generally possible to distinguish several delta deposits that are separated from each other by fine-grained layers; furthermore, there are significant differences in both the sedimentary structure and the petrographic composition of the different CMV bodies (Boni & Peloso 1973; Boni et al. 1976; Boni 1984; Gnaccolini 1998; Marini 2000, 2001; Breda et al. 2007, 2009). Moreover, it should also be underlined that the aforementioned general lithostratigraphic scheme (BDT, ORV, CMV) is just indicative. Most of the Ligurian Pliocene basins do not display the whole succession, and lateral facies transitions as well as facies interdigitations are very common (Boni & Peloso 1973; Boni et al. 1976; Boni 1984; Marini 2000, 2001; Giammarino et al. 2010; Dalla Giovanna et al. 2016).

In the study area, which is located between the headlands of Capo Berta and Capo Mimosa, several Pliocene outcrops are known from the localities of Diano Castello, Pairola and Poiolo, the latter two being located very close to each other (Boni et al. 1976) (Fig. 1D). At Diano Castello, the Pliocene deposits include the ORV and the CMV fms and mainly consist of poorly consolidated sands and sandy marls with small conglomeratic lenses. They feature abundant bivalves, bryozoans, benthic foraminifera (including both shallow-water taxa such as *Amphistegina* and taxa related to deeper conditions such as *Uvigerina*) and planktic foraminifera (Boni et al. 1976). The investigated outcrop of Pairola includes a basal portion made by coarse-grained, bioclastic-rich deposits (ascribed to the CMV Fm). This coarse-grained division, which represents the main target of our research, passes upwards and distally into sandy and marly strata (Boni et al. 1976). The nearby outcrop of Poiolo (Fig. 1D) entirely consists of marly deposits (ORV Fm) that recall those of the upper and distal parts of the Pairola outcrop, albeit differing from the latter for several petrographic characters (Boni et al., 1976); these deposits are characterised by a foraminiferal assemblage with
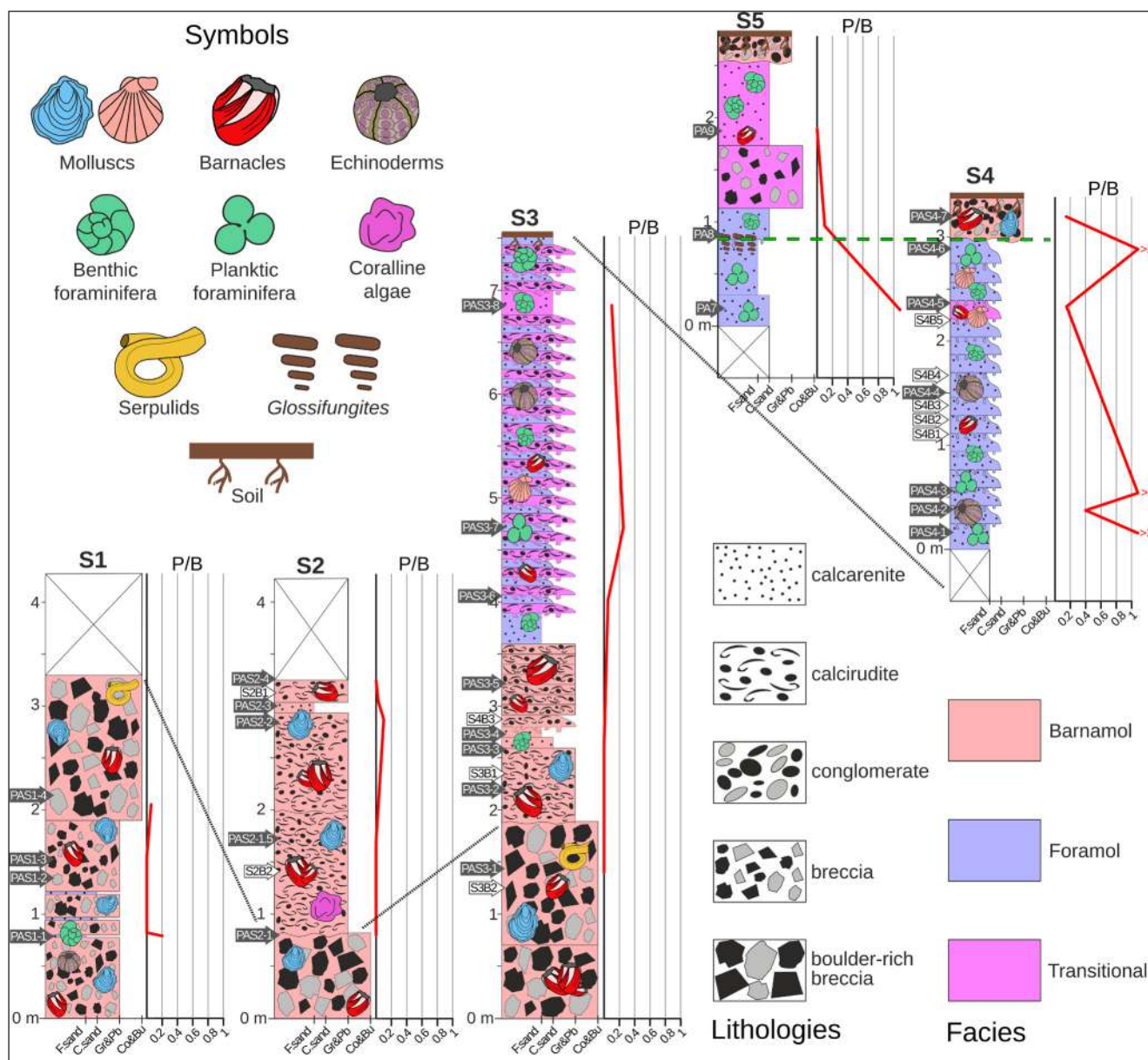
Fig. 3 - Measured stratigraphic sections and facies distribution at Pairola. The coordinates of the measured sections are the following: S1: 43°56'28.9" N, 08°05'47.8" E; S2, S3: 43° 56' 27.5" N, 08°5'48.4" E; S4: 43°56'14.13" N, 08°5'50.65" E; S5: 43°56'22.9" N, 08°05'55.5" E. Vertical scale in meters. Saint Andrew's crosses indicate portions hidden by buildings and/or vegetation. Dashed lines serve to correlate the sections. The thick green dashed line indicates a sequence boundary (see Discussion section in the main text). Grey arrows indicate bulk samples; white arrows indicate macrofossil samples (PA = Pairola; S1 = Section 1). The macrofossil content has been drawn on the basis of field and microscopic observations. P/B (plankton/benthos foraminiferal ratio) is based on thin section area counting. F= fine; C= coarse; Gr= granules; Pb=pebbles; Co=cobbles; Bu=boulders.

shallow-water benthic genera (including *Ammonia* and *Elphidium*) and planktic foraminifera (Boni et al. 1976).

Pliocene deposition in Western Liguria started immediately after the Zanclean reflooding of the basin, as testified at the base of the succession by the common presence of biozone MPL1 (*Sphaeroidinellopsis* acme zone) of Cita (1975) and Sprovieri (1992) (corresponding to the 5.3–5.1 Ma interval; Violanti 2012). The uppermost deposits are attrib-

uted to the biozone MPL5. The latter ranges from the last occurrence of *Sphaeroidinellopsis* to the first occurrence of *Globorotalia inflata* (3.2 – 2-1 Ma) and is characterised by the common presence of *Globorotalia aemiliana* (Violanti, 2012). According to Boni et al. (1976), the Pairola succession spans most of the Pliocene, with the basal strata displaying a MPL1 (lowermost Zanclean) assemblage and the uppermost strata being characterised by the presence of *Globorotalia bonomiensis* and the lack of *G.*

aemiliana, which suggests a late MPL4b age (3.3–3.2 Ma; middle Piacenzian; Violanti 2012).

MATERIAL AND METHODS

The beds of the basal portion of the Pairola succession, which are the main target of this research, are exposed within the village of Pairola, and as such, they are largely hidden by buildings and agricultural terraces. However, small outcrops occur at the base of several buildings and along the main alley of the village (via Garibaldi, Fig. 2). Five short sections, located close to the church square and along the main alley, were studied for the purposes of the present paper (Fig. 2). Each section was measured with a Jacob's staff. The lithology, grain-size, texture, composition, sedimentary structures and macrofossil content were described directly in the field. Close-by sections were then correlated on the basis of field evidence and recurring petrographic similarities. Thirty representative bulk rock-samples were collected from each section for the microfacies analysis (and additional samples were collected from other small exposures within the Pairola village (Fig. 3; Table S1 in Appendix 1). Specimens of barnacles and molluscs were also collected from the outcrops for taxonomic identifications (Fig. 3). Special attention was given to the study of barnacles, and in particular to their systematic affinities, distribution and preservation style. Barnacle taphonomy was investigated following the methods of Donovan (1988), Doyle et al. (1997), Nomura & Maeda (2008) and Nielsen & Funder (2003). Thirty-seven thin sections were manually produced by the authors from bulk rock samples and then observed using a Leica Leitz Laborlux S transmitted light optical microscope at the Università degli Studi di Milano-Bicocca. The skeletal assemblages were quantified through point-counting of twenty-seven thin sections (Flügel 2010) by using a 250 μm mesh and counting more than 500 points for each section. Foraminiferal assemblages were studied by counting all the recognizable specimens occurring in each section (area counting method). All the data from point counting and area counting are provided in Table S1 (Appendix 1). Thin sections were also used to support barnacle identifications. The internal microstructure of the shells, and especially the interlaminate figures (which are created by the organic matrix during the formation of the denticles that connect the barnacle wall plates to the basal calcareous plate), represents a powerful instrument for barnacle systematics (Cornwall 1956, 1958, 1959, 1960, 1962; Davadie 1963; Menesini 1965, 1967; Newman et al. 1967, 1969; Newman & Ross 1971; Buckeridge 1983; Coletti et al. 2019; Collareta et al. 2019).

RESULTS

Lithostratigraphy and field observations

The contact between the Pliocene deposits and the underlying Mesozoic substrate was not directly observed in the field. In the northernmost part of the Pairola village, along a small country lane leading to agricultural terraces, a small exposure of clast-supported breccia could be studied (Fig. 2 (α)). This breccia consists of poorly-sorted angular elements, ranging from granule- to boulder-size, embedded in a sandy matrix (Fig. 4A). The

clasts originate from the breakdown of the calcareous layers of the underlying Mesozoic flysch units, whose outcrops can be found a few meters down the same country lane (Fig. 2 (β)). The breccia is separated by several meters of vegetation and soil from another small outcrop (Fig. 2 (γ)) consisting of coarse-grained, layered, mixed siliciclastic-bioclastic calcirudites (Fig. 4B). The siliciclastic fraction is represented by pebbles and cobbles (ranging from angular to sub-rounded) eroded from the Mesozoic substrate, while bioclastic elements are mainly represented by large barnacles and bivalve shells, with rarer calcareous algae (Fig. 4C). The shells do not display any preferential orientation, while the individual strata display a roughly fining-upward trend (Fig. 4C).

Within the village itself, the base of several buildings and the walls of several alleys are carved into the well-cemented Pliocene rocks (Fig. 2 (δ, ε)). The outcropping lithologies range from clast-supported conglomerates featuring bored limestone clasts (eroded from the Mesozoic flysch) to well-sorted, mixed calcirudites with abundant bivalve shells (Fig. 4D, E). Due to the patchy nature of these small outcrops, the stratigraphic relationships between these lithologies cannot be properly defined.

Further south, one side of the main alley of the village (via Garibaldi) is carved into the Pliocene rocks (Figs. 2 (S1)). The outcrop follows the alley for several meters, allowing the exposure to be properly studied. The base of this succession (S1) consists of layers of a matrix-supported breccia, with pebble-sized elements and a bioclastic matrix that is rich in barnacle and bivalve shells (Figs. 3, 4F-H). The breccia layers alternate with thin and discontinuous calcarenite intervals (Figs. 3, 4F). These strata are overlain by a, 1-m-thick, matrix-supported breccia formed by cobble to boulder-sized clasts floating in a bioclastic matrix (Figs. 3, 4H). These deposits gently and irregularly dip southward, i.e. toward the present-day (and Pliocene) coastline.

The second section (S2) is located few meters South of S1 and it is separated from the former by a built area (Figs. 2 (S2)). The base consists of a poorly-sorted, matrix-supported breccia with boulder-sized elements floating in a coarse-grained bioclastic matrix (Figs. 3, 5A). This breccia body is overlain by irregularly layered calcirudites that are mainly composed of barnacles (*Concavus concavus*)

Fig. 4 - Small outcrops in the northernmost part of the Pairola village and section S1. A) Poorly sorted, clast-supported breccia (Fig. 2 (α)). B) Coarse-grained, layered, mixed siliciclastic-bioclastic calcirudite (Fig. 2 (γ)). C) Detail of the calcarenites, displaying a fining-upward organization; white arrowhead = bivalve, black arrowhead = barnacle. D) Clast-supported conglomerates featuring bored limestone clasts (Fig. 2 (ε)), white arrowhead = date mussel boring (*Gastrochaenolites* isp.). E) Well-sorted calcirudites with abundant bivalve shells (Fig. 2 (δ)), black arrowhead = pectinids. F) Section S1, matrix-supported breccia, with pebble-sized elements, alternating with thin and discontinuous calcarenite intervals (white arrowhead). G) Fine grained bioclastic fraction of the breccia layer, displaying abundant barnacle plates (black arrowhead). H) Section S1, matrix-supported breccia with cobble to boulder-sized clasts.
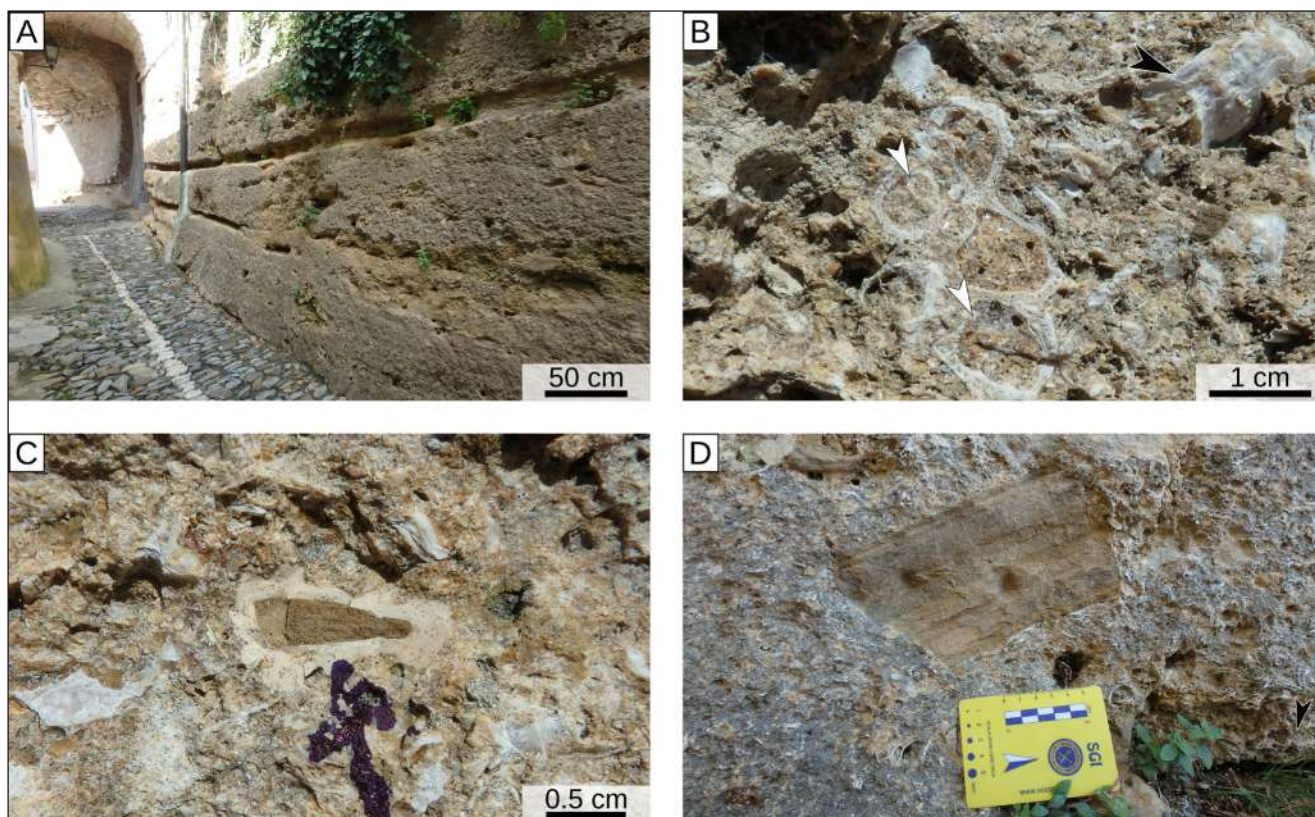
Fig. 5 - Section S2. A) Poorly-sorted, matrix-supported breccia with boulder-sized elements floating in a coarse-grained bioclastic matrix. B) Detail of a barnacle cluster having the body chambers partially filled by sparry calcite (white arrowheads) indicating post-mortem displacement of the specimens, black arrowhead= oyster. C) Small angular pebble encrusted by *Lithophyllum racemus*. D) Detail of a cobble in the breccia layers of S2.

and bivalves (Figs. 3, 5B); rare coralline algae also occur (Fig. 5C). Rare cobble-sized angular clasts are also observed floating within the calcirudite body (Fig. 5D). All the strata gently and irregularly dip southwards (Fig. 5A).

S3 is continuous with **S2**; however, while the upper part of **S2** is covered by the support wall of a house, the upper part of **S3** is beautifully exposed in the village church square (Figs. 2 (**S3**), 6A-B). This part of the succession consists of centimeter-thick calcirudites layers displaying a thoroughly bioturbated base and alternating with calcarenites (Figs. 3, 6C-E). Calcirudite layers consist of barnacles (mostly *Concavus concavus*) and mollusc shells (including *Saccostrea*) exhibiting a common orientation (Fig. 6D). Locally, the calcirudite layers appear as filling decimeter-large scours carved into the underlying calcarenites (cut-and-fill structures; Fig. 6E).

S4 is located several hundreds of meters South of **S3,** along the main road that connects the village of Pairola to the coastal city of San Bartolomeo (Figs 1D, 2 (**S4**)). The lower portion of this section consists of coarse-grained calcarenite layers,

displaying common barnacles referred to *Concavus concavus* and bivalves, and an often bioturbated base, alternating with fine-grained silty calcarenite intervals (rare mollusc shells and barnacle clusters were also observed within these finer-grained layers) (Figs. 3, 7A-C). The top of **S4** consists of a decimeter-thick, clast-supported conglomerate comprised of well-sorted, rounded to sub-angular pebbles created from the erosion of the Mesozoic substrate (Figs. 3, 7D). Large pebbles exhibit common date mussel borings referable to the ichnogenus *Gastrochaenolites*. Rare barnacles and mollusc fragments do also occur. The base of the conglomerate is clearly erosive and carved into the underlying fine-grained silty calcarenite (Fig. 7). Similar to the other sections, the strata that comprise **S4** gently dip southwards (Fig. 7A). Moving further South along the road, the Pliocene deposits are mostly covered by vegetation, and wherever outcrops are available, the exposed rocks entirely consist of fine-grained silty materials that are almost devoid of macrofossils.

The **S5** section is located slightly southward and roughly 20 meters above **S3** (along via dei Tufi;

Fig. 6 - Section S3. A) Overview of S3 from the church square. B) Detail of the basal breccia layer of S3. C) Overview of the fine-grained calcirudite layers from the upper part of S3 alternating with calcarenites. D) Detail of a fine-grained calcirudite layer displaying a thoroughly bioturbated base (black arrowhead); white arrowhead = bivalve shells. E) Fine-grained calcirudite layer filling a scour carved into the underlying calcarenites; white arrowhead = cut-and-fill structure.

Fig. 2 (**S5**)). The base of **S5** consists of a coarse-grained calcarenite overlain by a decimeter-thick interval of fine-grained calcarenite that is further overlain by another layer of coarse-grained calcarenite exhibiting a complex system of burrows at its base (Figs. 3, 8A-C). These burrows are mostly comprised of subhorizontal and obliquely oriented *Thalassinoides* shafts, and rarer *Skolithos* specimens that might reflect the burrowing activity of polychaete worms (Fig. 8B-C). Overall, this ichnoassemblage is reminiscent of the *Glossifungites* ichnofacies of shallow-marine settings in which scouring has

removed the unconsolidated layers at the sediment surface, thus disclosing the semiconsolidated (firmground) substrate (Pemberton et al. 1995). Further above there is a decimeter-thick layer of matrix-supported breccia with poorly-sorted clasts (ranging from pebble to boulder-sized) and a calcarenite matrix (Figs. 3, 8A). Differing from the breccias of **S1**, **S2**, **S3**, which are characterised by clasts eroded from the underlying Mesozoic substrate, this one displays angular clasts deriving from the coarse-grained Pliocene calcarenites (Fig. 8D). Above this breccia, a further layer of coarse-grained calcarenite
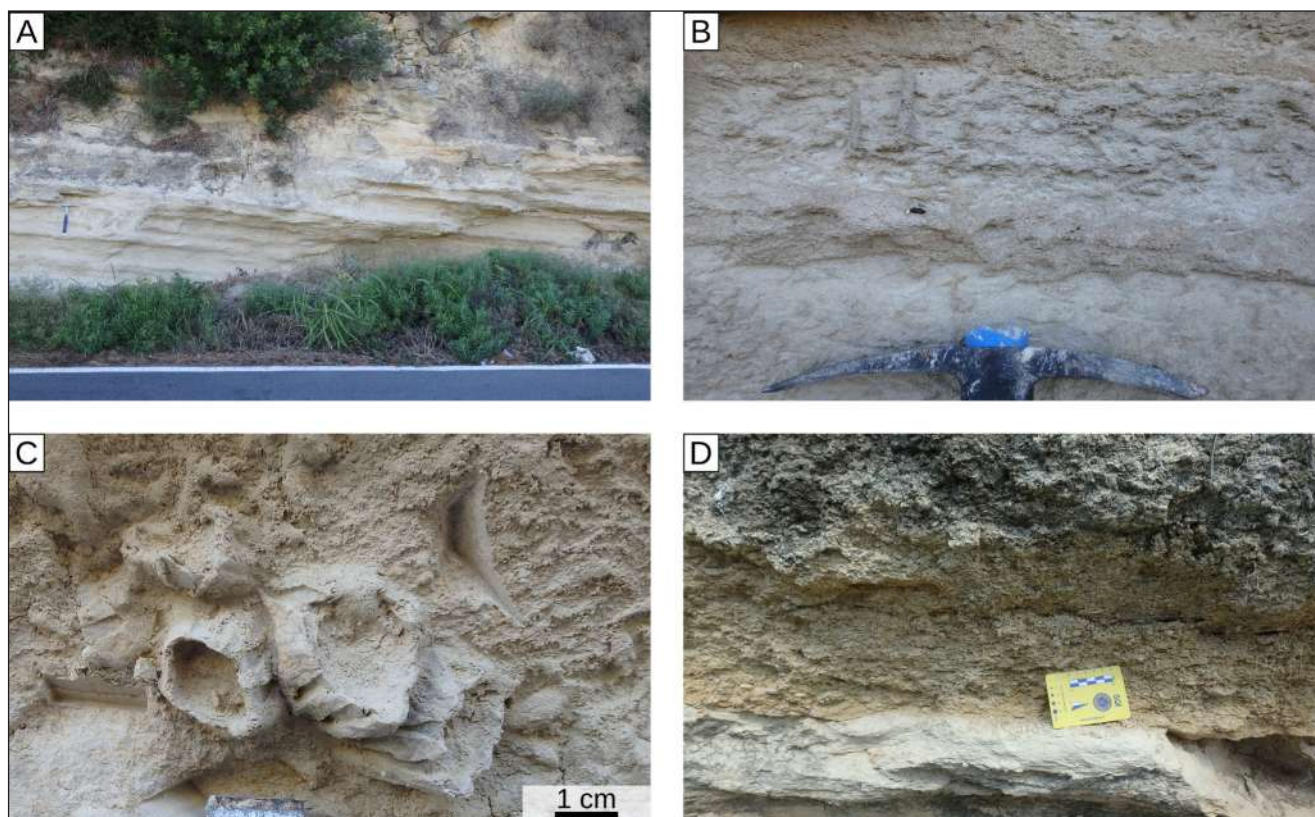
Fig. 7 - Section S4. A) Overview of the section with coarse-grained calcarenite layers alternating with fine-grained silty calcarenite. Note the hammer on the left for scale. B) Detail of a thoroughly bioturbated base of a calcarenite layer. C) Barnacle cluster in the silty calcarenites. D) Base of the upper conglomerate of the section.

crops out (Figs. 3, 8A). A well-sorted, clast-supported conglomerate, composed of pebbles eroded from the Mesozoic flysch, occurs at the top of **S5** (Fig. 3). The contact between the conglomerate and the underlying coarse-grained calcarenite was not observed since the conglomerate is heavily weathered.

Facies

Based on thin section analyses, two main facies were recognised in the Pairola Pliocene deposits, namely: a barnacle-molluscs dominated facies (barnamol assemblage) and a foraminifera-dominated facies (foramol assemblage) (Table 1; Fig. 3). A transitional (i.e. intermediate) facies was also observed in most sections (Table 1; Fig. 3; Table S1, Appendix 1).

Barnamol. This facies characterises the coarse-grained lithologies, rich in detrital material, that occur within the village itself (except for the basal clast-supported breccia, Fig. 2 (α)) and in sections **S1, S2, S3, S4** and **S5** (Fig. 3). The terrigenous fraction is abundant and includes coarse (pebble to cobble-sized) clasts. The bioclastic fraction is composed of abundant barnacles (20% to 80%) and molluscs (5% to 65%) (Table 1; Fig 9A, B). Echinoderms (either occurring as spines or test fragments of both regular and irregular taxa) and benthic foraminifera are also quite common (5% to 25% and 2% to 10%, respectively) (Table 1). Serpulids are generally rare but they locally occur in small clusters in the coarser intervals (Table 1; Fig. 9C). Coralline algae are rare and occur as small nodules of *Lithophyllum racemus* growing over angular pebble-sized clasts or as thin crusts of lithophylloids algae growing over large bioclasts (Table 1; Fig. 9C, D, E). Bryozoans are rare and mainly represented by flexible erected forms and thin unilaminar crusts growing over large bioclasts (Table 1; Fig. 9F). The foraminiferal assemblage is dominated by *Cibicides* associated with common *Elphidium* and other small rotaliids (Table 1; Fig. 9G). *Amphistegina*, *Planorobulina*, and textulariids (mainly *Textularia* and *Bigenerina*) also occur (Fig. 9H). Rare encrusting foraminifera were also observed growing over large skeletal fragments. Miliolids are rare, and so are planktic foraminifera, the latter representing on average less than 5% of the total foraminiferal assemblage (Table 1).
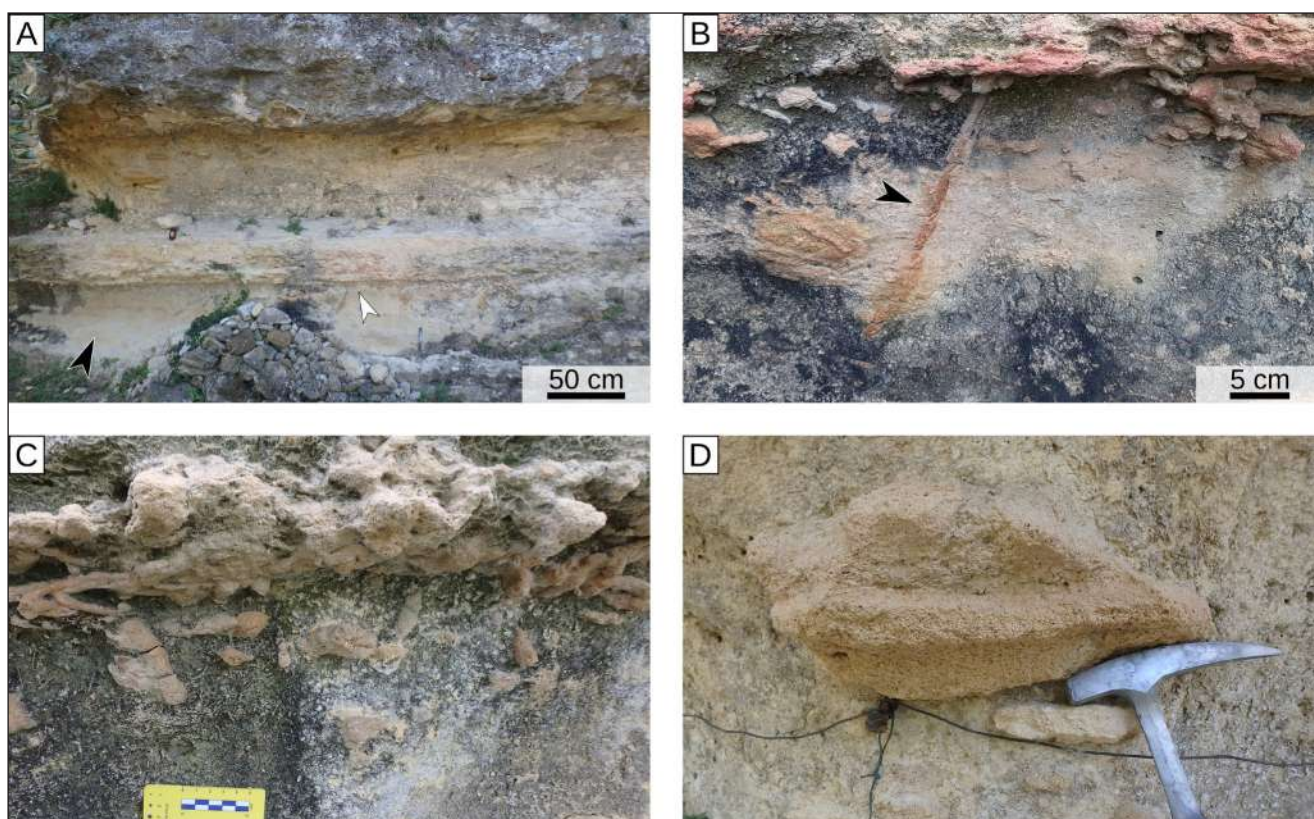
Fig. 8 - Section S5. A) Overview of the section showing a *Glossifungites* ichnofacies (white arrowhead) carved into the underlying layer (black arrowhead). B) Detail of the *Glossifungites* ichnofacies with a long *Skolithos* shaft (black arrowhead). C) Detail of the *Thalassinoides* burrows. D) Detail of the breccia layer including large angular clasts of coarse-grained Pliocene calcarenites.

Foramol. This facies characterises the fine-grained layers of **S1**, **S3**, **S4** and **S5** (Fig. 3). It exhibits much finer detrital material than the barnamol facies (Fig. 10A, B). The skeletal assemblage mainly consists of foraminifera (both planktic and benthic taxa) that comprise from 55% to 80% of the whole skeletal assemblage (Table 1; Fig 10A, B). Echinoderm fragments are abundant (5% to 35%), molluscs are common (up to 15%), and ostracods and barnacles are rare (Table 1; Fig. 10A). Planktic foraminifera are very common and dominate the foraminiferal assemblage of the silty calcarenites of **S4** and of the calcarenites at the base of **S5** (Fig. 3). In these layers, planktic foraminifera are associated with common specimens of *Cibicides*, *Elphidium*, *Neoconorbina/Asterigerinata* (note that it is difficult to separate these two genera in thin section), other small benthic rotaliids, and rare textulariids and bolivinids (Fig. 10A). Benthic foraminifera dominate the calcarenites of **S1**, **S4**, **S3**, and **S5** (except at the base; Fig. 3); they mainly consist of *Cibicides* and *Elphidium* associated with *Neoconorbina/Asterigerinata*, small rotaliids, textulariids, and rare *Amphistegina*, *Lenticulina*, bolivinids and lagenids (Fig. 10C-F).

Overall, the percentage of planktic foraminifera ranges from 60 to 70% in the silty calcarenites and from 10 to 30% in the calcarenites (Table 1).

Transitional. It is possible to observe a transitional facies that is somewhat intermediate between the barnamol and the foramol in the calcirudites of the upper part of **S3**, in the most coarse-grained calcarenite layer of **S4**, and in the uppermost calcarenite layer of **S5** (Fig. 3). Transitional assemblages are characterised by common barnacles, foraminifera, molluscs and echinoiderms (Table 1; Fig. 11A, B). The foraminiferal assemblage is dominated by *Cibicides*, *Elphidium* and *Amphistegina* (the latter being extremely common in the uppermost calcarenite layer of **S5**), and features a conspicuous percentage of planktic foraminifera (between 5% and 10% of the whole foraminiferal assemblage) (Table 1; Figs. 3, 11C, D).

Macrofossils
Barnacles. The barnacle assemblage from the CMV strata exposed at Pairola is dominated by a single species of relatively large-sized (up to ca 4 cm

Facies	Barnamol	Transitional	Foramol
Terrigenous fraction (average)	**40%**	**40%**	**15%**
Terrigenous fraction (min-max)	10% - 80%	15% - 60%	5% - 35%
Bioclastic fraction (average)	**60%**	**60%**	**85%**
Bioclastic fraction (min-max)	20% - 90%	40% - 85%	65% - 95%
Skeletal assemblage (based on recognisable grains of the bioclastic fraction)			
Barnacles (average)	**43%**	**28.5%**	**3.5%**
Barnacles (min-max)	25% - 80%	15% - 50%	0% - 9%
Molluscs (average)	**31%**	**10%**	**6%**
Molluscs (min-max)	5% - 65%	0% - 25%	0% - 15%
Echinoderms (average)	**10%**	**16%**	**21.5%**
Echinoderms (min-max)	0% - 25%	10% - 25%	5% - 35%
Benthic foraminifera (average)	**7%**	**38%**	**49%**
Benthic foraminifera (min-max)	0% - 15%	15% - 60%	35% - 60%
Serpulids (average)	**5%**	**0%**	0%
Serpulids (min-max)	0% - 50%	//	//
Bryozoans (average)	**2%**	**6%**	0%
Bryozoans (min-max)	0% - 15%	0% - 25%	//
Coralline algae (average)	**1.5%**	**0%**	0%
Coralline algae (min-max)	0% - 8%	//	//
Planktic foraminifera (average)	**0.5%**	**1.5%**	**20%**
Planktic foraminifera (min-max)	0% - 2%	0% - 5%	2% - 45%
Foraminiferal assemblage (area counting)			
Dominant taxa	*Cibicides-Elphidium*	*Cibicides - Amphistegina*	Planktic foraminifera-*Cibicides*
Planktic/Benthic ratio (average)	**0.06**	**0.08**	**1.21**
Planktic/Benthic ratio (min-max)	0 - 0.15	0 - 0.16	0.2 - 2.63

Tab. 1 - Petrographic characteristics, skeletal assemblages and foraminiferal assemblages of the recognised facies.

in height) balanid balanomorphs. These are globulo-conical shells with ribbed, high-triangular parietes and a toothed, diamond-shaped orifice (Fig. 12A-D). The parietes are tubiferous, bi-lamellar, with a single row of large parietal tubes and complex, arborescent, interlaminate figure (Fig. 12E, F). The sutural edges of the moderately broad radii have secondary denticles on the lower side only. The sheath is largely appressed, displaying prominent transverse growth lines on the carinolatera only, and the alae are cleft. On the whole, these characters allow us to identify the specimens as belonging to the extinct species *Concavus concavus* of the balanid subfamily Concavinae (Newman 1982; Zullo 1992; Pitombo 2004), which is a common constituent of the Pliocene barnacle assemblages of the Mediterranean region (Davadie 1963; Menesini 1965). A single small-sized specimen from the lowermost calcirudites of section **S3** does not conform to the above characterization and is here referred to cf. *Amphibalanus* sp. Small mural plates, characterised by simple interlaminate figures with a rather limited number of secondary processes (Fig. 12F, G) and

differing significantly from those attributed to *C. concavus* (Fig. 12E), have also been observed in the thin sections of the bulk-samples. Furthermore, the sole

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Fig. 9 - Barnamol facies. A) Sample PA5A (Fig. 2 (γ)), typical view of the barnamol facies, displaying large barnacles (Bar), mollusc fragments (Mol) and siliciclastic elements issued from the Mesozoic flysches that comprise the basement of the basin (MF). B) Sample PAS4-7, uppermost conglomerate of S4, displaying an abundant siliciclastic fraction (MF) and some barnacle fragments (Bar). C) Sample PA5V (Fig. 2 (γ)), serpulids with local encrustations of lithophylloids algae (black arrowhead). D) S2, *Lithophyllum racemus*, overview of the thallus, white arrowhead= uniporate conceptacles (perithallial cells length, average = 16.5 μm, min =14 μm, max = 19 μm; perithallial cells diameter, average = 11 μm, min = 10 μm, max = 12 μm; conceptacle chamber diameter, average = 250 μm, min = 210 μm, max = 310 μm; conceptacle chamber height, h2 sensu Basso et al. (1996), average= 130 μm, min= 100 μm, max= 150 μm; pore canal length, average = 75 μm, min = 60 μm, max = 110 μm; pore canal basal diameter, average = 50 μm, min = 35 μm, max = 70 μm. E) S2, *Lithophyllum racemus*, detail of two partially fused conceptacles, white arrowhead = central columella. F) Sample PAS2-1.5, fragment of a flexible erected bryozoans colony. G) Sample PAS4-7, *Elphidium*. H) PA5A (Fig. 2 (γ)), textulariids.
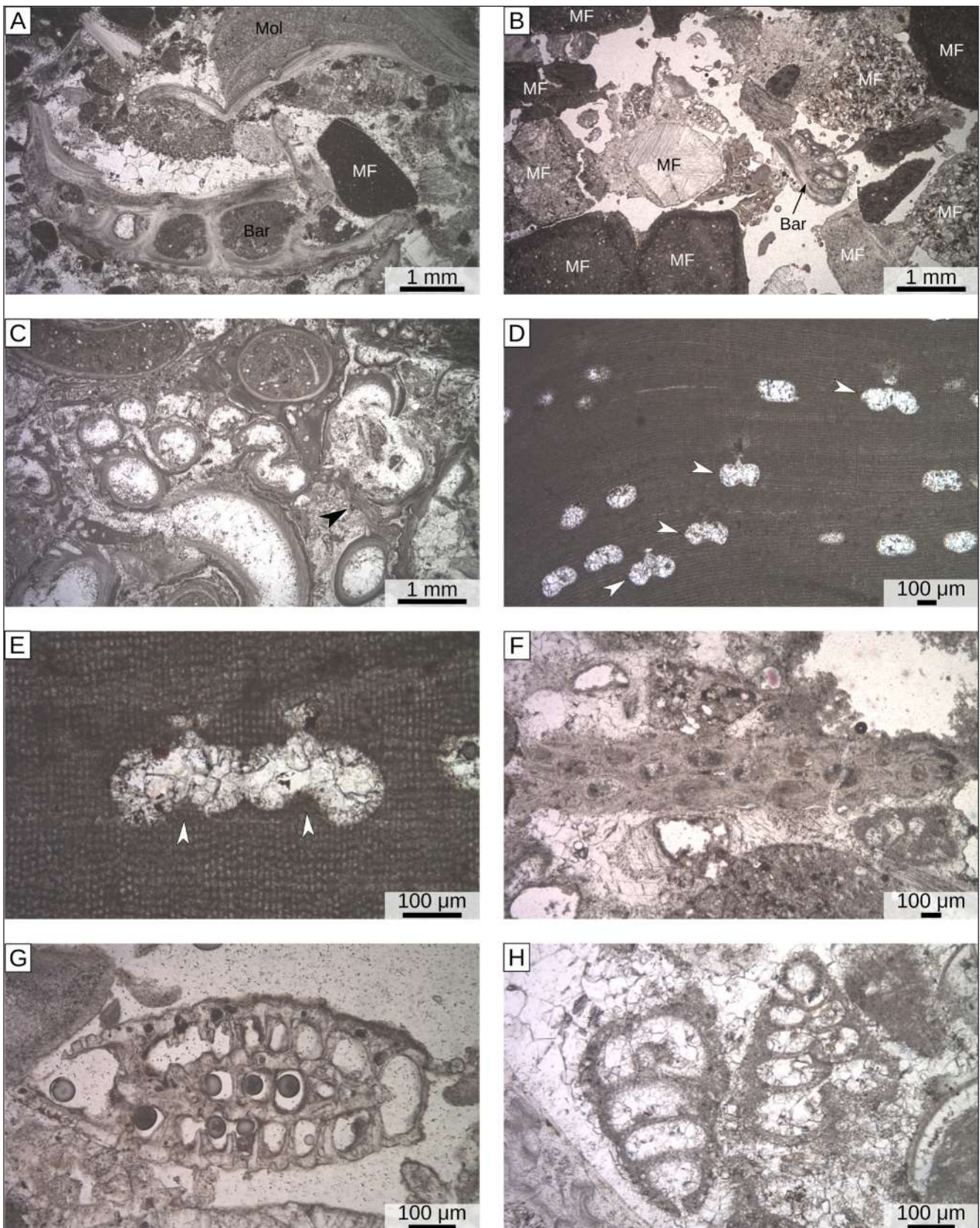
opercular plate that was recovered from the Pairola outcrop consists of a small-sized, moderately worn scutum that does not exhibit the cancellate pattern of radial striae and transverse growth lines that is typical of *C. concavus*, displaying instead more similarities with the scuta of *Amphibalanus* and *Perforatus*.
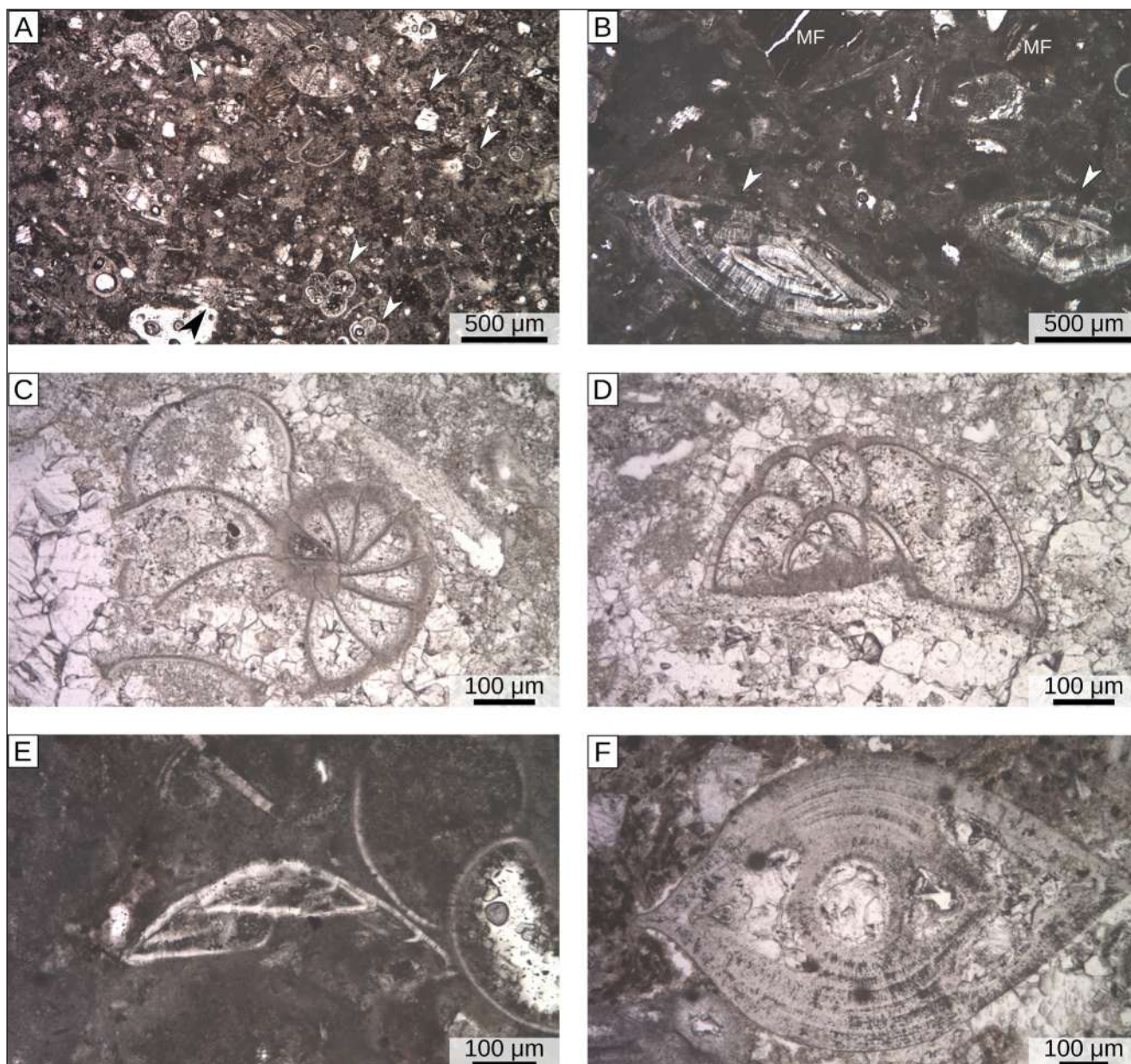
Fig. 10 - Foramol facies. A) Sample PAS4-1, typical view of the foramol facies dominated by planktonic foraminifera (white arrowhead) and characterised by abundant echinoderm fragments (black arrowhead). B) Sample PA7, section S5, foramol facies with abundant *Amphistegina* (white arrowhead) and small-sized siliciclastic grains (MF). C) Sample PA8, section S5, *Cibicides* specimen (sub-equatorial cut). D) Sample PA8, section S5, *Cibicides* specimen (axial cut). E) Sample PA7, section S5, *Neoconorbina/Asterigerinata* (axial cut). F) Sample PAS3-7, *Lenticulina*.

In the barnamol facies of sections **S1**, **S2** and **S3**, barnacle specimens mostly occur in form of displaced shell clusters and displaced shells lacking the opercula (Fig. 12A, B). The shell clusters and isolated shells are invariably detached from their original substrate (Type 2 of Doyle et al. 1997; Type C of Nomura & Maeda 2008), and no specimens were observed attached to the cobbles and boulders that characterise **S1**, **S2**, **S3** and the small outcrops inside the village. The geometric relationship between shells in a single cluster demonstrate

the existence of up to three generations of barnacles. The preservation degree of these specimens is moderate to good (Grades 0 and 1 of Nielsen & Funder 2003), the finer details of the external shell ornamentation being only occasionally observed due to limited but widespread abrasion. A few exquisitely preserved specimens retain trace of their pinkish pigmentation (Fig. 12C). Some of the most complete shells are filled by hardened sediment (Fig. 12D) and might even display druze-like structures made by a beige-coloured carbonate. The
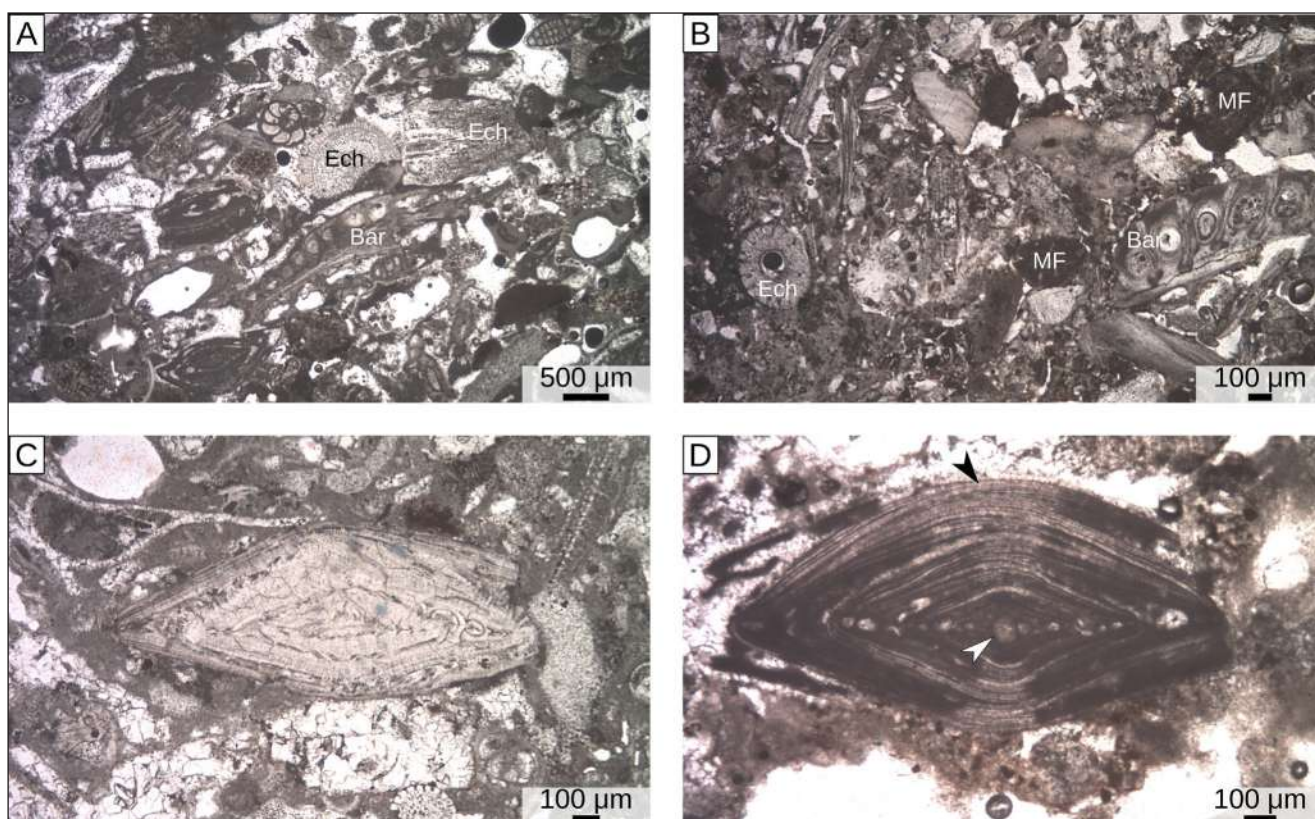
Fig. 11 - Transitional facies. A) Section S5, sample PA9, typical view of the transitional facies with abundant benthic foraminifera, echinoderms (Ech) and barnacles (Bar). B) Sample PAS4-5, transitional facies from a shell-rich bed of S4, with barnacles (Bar), echinoderms (Ech) and siliciclastic granules (MF). C) Section S5, sample PA8, *Amphistegina*. D) Section S5, sample PA9, *Amphistegina* black arrowhead, white arrowhead = protoconch.

barnacle remains often display evidence of bioerosion in form of penetrative trace fossils (Fig. 12B, D, H, I; see also the ichnological observations below) as well as encrusted remains of episkeletozoan unilaminar (cheilostomate?) bryozoans (Fig. 12E). Isolated mural plates and mural plate fragments are also present in the Pairola foramol facies; these are the main barnacle remains observed in some of the distal coarse-grained calcarenite beds of section **S4** (Type 7 of Doyle et al. 1997; Type D of Nomura & Maeda 2008). Here the barnacle remains are often greatly fragmented, disarticulated and heavily abraded, often exposing their inner architecture (Grade 2 of Nielsen & Funder 2003). Rare displaced clusters (Type C of Nomura & Maeda 2008; Type 2 of Doyle et al. 1997) also occur in the fine-grained foramol beds of **S4** (Fig. 7C).

Bivalves. Molluscs are quite abundant along the whole Pairola succession and in all the analysed facies, namely, the barnamol, foramol and the transitional facies. The molluscan assemblage is poorly diversified and mainly composed of bivalves (most-ly ostreids associated with rarer pectinids). Most of the identified specimens were provided by the poorly lithified, shell-rich beds of section **S4** (Fig. 3). They include: three small specimens belonging to the genus *Saccostrea*; two right valves attributed to *Ostrea* sp. (one of the specimens is from **S2**) whose morphology resembles *Ostrea edulis* (Fig. 13A); a left valve belonging to *Neopycnodonte* sp. (Fig. 13B); and a large-sized left valve attributed to the family Gryphaeidae (Fig. 13C). Bivalve specimens from **S4** also include several pectinid fragments and a complete right valve displaying diagnostic characters of *Aequipecten scabrella* (Fig. 13D).

Bivalves are generally preserved as disarticulated valves, and they often appear as fragmented and/or abraded. Shells are usually characterised by the presence of common ichnofossils (see below).

Ichnological observations on the bioclastic fraction. The largest biogenic elements (consisting of complete and fragmentary barnacle and bivalve shells) that comprise the bioclastic fraction of the studied deposits serve as a substrate for a moderately di-

verse ichnoassemblage. The latter consists of traces referred to five ichnogenera, namely: *Oichnus* and *Entobia* (both being abundant on barnacles and bivalves), and *Anellusichnus*, *Caulostrepsis* and *Meandropolydora* (rare). Crucially, most of these ichnotaxa testify to faunal elements that have otherwise not been detected as skeletal elements in the Pairola deposits. The *Oichnus* traces (Fig. 12B, H) are complete borings that show more similarities with *Oichnus simplex* than with *Oichnus paraboloides*; as such, they demonstrate the predatory action of carnivorous gastropods (likely muricids; Bromley 1981). Specimens of *Entobia* (Fig. 12B, D, H, I) are widespread, sometimes occurring on the interior of the bivalve and barnacle shells; they resulted from the boring activity of *Cliona*-like sponges (Bromley 1970; Bromley & D'Alessandro 1984). *Anellusichnus*, here represented by *Anellusichnus circularis*, is an attachment scar produced by the fouling of balanid barnacles (Santos et al. 2005); along with the remains of balanid basal plates, it occurs on the Pairola specimens of *Concavus concavus*, where it is attributable to conspecific barnacle individuals attaching and growing on each other. *Caulostrepsis* (Fig. 12B) and *Meandropolydora*, both being relatively uncommon at Pairola, are the result of carving of the shell substrate by polychaete worms; in particular, the former have been attributed to members of the family Spionidae (Lopes 2011, and references therein).

Discussion

Facies interpretation

Similar to other Pliocene basins of Western Liguria, the clast-supported breccia cropping out in the northernmost part of the village (Fig. 2 (α)), are interpreted as sub-aerial deposits that formed before the Zanclean transgression that ended the Messinian Salinity Crisis (Boni et al. 1976; Marini 2000, 2001; Breda et al. 2007, 2009). The breccia probably formed originally as a colluvial deposit on the lower slope of the palaeo-valley or as the result of in situ, sub-aerial alteration of the Mesozoic flysch units during the Messinian Salinity Crisis. These breccias might have been further reworked during the subsequent Zanclean transgression.

Barnacle-dominated facies are generally rich in mollusc fragments and often display a sizable siliciclastic fraction; they usually form in high-energy

settings, less than 50 m of water depth, and most of the times, less than 20 m (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; Coletti et al. 2018b). The barnamol facies of Pairola is consistent with this general framework, and as such, it probably formed on a high-energy, nearshore, rocky substrate at depths shallower than 15 m (i.e. above the fair-weather wave base; hereinafter: FWWB). The foraminiferal assemblage supports this interpretation as the most common genera (*Cibicides* and *Elphidium*) typically occur in marginal-marine environments (Murray 2006); furthermore, the plantkic/benthic ratio suggests a water depth of less than 10 m (based on Van Der Zwaan et al. 1990: equation 2). The presence of *Lithophyllum racemus* is consistent with a sub-

Fig. 12 - Barnacles. A) Isolated shell of *Concavus concavus* from section S2 (notice the globulo-conical morphology of the shell). B) Cluster of shells of *C. concavus* (notice the globulo-conical morphology of the shell, the ribbed, high-triangular parietes and the toothed, diamond-shaped orifice) serving as substrate for various traces (arrowheads) from section S3. C) Juvenile specimen of *C. concavus* preserving its original pinkish pigmentation from section S4. D) Specimen of *C. concavus* having the body chamber filled by cement and sparry calcite and the shell exterior punctuated by *Entobia* holes from section S2. E) Sample PA5V (Fig. 2 (γ)), barnamol facies, thin section through the mural plate of a specimen of *C. concavus* (note the presence of encrusting bryozoans coating the interior of the shell, the tubiferous, bi-lamellar paries with a single row of large parietal tubes and complex, arborescent, interlaminate figure). F) Sample PAS3-2, barnamol facies, thin section through the mural plate of a small-sized, indeterminate balanid specimen (cf. *Amphibalanus* sp.), note the simple interlaminate figures with a rather limited number of secondary processes. G) Sample PAS3-2, barnamol facies, close-up of the interlaminate figures of a small-sized, indeterminate balanid specimen (cf. *Amphibalanus* sp.). H) Isolated mural plate of *C. concavus* with associated shred of basal plate from section S4 (note the polished aspect of the paries) serving as substrate for various traces (arrowheads). I) Isolated mural plate of *C. concavus* with associated shred of basal plate from section S4 (note the heavily bioeroded aspect of the paries) serving as substrate for various traces (arrowheads). White arrowhead = *Oichnus* isp.; red arrowheads = *Entobia* isp.; black arrowheads = *Caulostrepsis* isp.; blue arrowhead = *Meandropolydora* isp.
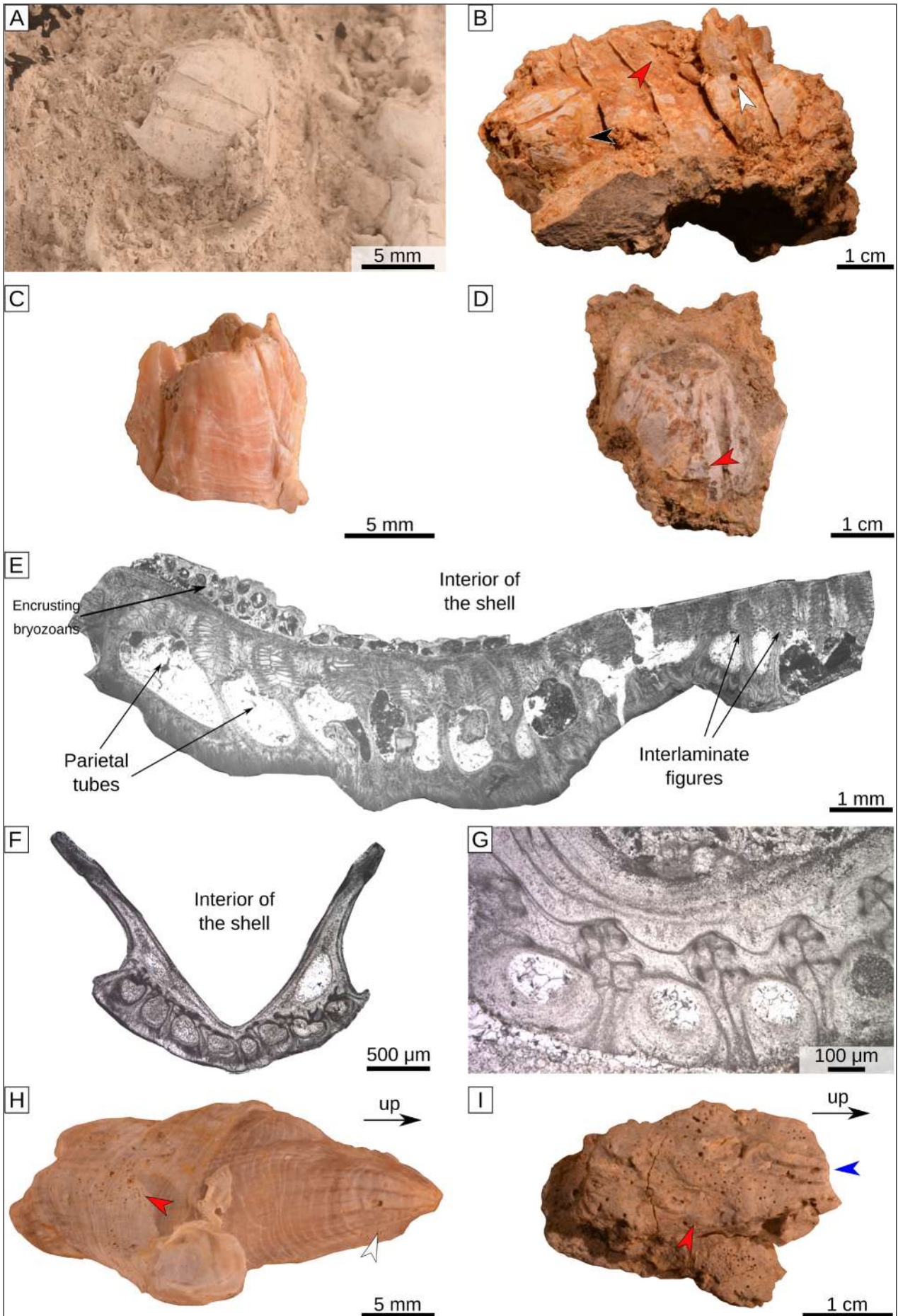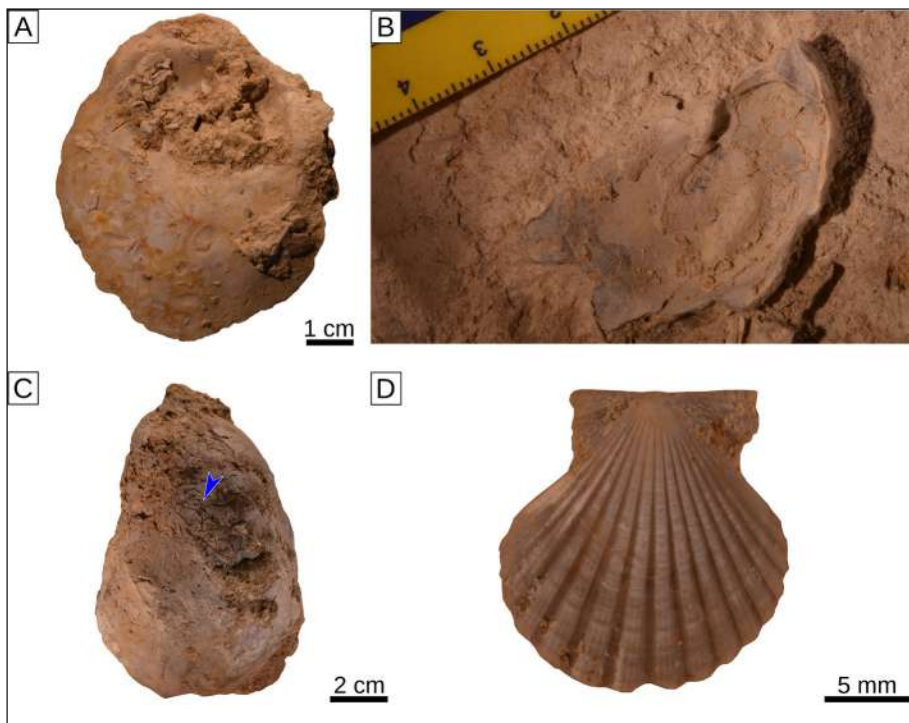
Fig. 13 - Bivalve molluscs. A) Internal view of an isolated right valve of *Ostrea* sp. from section S4 (notice the heavily bioeroded aspect of the valve). B) Internal view of an isolated left valve of *Neopycnodonte* sp. from section S4. C) External view of a gryphaeid specimen from section S4 serving as a substrate for abundant *Meandropolydora* traces (blue arrowhead). D) External view of an isolated right valve of *Aequipecten scabrella* from section S4. The limited number of relatively wide radial costae ornamented by at least three thin rib each are typical of this species, allowing for distinguishing it from *Aequipecten opercularis* (Jiménez et al. 2009; Crippa & Raineri 2015).

tidal, high-energy, shallow-water setting (Basso et al. 1996; Bressan & Babbini 2003). The date mussel borings (*Gastrochaenolites* isp.) that are observed on large pebbles (Fig. 4D) are also consistent with a shallow-water environment. The molluscan assemblage includes specimens with different environmental preferences. The rock-encrusting, tropical to sub-tropical genus *Saccostrea* is typical of intertidal environments and generally inhabits waters shallower than 10 m (Cox et al. 1971). Such a distribution agrees with the barnacle-dominated facies in terms of both water depth and hard substrate preference. On the other hand, the presence of the circalittoral species *Aequipecten scabrella* and the circalittoral to bathyal genus *Neopycnodonte* might suggest greater water depths. However, it must be stressed that *Neopycnodonte* currently displays broad bathymetric habits, and has been recorded in waters as shallow as 27 m (Harry 1985), suggesting a broader depth range. Furthermore, most of the identified mollusc specimens belong to the shell-rich beds of **S4**, which likely represent the result of downslope transport of the shallow-water barnamol material and mixing of the former with in situ foramol deposition (see below).

While the skeletal assemblage clearly points towards a setting above the FWWB, the lack of cross lamination, sorting and extensive rounding of the largest skeletal particles suggest that the depo-

sitional environment was probably slightly deeper than the setting from which most of the bioclastic fraction originated. Some hints at the mechanism of formation of these barnacle-bearing deposits come from the study of the Miocene Chilcatay Fm of the East Pisco Basin of southern Peru. The Chilcatay Fm includes coarse-grained mixed siliciclastic-bioclastic barnamol deposits that are similar to those exposed at Pairola (Coletti et al. 2018b; Di Celma et al. 2018). Some of these deposits are interpreted as submarine debris-flows deposited below the wave base, while others are thought to represent prograding sediment wedges deposited above the wave base (Di Celma et al. 2018). While the Chilcatay strata that deposited below the wave base exhibit rounding and sorting degrees and are similar to their analogs at Pairola, those that deposited around the wave base depth display much higher degrees of both sorting and rounding (Fig. 14). Consequently, we interpret the barnamol facies of Pairola as produced by a barnacle-dominated carbonate factory that developed on a rocky substrate at a water depth of less than 15 m, and whose bioclasts were transported downslope, below the level of action of waves (except for storm waves). The barnamol deposits of **S1**, **S2**, and **S3** represent the proximal portion of these debris flow deposits, located very close to the coastline. The thin shell-rich beds of **S4** represent the distal terminations of these deposits.
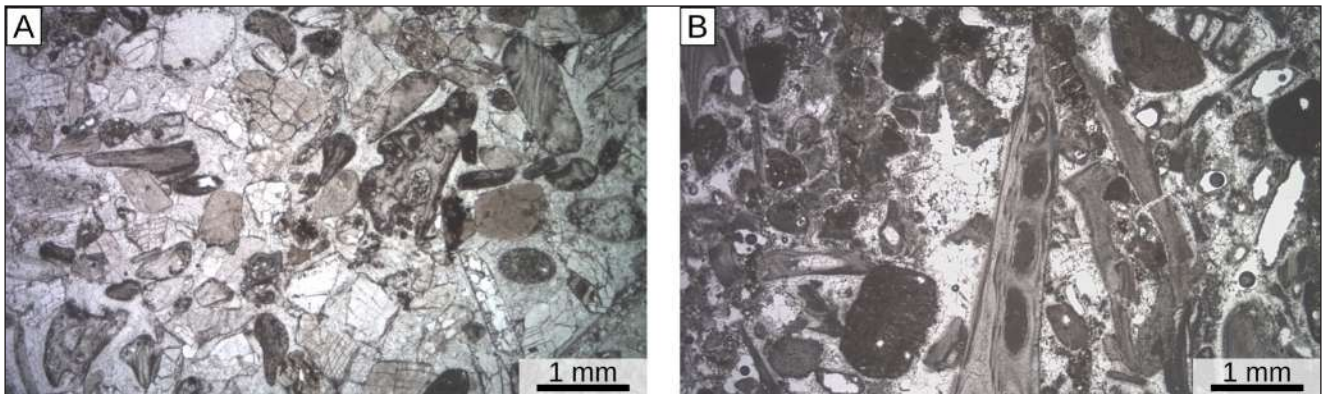
Fig. 14 - Comparison between the barnamol deposits of the Chilcatay Formation and those of Pairola. A) Chilcatay Formation, allomember Ct1b (sensu Di Celma et al. 2018), deposited above the storm wave base (notice the high degree of rounding and sorting of both clastic and bioclastic elements). B) Sample PAS3-2, barnamol facies of Pairola (notice the poor sorting as well as the angular nature of bioclastic elements).

Since barnacle-dominated carbonate factories usually develop in high-energy settings (e.g. the intertidal fringe of a rocky coast), the bioclastic material that originates there is usually rapidly swept away towards more sheltered and/or deeper areas where it can rest and accumulate (Foster & Buckeridge 1987; Scoffin 1988; Henrich et al. 1995). Consequently, barnacle-dominated facies commonly consist of downslope transported materials (e.g. Buckeridge et al. 2018; Coletti et al. 2018b). Even if downslope transport is a common feature of barnamol deposits, the length of the transport can be minimal, as exemplified by the barnacle-rich facies from the Pliocene of Tobago (Caribbean region) described by Donovan (1989). Similar to the barnamol facies of Pairola, the thickness and grain size of the Tobago deposits dramatically decrease moving away from their source area, i.e. the rocky substrate that was originally inhabited by the barnacles (Donovan 1989). In the Chilcatay Fm of Peru, barnacle-rich deposits are extensive and display a remarkable taphonomic variability, including barnacle fragments abraded in an infralittoral setting (Fig. 14) (Coletti et al. 2018b; Di Celma et al. 2018, 2019; Kočí et al. 2021), suggesting a coastal system with a broad shoreface zone. On the other hand, the barnamol deposits of Pairola are relatively restricted (they extend for a little less than 500 m N-S and for roughly 150 E-W; Fig. 2) and are almost homogeneously characterised by angular fragments devoid of evidence of rounding in very shallow water (Fig. 14). This suggests that the Pairola coastline was probably narrow and steep, with no room for extensive reworking of barnacles fragments in the shoreface as it was the case for the Chilcatay Fm.

The transitional facies is less enriched in barnacles and more enriched in benthic foraminifera compared to the barnamol facies. It also displays a slightly higher amount of planktic foraminifera, thus suggesting a slightly deeper depositional setting. This facies was located at the distal boundary of barnamol debris flows, and it formed due to mixing between displaced barnamol skeletal grains and the benthic foraminifera-dominated assemblage that was produced into slightly deeper water (as clearly observable in **S4**; Fig. 3). This facies is characterised by very common specimens of *Amphistegina*. Nowadays, in the Mediterranean Sea, this large benthic foraminifer genus occurs in warm coastal areas (e.g. along the shores of Tunisia, Egypt, Israel, Turkey, Cyprus, Greece, Malta and Sicily), where it is especially abundant between 10 and 30 meters of water depth (Hyams et al. 2002; Triantaphyllou et al. 2009; Langer et al. 2012; Caruso & Cosentino 2014; El Kateb et al. 2018; Guastella et al. 2019). Considering also that the moderate sorting and common orientation of the skeletal grains suggests a certain degree of hydraulic energy, we suggest that the transitional facies formed at a water depth of slightly more than 15 m and above the storm weather wavebase (hereinafter: SWWB).

Compared to the other facies, the foramol features less abundant terrigenous material, rarer barnacle fragments and more common planktic foraminifera. This indicates a deeper environment. A water depth comprised between 40 and 100 m can be hypothesised on the basis of the planktic/benthic foraminiferal ratio (following Van Der

Zwaan et al. 1990: equation 2). The lack of sorting and cross-lamination suggests a depositional environment below the SWWB, which is currently placed at around 30 m depth off the Ligurian coasts (Vacchi et al. 2012). Based on the molluscan and foraminiferal assemblages, the fine-grained Pliocene deposits of western Liguria are usually related to a deep water (~500 m) bathyal setting (Robba 1981; Giammarino & Tedeschi 1976, 1982, 1983). This interpretation can be rejected for the observed foramol facies exposed at Pairola. Here, the foramol facies alternates with the barnamol facies and includes well preserved barnacle clusters and barnacle fragments (e.g. S4; Fig 7C), thus indicating a depositional environment in relatively close proximity to the rocky coast that housed the barnamol carbonate factory. The presence of common *Elphidium*, *Cibicides*, and *Neoconorbina/Asterigerinata* also clashes with the bathyal interpretation. The outcrop of Poiolo (Fig. 1D, E), located South of Pairola (and as such, slightly basinward), is characterised by fine-grained deposits assigned to the ORV Fm that are similar to the foramol facies observed in sections **S3**, **S4**, **S5** at Pairola. The ORV strata exposed at Poiolo display a benthic foraminiferal assemblage characterised by littoral taxa and an otolith assemblage mostly consisting of deep-water teleost taxa (Boni et al. 1976), thus suggesting that littoral- and deep-water habitats were contiguous off the Ligurian coast in early Pliocene times. This evokes the absence of significant morphological barriers (e.g. salient sills) dividing the inshore and open-sea areas, as well as a rather abrupt morphology of the seabed that resulted in a short horizontal distance between shallow shelfal water and bathyal environments. All these elements are consistent with the ria-like physiography envisaged by previous authors for the Ligurian coast during the Pliocene (e.g. Boni 1984; Marini 2000; Breda et al. 2007, 2009). During the early Pliocene, the Pairola area was probably a small fjord with an outline similar to that of the modern Steria valley and a rocky coast colonised by a barnacle-dominated carbonate factory. The abundant bioclastic materials that continuously originated here mainly accumulated in a slightly deeper setting located at the toe of the cliff. At the border of these bioclastic fans, storm waves were able to provide a certain degree of mixing between the barnacle-dominated sediments and the locally depositing sediments characterised by a foramol skeletal assemblage. The latter

mainly accumulated in the central part of the flooded valley; it was dominated by benthic foraminifera close to the coast and by planktic foraminifera basinwards (i.e. southwards). Given these palaeobathymteric considerations, from the base of **S1** to close to the top of **S4** (green and thick dashed line in Fig. 3), we recognise a general deepening-upward trend, which should correspond to a relative sea-level rise of about 40-50 m (from a minimum of 10 m, calculated as the difference between SWWB and the minimum depth of the foramol facies, to a maximum of 85 m, calculated as the difference between FWWB and the maximum depth of the foramol facies). In turn, the barnamol conglomerate of **S4** testifies to a relative sea-level drop of the same extent. The barnamol conglomerate of **S4** most likely correlates with that of **S5** (Fig. 3). In the latter section, a marine regression is recorded by a progressive decrease in planktic foraminifera and the parallel increase in benthic foraminifera (in particular *Amphistegina*; Fig. 3), the occurrence of reworked clasts of Pliocene calcarenites, and the presence of a *Glossifungites* ichnofacies (Figs. 3, 8). The *Glossifungites* ichnofacies develops as a result of periods of erosion or pauses in sedimentation during which an incipient lithification of the sediment occurs (Fig. 8A, black arrowhead) (MacEachern et al. 1992; Abdel-Fattah et al. 2016). Such lithification allows for the burrowing of long shafts (Fig. 8B) in a fine-grained sediment that otherwise would have been too soft to support these structures; once deposition resumes, all the burrows are filled by sediment (MacEachern et al. 1992; Abdel-Fattah et al. 2016). Therefore, the *Glossifungites* ichnofacies is related to erosional/non depositional discontinuities that generally correspond to sequence boundaries (MacEachern et al. 1992; Abdel-Fattah et al. 2016) (green and thick dashed line in Fig. 3). Consequently, the composite succession ranging from the base of **S1** to the fine-grained beds below the barnamol conglomerate of **S4** should represent a single sequence of marine transgression. The succession from the *Glossifungites* to the upper conglomerate (observed in both **S4** and **S5**) should represent a second sequence of marine transgression, in which the lowstand system tract is recorded in **S5** and extends from the *Glossifungites* to the base of the conglomerate; the latter represents the first deposit of the following transgressive system tract. The possibility that the *Glossifungites* merely represents an

autogenic surface (sensu Abdel-Fattah et al. 2016) rather than a sequence boundary cannot be ruled out due to the limited extensions of the examined outcrop. However, the skeletal assemblages of both **S4** and **S5** indicate a remarkable sea level drop. The biostratigraphic data provided by Boni et al. (1976) indicate that **S1**, **S2** and **S3**, should be included in the zone MPL1 (early Zanclean, 5.33–5.08 Ma; Violanti 2012), while **S4** and the upper barnamol conglomerate would take their place between the base of the zone MPL2 and the top of the zone MPL3 (early to middle Zanclean, 5.08–3.98 Ma; Violanti 2012). Within this time window, a limited sea level drop, consistent with the 40–50-m-range reconstructed from our analysis and related to a minor cooling event, occurred globally around 4.5-4.0 Ma (Kloosterboer-van Hoeve et al. 2001; Capozzi & Picotti 2003; Prista et al. 2015; Miller et al. 2020), thus suggesting an eustatic control for the sedimentary succession observed at Pairola.

The northwestern Mediterranean Pliocene palaeoenvironment

The rock-forming abundance of barnacles of the Pairola deposits is quite unsual among the Italian Pliocene. Barnacles have been reported from the macrofossil assemblage of several Pliocene basins of NW Italy (e.g. Menesini 1965; Boni et al. 1976; Landini et al. 1990; Checconi et al. 2007; Bonci et al. 2010; Nalin et al. 2010; Collareta et al. 2016, 2017, 2020; Bianucci et al. 2019; Dominici et al. 2018). That said, except for a few cases such as the bioclastic-rich debris-flow deposits of Albisola, Savona (Giammarino & Tedeschi 1983; Fig. 1B) or the calcarenites of Montefollonico in Tuscany (Nalin et al. 2016), barnacles are not rock-forming elements in the Italian Pliocene. Barnacles typically require high hydrodynamic energy conditions, the presence of hard substrates suitable for colonization, and plankton-rich water (Foster 1987; Foster & Buckeridge 1987; Newman 1996; Sanford & Menge 2001; Coletti et al. 2018b). This kind of optimal environmental scenario was probably uncommon during the Pliocene in Northwestern Italy. Food abundance was likely not the main limiting factor, as productivity in the Northwestern Mediterranean Sea might have been higher during the Pliocene than it is today (Dominici et al. 2018), and there is no indication that hard substrates were scarcer then than they are now. The relatively close

and palaeoenvironmentally similar outcrop of Il Poggio (near Pontedassio; Fig. 1D), which represents a small shallow-water delta (around 3 m of water depth; Giammarino & Piazza 2000), is rich of hard substrates theoretically suitable for barnacle colonization, but attached to boulder and cobbles there are only oysters (*Saccostrea* and *Cubitostrea*) (Giammarino & Piazza 2000). A similar situation can be observed in the Frantoio Bianco outcrop (near Borgo d'Oneglia; Fig. 1D) (Giammarino & Piazza 2000; G.C., personal observation). Such an underrepresentation of barnacles in otherwise suitable hard-substrate settings suggests the absence of some other element necessary for barnacles to thrive. At the feet of the still partially submerged and rising Alps and Apennines, the ragged post-Messinian physiography of the shoreline might have made coastal lagoons, meandriform fjords and other semi-protected basinal habitats common. These partly sheltered palaeolandscapes might have reflected in a low hydrodinamic energy at the surf line, which also correlates with a shallow depths of the wave base. This would have been particularly true for the late Neogene basins of inner Tuscany, which were mostly restricted and bordered seawards by a fringe of topographic highs, resulting in carbonate bodies displaying evidence of deposition in relatively low-energy water (Nalin et al. 2010, 2016). In this respect, the Pliocene embayments of western Liguria, with their comb-like orientation relative to the coastline, might have proven less efficient in providing a sheltered environment than the innermost basins of Tuscany, thus allowing more easily for the high hydrodynamic energy that barnacles need to thrive.

Similar to many other Pliocene deposits of Italy (e.g. Boni et al. 1976; Conti et al. 1983; Di Bella et al. 2005; Caruso & Cosentino 2014; Nalin et al. 2016), the foraminiferal assemblage of Pairola is characterised by the presence of *Amphistegina*, which occurs in both the transgressive and regressive parts of the investigated succession. *Amphistegina* is relatively eurythermal among the tropical genera of large benthic foraminifera, being indeed able to survive as long as winter sea temperatures do not fall below 14 °C for extended periods of time (Langer & Hottinger 2000; Beavington-Penney & Racey 2004; Langer et al. 2012). Currently, due to increasing seawater temperatures, *Amphistegina* is expanding its Mediterranean biogeographic

range northwestwards, thus approaching both the Adriatic and Tyrrhenian seas (Triantaphyllou et al. 2009; Langer et al. 2012; Caruso & Cosentino 2014; Guastella et al. 2019). However, during the early Pliocene, this genus was well-established in the northernmost sectors of the Mediterranean, which obviously indicates water warmer than today. In fact, average Zanclean temperatures are assumed to have been some 2-3 °C higher than today (Prista et al., 2015). Nowadays, near the study area (Fig. 1), the average sea surface temperature (SST) is around 18.5 °C, with an average summer SST of 23.5 °C and a winter SST of 13.5 °C (based on a 10-year average of MODIS Aqua, data from GIOVANNI NASA; Acker & Leptoukh 2007). We might thus suppose that in Zanclean times the average SST off Western Liguria was around 20-22 °C, with winter temperatures of 15-17 °C and summer temperatures of 25–27 °C. This suggests that, during the Zanclean, the Western Ligurian sea was only slightly cooler than the present-day SE Mediterranean (i.e. along the coast of Israel; Hyams et al. 2002). This is consistent with large benthic foraminiferal diversity, which generally increases as temperature increases (Beavington-Penney & Racey 2004): indeed, whereas *Amphistegina* is the only large tropical rotaliid observed in the Zanclean of Pairola, several rotaliid genera are known from present-day coast of Israel (Hyams et al. 2002). Our temperature estimates are also in agreement with the results of high-resolution oxygen-isotopes analyses performed on early Pliocene mollusc material of NW Italy (Ragaini et al. 2019). This hypothesis is also consistent with palynological data from the Pliocene deposits of the Western Ligurian area, which indicate a humid climate, with plant species typical of present-day Southeast Asia (Zheng & Cravatte 1986). This warm-humid period lasted until 3.2 Ma, when the climate turned drier and characterised by a more pronounced seasonality (Zheng & Cravatte 1986). Around 3 Ma, a remarkable climate degradation also significantly affected marine macrobenthos (Raffi & Monegatti 1993; Monegatti & Raffi 2001), being related to the definitive onset of the Northern Hemisphere glaciation (De Schepper et al. 2014), and likely leading also to the extirpation of several taxa of thermophilic marine vertebrates (e.g. Sorbi et al. 2012; Prista et al. 2013; Collareta et al. 2017). The latest *Amphistegina*-bearing calcarenites of the Italian peninsula are Gelasian in age

(Di Bella et al. 2005; Caruso & Cosentino 2014). At the time of the Gelasian-Calabrian transition, the Mediterranean experienced a strong increase in thermal seasonality as well as a strong decrease of the average winter temperatures (Crippa et al. 2016). Such a remarkable cooling pulse is witnessed in the Mediterranean fossil record by the appearance of cold-water Atlantic taxa such as the ocean quahog *Arctica islandica* and the foraminiferan *Hyalinea balthica* around 2.0–1.8 Ma (e.g. Gibbard & Head 2010), and its effects can even be spotted as regards the vertebrate fauna (Tsai et al. 2017; Collareta et al. 2018). During the subsequent part of the Pleistocene, although several warm-water species entered the Mediterranean Sea in occurrence of warm interglacial periods (i.e. the so-called "tropical guests"; Monegatti & Raffi, 2001), *Amphistegina* is completely absent from the Mediterranean record (Caruso & Cosentino 2014). Conversely, in the Red Sea, where warm (tropical) conditions persisted for the whole Pleistocene, *Amphistegina* occurs in both modern sands and Pleistocene deposits (Parker et al. 2012; Caruso & Cosentino 2014). Overall, these observations indicate that, in the northern Mediterranean region, the average SST values were higher during the Pliocene (including the Pliocene cool intervals) than they were during the Holocene and the warm intervals of the Pleistocene. Thus, the present-day rapid expansion of *Amphistegina* towards the northern recesses of the Mediterranean Basin is foretelling us that Anthropocene temperatures might soon match and even break the Pliocene records.

The early Pleistocene climatic deterioration not only affected molluscs, foraminifera and marine vertebrates, but also barnacles. *Concavus concavus* commonly dominated the Mediterranean barnacle assemblages of the Pliocene. During the early Pliocene, this species was so common to be locally rock-forming, as testified by the *Concavus*-dominated facies occurring in Spain (Aguirre et al. 2008), Italy (this work) and Greece (Radwańska and Radwański 2008). During the Calabrian, *C. concavus* became rarer and disappeared afterwards (Menesini 1965; Newman 1982; Zullo 1992); recent Mediterranean concavines are represented only by *Perforatus perforatus* (Pitombo 2004). This decline with decreasing temperatures might indicate a preference towards warm climate for the extinct *C. concavus*. Such a pattern is uncommon as most of extensive barnacle-dominated facies occur at high latitudes, in

cool, turbulent and plankton-rich water, whereas at low latitudes barnacle-dominated facies are substantially restricted to areas of coastal upwelling (Coletti et al. 2018b: table 2, and references therein). The presence of specimens of *C. concavus* in fine-grained deposits (e.g. the upper Pliocene of Central Italy, Collareta et al. 2020; the Gelasian of Sicily, Massari and D'Alessandro 2012) suggests that this species was very adaptable and not limited to nearshore environments with high hard-substrate availability. Overall, *C. concavus* was probably well suited for Mediterranean Pliocene palaeoenvironments. It was able to survive in suboptimal settings and to grow to large numbers wherever and whenever favourable conditions were available, as testified by the early Pliocene rock-forming amount of *C. concavus* of Spain, Italy and Greece.

CONCLUSIONS

Based on sedimentological features as well as on skeletal and foraminiferal assemblages, three main bioclastic facies have been recognised in the Pliocene deposits exposed at Pairola, namely:

1) A coarse grained mixed siliciclastic bioclastic facies characterised by a barnamol skeletal assemblage and a suite of shallow-water benthic foraminifera. This facies formed on a nearshore, high-energy, rocky substrate at a water depth of less than 15 m. The material produced by this barnacle-dominated carbonate factory, together with the coarse-grained terrigenous fraction, was later moved slightly downslope (between 15 m and 30 m of water depth) through short-lived debris flows.

2) A fine-grained foramol facies, dominated by benthic foraminifera in its proximal part and by planktic foraminifera at its distal end, and here interpreted as formed at a water depth of more than 40 m.

3) A transitional facies that formed at a water depths between 15 and 30 m as a result of the mixing of the two aforementioned facies.

The abundance of benthic acorn barnacle remains as well as their preservation quality generally decreases with increasing water depths, but such a relationship is far from being linear, mostly due to downslope transport processes.

Following this facies interpretation, it is possible to separate the Pairola succession into two depositional sequences. The first sequence locally records the Zanclean flooding of the Mediterranean Basin that followed the Messinian Salinity Crisis. The second sequence can be divided into a lowstand system tract and a transgressive system tract, and is related to a subsequent marine transgression. The relative sea-level fall that is recorded at the boundary between the two sequences could be related to a minor cooling event of the early Pliocene.

The Pliocene basin in which the aforementioned sequences deposited was most likely a small flooded valley with steeply sloping flanks, which resulted in shallow-coastal, relatively high-energy settings (represented by the coarse-grained barnamol deposits) being very close to relatively deep and quiet environments (represented by foramol deposits dominated by planktic foraminifera). A similar physiography must have been pretty common during the early Pliocene in Italy since during the Messinian Salinity Crisis most of the rivers developed deep canyons that were flooded later, during the Zanclean. However, while several of these rias and embayments where probably sheltered from strong waves, the Pairola Pliocene embayment was rather exposed to hydrodynamic energy, thus favouring barnacle dominance in its shallower settings. Given these considerations, it is clear that differences between the Plio-Pleistocene coastal morphology of Italy and the present-day one must be taken into due account when proposing palaeoenvironmental and palaeoceanographical reconstructions in light of actualistic data and approaches.

The common presence of *Amphistegina* throughout the whole Pairola succession points towards a sub-tropical climate. Based on present-day SST temperatures, Mediterranean palaeotemperature estimates, and large benthic foraminifera distribution, an average annual temperature of 20-22 °C (with average winter temperatures of 15-17 °C and average summer temperatures of 25-27 °C) is here proposed for the early Pliocene of Western Liguria. A warm climate is also supported by the presence of the oyster genus *Saccostrea*, which is known as a tropical to sub-tropical genus. These temperatures are just slightly cooler than those of the present-day Southeastern Mediterranean. *Amphistegina* is a common component of the Pliocene and lowermost Pleistocene (i.e. Gelasian) foraminiferal assemblages of Italy, suggesting warm temperatures for the whole time span. After the Gelasian, this tropical

taxon entirely disappeared from the Italian geological record as it is even missing from marine deposits related to warm interglacial periods. Nowadays, *Amphistegina* has regained a place in the Eastern Mediterranean biocoenoses (much like *Saccostrea*) and is advancing northwards at a fast pace, thus strongly suggesting that Anthropocene temperatures are soon going to overcome those of the Pleistocene interglacials.

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