



New paleoenvironmental insights on the Miocene condensed phosphatic layer of Salento (southern Italy) unlocked by the coral-mollusc fossil archive

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Abstract

From the Late Oligocene to the Late Miocene, the central Mediterranean area was characterized by the extensive deposition of phosphate-rich sediments. They are usually represented by 10 to 20-cm-thick hardgrounds made of phosphatic and glauconitic sediments containing a rich macrofossil association. This study represents the first thorough investigation of the biotic assemblage of Mediterranean phosphorites aimed at collecting new information on the environmental factors controlling their deposition. The Serravallian/Tortonian phosphatic deposits of the Salento Peninsula (“*Aturia level*”) have been selected for the abundance of fossil remains and special attention is given to the coral–mollusc association. Two different facies have been recognized: a basal coral rudstone that includes most of the macrofossils, superimposed by a detrital rudstone made of thin layers mainly composed of phosphatic fragments. These two facies are separated by a phosphatic crust several millimeters in thickness. The coral assemblage contains at least 17 azooxanthellate taxa belonging to four families, while the molluscs are represented by a rich gastropod fauna (26 species), associated with bivalves (18 species) and cephalopods (two species). Four distinct depositional phases have been recognized, with the coral rudstone representing the key-facies to reconstruct the onset of the “*Aturia level*” and the original environment of its fossil content. The composition of the coral–mollusc association has been reliably compared with present-day analog taxa, suggesting the occurrence of a heterogeneous seafloor formed by rocky substrates and accumulations of soft sediment, at around 100–350-m water depth, and under the influence of moderate-to-strong bottom currents rich in nutrients and resuspended organic matter.

Keywords Phosphatic hardground · Az-corals · Molluscs · Miocene · Central Mediterranean

Introduction

Phosphoritic deposits are relatively common in the Mediterranean basin and known from the Malta archipelago (Chattian/Tortonian: Pedley and Bennett 1985; Jacobs et al. 1996; John et al. 2003; Föllmi et al. 2008), southeastern Sicily (Chattian/Burdigalian: Föllmi et al. 2008), Salento Peninsula

(Serravallian/Tortonian: Giannelli et al. 1965; Bosellini et al. 1999; Bossio et al. 2002; Föllmi et al. 2015), Matese Apennines (Langhian/Serravallian: Carannante 1982), Maiella mountains (Aquitanean/Burdigalian: Mutti et al. 1997), Latium-Abruzzi Apennines (Tortonian/Messinian: Brandano et al. 2009) and from Menorca island, toward the boundary

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with the western Mediterranean (lower Tortonian: Brandano et al. 2016) (Fig. 1a).

Despite the different ages and locations, these deposits exhibit quite similar stratigraphic, sedimentary, and paleontological features: they are usually represented by 10 to 20-cm-thick, sub-horizontal hardgrounds, made of phosphatic and glauconitic sediments, arranged in several thin layers separated by erosion surfaces. Macrofossils are very abundant and their assemblage is composed of corals, molluscs, echinoderms, brachiopods, bryozoans, and fish teeth, frequently associated with micritic sediments rich in planktonic foraminifera. Phosphatic pebbles, derived from the erosion of older portions of the hardground, can also be present in variable quantities. In some areas (e.g., Malta and south-central Apennines) these fragments constitute the total amount of the phosphatic sediments, forming up to 1-m thick layered accumulations (Carannante 1982; Föllmi et al. 2008).

In the past decades, the Mediterranean phosphatic deposits have been the subject of several studies, mainly aimed to understand the depositional processes and the mechanisms leading to phosphogenesis (Carannante 1982; Pedley and Bennett 1985; Jacobs et al. 1996; Bossio et al. 2002; John et al. 2003; Mutti et al. 1997; Brandano et al. 2009, 2016; Föllmi et al. 2008, 2015; Auer et al. 2016). In particular, Föllmi et al. (2015) interpreted the formation of these sediments as associated with the occurrence of a complex system

of upwelling currents, flowing into the central Mediterranean from the deeper, eastern region of the basin. From the Late Oligocene to the Late Miocene, changes in direction and intensity of these bottom currents sustained a complex and variable depositional environment, where areas of low sedimentation rate, phosphogenesis and formation of hardgrounds, alternated in space and time with areas with prevalent erosion and reworking of the phosphatic fragments. The study by Föllmi et al. (2015), as well as the other contributions to the knowledge of Mediterranean phosphorites, mainly relies on stratigraphic, sedimentary and geochemical features, whereas the macrofossil assemblage, despite its abundance and diversity, has never been analyzed in detail. The main goal of this study is thus a thorough investigation, mainly from a paleontological/paleoecological perspective, of the phosphatic deposits of the Salento Peninsula (Fig. 1b). These are named “*Aturia level*” (AL) after the common occurrence of small shells of this cephalopod genus (Giannelli et al. 1965) and crop out extensively in the southeastern sector of the Peninsula (Bosellini et al. 1999; Bossio et al. 2002; Föllmi et al. 2015). A recent survey has led to the identification of a site where a 25-cm-thick hardground rests on a sub-horizontal substrate, cropping parallel to the ground level on a surface of several hundreds of square meters. This favorable setting, allowing the study of large portions of the phosphatic hardground and a substantial sampling, represents an ideal context for the study

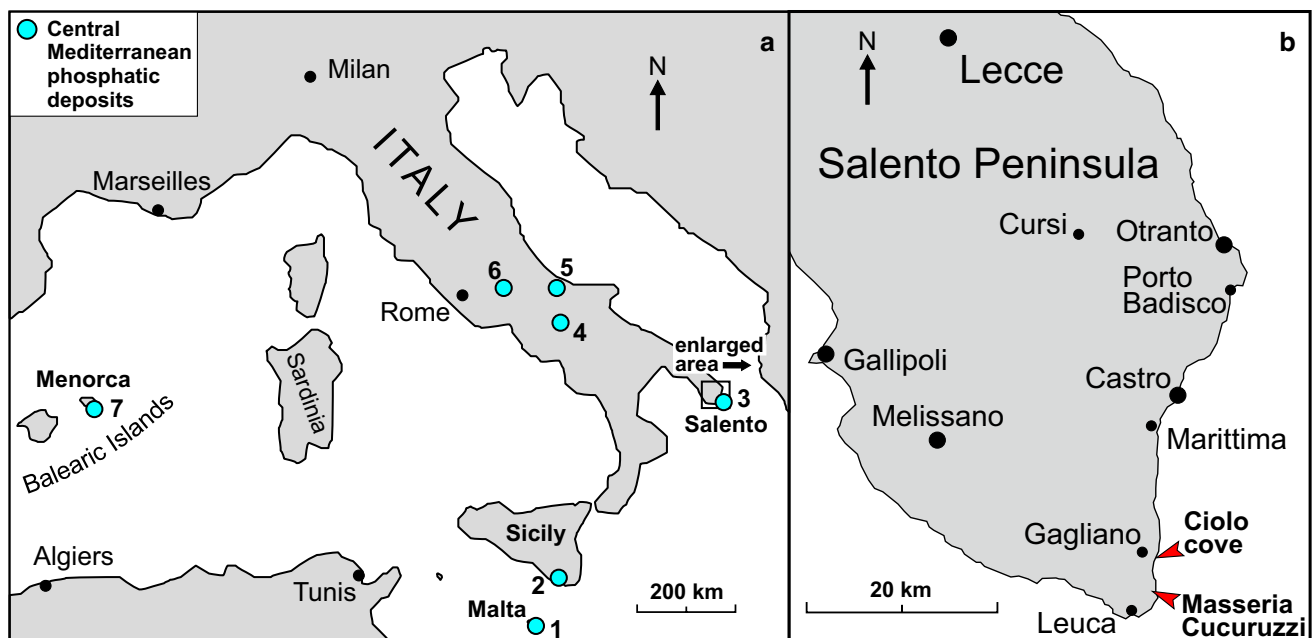


Fig. 1 a Location map of the central Mediterranean phosphatic deposits: 1- Malta archipelago (Chattian/Tortonian), 2- southeastern Sicily (Chattian/Burdigalian), 3- Salento Peninsula (Serravallian/Tortonian), 4- Matese Apennines (Langhian/Serravallian), 5- Maiella

mountains (Aquitanian/Burdigalian), 6- Latium-Abruzzi Apennines (Tortonian/Messinian), 7- Menorca island (lower Tortonian); references in the text. **b** Close-up of the southern Salento Peninsula; arrows indicate the studied localities

of the AL macrofossil assemblage. Here we present the first detailed description of the corals and molluscs associations, which constitute the most significant and abundant biotic component of the Salento hardground. In addition, given the particular sensitivity of these organisms to changing in environmental conditions, new insights on the paleoenvironmental settings during the time of the phosphorites deposition are provided.

Geological and stratigraphic setting

The Salento Peninsula belongs to the Adria Platform, a major structural element of the northern sector of the African plate. Starting from the Late Triassic, this margin acted as a shallow-water carbonate platform and from the Late Cretaceous, the progressive collision between the African and the European plates led to a further shallowing, with the partial emersion of the area corresponding to the present-day Salento Peninsula (Ricchetti and Ciaranfi 2013 and references therein). Despite this active geodynamic context, from the Late Cretaceous through the whole Cenozoic the Salento region was characterized by relatively stable tectonic conditions. As a

result, sedimentation was controlled by sea-level oscillations of moderate amplitude, that only during the Miocene and Early Pliocene led to the partial drowning of the inner areas of the platform (Bosellini et al. 1999). This situation created on the Salento Peninsula a complex stratigraphic architecture, well exposed on its south-eastern margin, along the coast from Otranto to Leuca (Fig. 1b). Sedimentation and carbonate production were concentrated on the distal portion of the platform, with the deposition of several carbonate sequences accumulated one upon the other on an Upper Cretaceous basement (Fig. 2). Their ages span from the Eocene to the Pleistocene (Bosellini et al. 1999; Ricchetti and Ciaranfi 2013), with only the deposition of Miocene and Lower Pliocene formations reaching the internal areas of the platform. Many of these sequences consist of clinostratified biocalcarenite/biocalcirudite deposits (e.g., Torre Tiggiano Limestone, Lutetian/Bartonian; Porto Badisco Calcarenites, upper Chattian; Salento Calcarenites, Lower Pleistocene) (Nardin and Rossi 1966; Bosellini and Russo 1992; Bossio et al. 1994; Parente 1994; Brandano et al. 2010), but most remarkable is the presence of two well preserved coral reef complexes of early Chattian (Castro Limestone) and early Messinian (Novaglie Formation) age (Bosellini et al. 1992, 2001, 2002, 2006; Brachert et al.

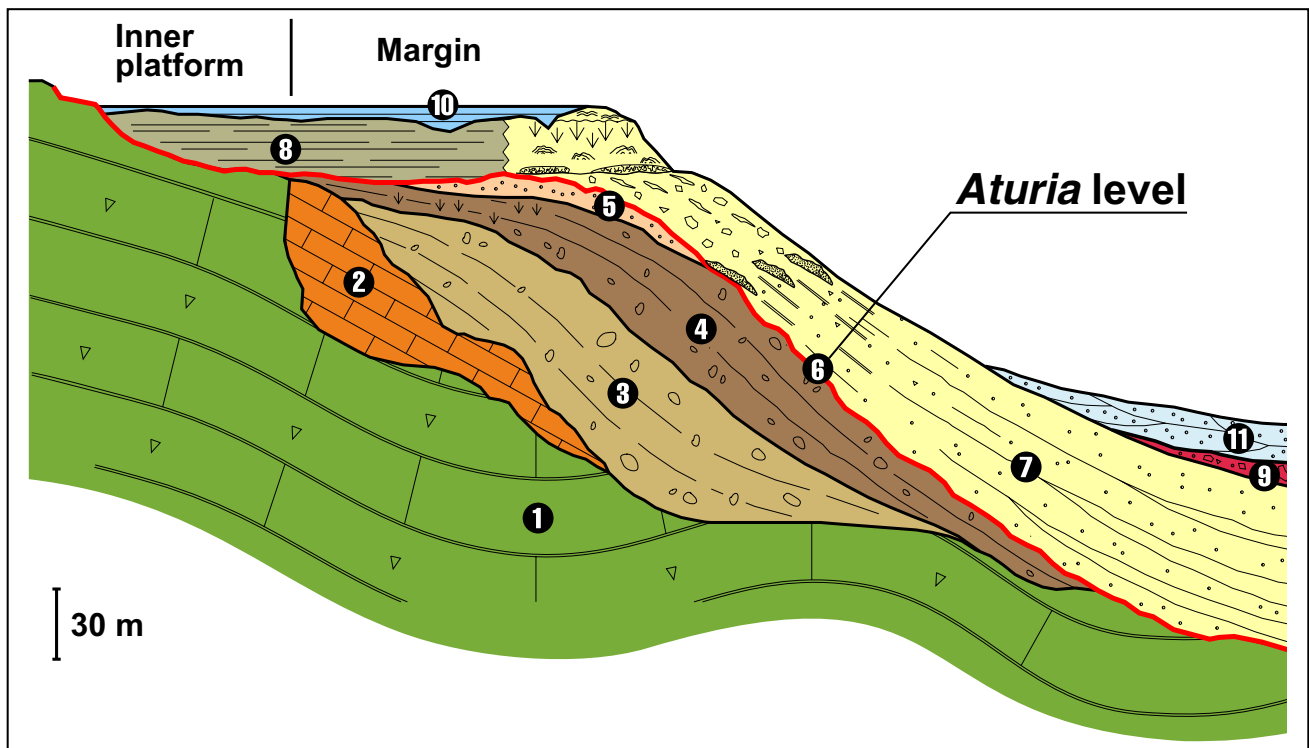


Fig. 2 Stratigraphic architecture of the eastern Salento Peninsula: 1- Upper Cretaceous substrate, 2- Torre Tiggiano Limestone (Lutetian/Bartonian), 3- Torre Specchialaguardia Limestone (Priabonian), 4- Castro Limestone (lower Chattian), 5- Porto Badisco Calcarenites (upper Chattian), 6- *Aturia level* (Serravallian/Tortonian), 7- Novaglie

Formation (lower Messinian), 8- Andrano Calcarenites (lower Messinian), 9- Leuca Formation (lower Pliocene), 10- Uggiano la Chiesa Formation (middle Pliocene), 11- Salento Calcarenites (lower Pleistocene) (modified from Bosellini et al. 1999)

2007; Vescogni et al. 2008, 2011; Braga et al. 2009; Guido et al. 2012).

The first notes on the Salento phosphatic sediments date back to the second half of the nineteenth century (e.g., Capellini 1869; De Giorgi 1884; Franco 1888), whereas Dainelli (1901), as a comment to the first geological map of the Salento southern portion, described a small phosphoritic outcrop some km north from the Leuca cape. Only several decades later, Giannelli et al. (1965) provided a more comprehensive lithological and stratigraphic characterization of these deposits, although limited to a single locality 1 km NE from the Porto Badisco harbor (Fig. 1b). There, a 45-cm-thick level of phosphatized macrofossils and phosphatic pebbles was identified, associated with a matrix of glauconitic calcarenite. Giannelli et al. (1965) dated the mollusc association from this locality to the middle/late Serravallian. The presence of the AL was subsequently documented in several other sites of the southern Salento and Bossio et al. (1989, 2002) were the first to suggest a relation between the deposition of phosphorites and the action of upwelling currents. The same authors, on the base of the planktonic foraminifera association, dated the AL to the late Burdigalian. The precise position of the phosphatic hardground within the Salento stratigraphic architecture was delineated by Bosellini et al. (1999). In particular, along the platform margin, the AL usually lies between the carbonate sequences of Oligocene age (Castro Limestone and Porto Badisco Calcarenite) and the lower Messinian reef unit of the Novaglie Formation, whereas in the internal platform the phosphoritic horizon rests directly on the Cretaceous basement (Fig. 2). Bosellini et al. (1999) considered the AL as a distal, heteropic facies of the Pietra Leccese, a calcarenite formation typical of the central/northern Salento and dated as late Burdigalian to early Messinian (Mazzei 1994). For this reason Bosellini et al. (1999) assigned the same age also to the phosphatic hardground. More recently, on the basis of strontium-isotope analyses and biostratigraphic data on calcareous nannofossils, Föllmi et al. (2015) restricted the age of the AL to the early Serravallian/late Tortonian. The same authors also underlined that the Salento phosphorites are represented in the southeastern areas by in situ hardgrounds (e.g., Ciolo cove, Marittima, Fig. 1b), while in the northern sectors (e.g., Cursi, Lecce surroundings, Fig. 1b) they occur as accumulations of allochthonous fragments, derived from the erosion, transport and redeposition of previously formed phosphatic and glauconitic deposits.

Materials and methods

Two main localities have been selected for this study: 1) the Ciolo cove, along the coastal road east of the town of Gagliano (39°50'39"/18°23'08"); 2) the site named "Masseria

Cucuruzzi" after an old farmhouse next to the coastal road between Gagliano and Leuca (39°49'22"/18°23'06") (Fig. 1b). In the Ciolo cove, the AL delineates a sharp horizon separating the Chattian Porto Badisco Calcarenite from the stratified deposits of the lower Messinian Novaglie Formation (Fig. 3a, b). Here, the phosphatic hardground measures about 15 cm in thickness and rests on a distinct erosion surface, filling also small fractures and cavities within the Chattian limestone (Fig. 3c). In the M. Cucuruzzi surroundings, the AL reaches over 25 cm and lies directly on the Cretaceous substrate (Fig. 3d, e). Although a thin cover of Messinian calcilutite (Novaglie Fm.) may occur on the top of the hardground (Fig. 3f), the phosphorites usually crop out at the ground level, on the surface of the cultivated fields in the vicinity of the farmhouse.

Both localities have been investigated to obtain data on the microstratigraphic, sedimentary, and paleontological features of the AL. However, special attention has been paid to the M. Cucuruzzi site where the large thickness and the wide, well exposed surface of the AL has allowed to collect a suitable amount of samples. In particular, sampling for macrofossil characterization was carried out by picking individual mollusc and coral specimens, together with the collection of some large blocks representative of the entire fossil association. Three blocks in particular, about 50 × 30 cm wide and 20 cm in thickness (Fig. 4), have been the object of subsequent, macroscopic and microscopic observations in laboratory, in order to include in the data-set also the smaller or less conspicuous coral and mollusc taxa.

Twenty-seven thin-sections (6 × 4.5 cm) and 15 additional hand samples (each of an average surface of ca. 400 cm²) have been considered for the study of the coral association. Specimens are mainly preserved as molds and/or as recrystallized skeletal rests and although several of them still preserve fine details of the original skeletal surface, in most cases diagnostic calicular elements (such as septa, pali, columella) are missing or incomplete and do not allow a proper classification at species level. Due to the poor preservation state, even the identification at genus level is dubious in some cases. The taxonomy of fossil azooxanthellate Scleractinia of the Mediterranean is currently under revision. The species names used in this paper (Table 1) derive from the critical analysis of the literature and the comparison with fossil and modern coral collections held in the following institutions: Museum of Palaeontology (University of Modena and Reggio Emilia, Italy); "G. Gemmellaro" Museum of Palaeontology and Geology (University of Palermo, Italy); Museum of Paleontology (University of Catania, Italy); Museum of Natural History (Turin University, Italy); Department of Earth and Environmental Sciences (University Milano-Bicocca, Italy); Department of Geology (Ghent University, Belgium); (formerly at) Station Marine d'Endoume (Marseille, France); Smithsonian

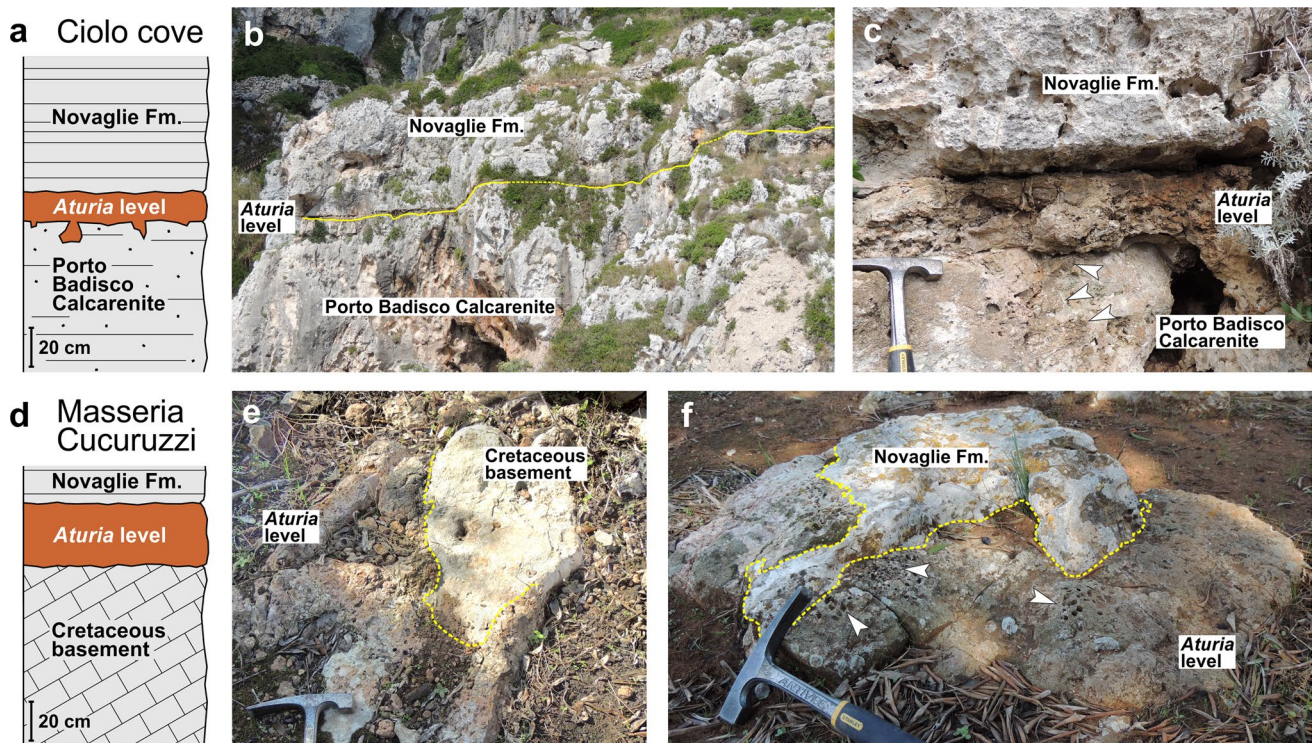


Fig. 3 **a** Ciolo cove, stratigraphic setting of the *Aturia* level. **b** Ciolo cove, the AL delineates the boundary between the Chattian Porto Badisco Calcarenites and the Messinian Novaglie Formation. **c** Ciolo cove, close-up of the AL; arrows indicate a fracture within the underlying Porto Badisco Calcarenites, filled by phosphatic sediment.

d Masseria Cucuruzzi, stratigraphic setting of the AL. **e** Masseria Cucuruzzi, close-up of the contact between the AL and the upper Cretaceous basement. **f** Masseria Cucuruzzi, close-up of the contact between the AL and the Messinian Novaglie Formation; arrows indicate the large bioperforations on the top of the hardground

National Museum of Natural History (Washington D.C., USA).

Concerning the mollusc assemblage, the shells are mainly preserved as cavities, only rarely as internal molds. Therefore, casts of the cavities were produced in the laboratory by infilling a two-component dental-silicone, yielding enough conchological features to allow a reliable identification (e.g., Fig. 8e, f). This collection has been compared to the lists reported by Dainelli (1901) and Giannelli et al. (1965), who provided the only previous descriptions of the AL mollusc association. These lists have been summarized and combined with our original data. For the literature-based species we list the names following the latest systematic and taxonomic revisions, but note that their presence in the assemblage remains debatable (Table 2). In some cases, the former identifications are almost certainly based on misinterpretations, e.g., the Oligocene to Early Miocene *Costellamussiopecten northamptoni* and the Eocene *Xenophora cumulans* are unlikely to occur in Serravallian strata. Identifications in open nomenclature (“sp.”) in former publications have been excluded herein, because these are too ambiguous to be interpreted without having seen the material.

One polished sample and 11 thin-sections have been prepared for microfacies analysis. Sediment textures have been named following the nomenclatures by Embry and Klovan (1971) and Dunham (1962).

The “*Aturia* level”

Microstratigraphy and facies analysis

Although characterized by different thickness, the AL from the two selected localities displays a similar stratigraphic arrangement, identified by the superimposition of two distinct facies separated by a phosphatic crust. In particular, at the base of the hardground lies a coral rudstone, followed by a detrital rudstone, the latter characterized by a succession of thinner layers mainly composed of phosphatic fragments (Fig. 5a, b).

The coral rudstone This facies consists of a coarse macrofossil accumulation (Figs. 4, 5a), about 7–10 cm thick in the Ciolo cove, up to 20 cm near Masseria Cucuruzzi.



Fig. 4 One of the large samples of *Aturia* level collected for laboratory analyses. The block has been placed upside down to show the macrofossil accumulation that constitutes the basal coral rudstone facies

Table 1 List of the identified coral taxa

Scleractinia
Family Dendrophylliidae
<i>Balanophyllia</i> (<i>Balanophyllia</i>) cf. <i>caryophylloides</i> Seguenza (1880)
<i>Balanophyllia</i> (<i>Eupsammia</i>) cf. <i>cornu-rupicaprae</i> Zuffardi-Comerci (1932)
<i>Balanophyllia</i> (<i>Eupsammia</i>) sp.
<i>Dendrophyllia</i> cf. <i>cornigera</i> (de Lamarck 1816)
Family Caryophylliidae
<i>Caryophyllia</i> sp.? <i>Acanthocyathus versicostatus</i> (Michelin 1841–1847)
<i>Trochocyathus multispinosus</i> (Michelotti 1838)
<i>Trochocyathus</i> (<i>Aplocyathus</i>) <i>armatus</i> (Michelotti 1838)
<i>Deltocyathus</i> sp.
<i>Ceratotrochus</i> (<i>Edwardsotrochus</i>) cf. <i>duodecimcostatus</i> (Goldfuss 1826)
<i>Ceratotrochus</i> (<i>Edwardsotrochus</i>) cf. <i>pentaradiatus</i> (Chevalier 1962)? <i>Stephanocyathus</i> sp.
Caryophylliidae 1
Caryophylliidae 2
Family Flabelliidae
<i>Flabellum</i> cf. <i>avicula</i> (Michelotti 1838)
<i>Flabellum</i> sp.
Family Micrabaciidae
<i>Stephanophyllia</i> sp.

Table 2 List of the mollusc taxa

Species	Previous identifications
Gastropoda	
<i>Amalda glandiformis</i> (de Lamarck 1810) ^a	<i>Ancillaria obsoleta</i>
<i>Ampulla deshayesiana</i> (Pereira da Costa 1867)	<i>Priamus deshayesianus</i>
<i>Bursa ranelloides</i> (Reeve 1844) ^a	<i>Triton</i> sp.
<i>Charonia lampas</i> (Linnaeus 1758)	<i>Triton nodiferum</i>
<i>Conilithes antdiluvianus</i> (Bruguière 1792) ^a	
<i>Eudolium</i> sp.	<i>Eudolium subfasciatum</i>
<i>Euthria</i> cf. <i>puschi</i> (Andrzejowski 1830) ^a	
<i>Ficus geometra</i> (Borson 1820–1825)	<i>Ficus geometra</i>
<i>Gemmula</i> sp. ^a	<i>Pleurotoma rotata</i>
<i>Genota</i> sp.	<i>Genota ramosa</i>
<i>Oligodia spirata</i> (Brocchi 1814) ^a	<i>Turritella subangulata</i>
<i>Ormastralium carinatum</i> (Borson 1821)	<i>Turbo speciosus</i>
<i>Plagioconus puschi</i> (Michelotti 1847)	<i>Conus russeggeri</i>
<i>Semicassis laevigata</i> (Defrance 1816–1830)	<i>Semicassis miolaevigata</i>
<i>Solariella?</i> sp. ^a	<i>Trochus</i> sp.
<i>Terebra acuminata</i> Borson 1820–1825 ^a	
<i>Tritia agatensis</i> (Bellardi 1882) ^a	
<i>Tritia brugnonis</i> (Bellardi 1872)	<i>Nassa brugnonis</i>
<i>Tritia</i> cf. <i>musiva</i> (Brocchi 1814)	<i>Nassa</i> sp. n.
<i>Tritia simulans</i> (Bellardi 1882) ^a	<i>Nassarius bisotensis</i>
<i>Tritia</i> sp. ^a	
<i>Tylacodes arenarius</i> (Linnaeus 1758) ^a	<i>Vermetus arenarius</i>
<i>Xenophora deshayesi</i> (Michelotti 1847) ^a	<i>Xenophora cumulans</i>
Cypraeidae gen. et sp. indet. ^a	<i>Cypraea</i> sp.
Fasciolaridae gen. et sp. indet. ^a	<i>Fusus</i> sp.
Naticidae gen. et sp. indet.	<i>Natica millepunctata</i>
Cephalopoda	
<i>Aturia aturi</i> (De Basterot 1825) ^a	<i>Aturia aturi</i>
<i>Aturia formae</i> Parona (1898)	<i>Aturia formae</i>
Bivalvia	
<i>Aquiptecten</i> aff. <i>malvinae</i> (Dubois de Montpéroux 1831) ^a	<i>Pecten malvinae</i>
<i>Asperarca</i> cf. <i>nodulosa</i> (O. F. Müller 1776)	<i>Arca</i> cf. <i>Nodulosa</i>
<i>Centrocardita globulina</i> (Michelotti 1839) ^a	<i>Cardita globulina</i>
<i>Chama gryphoides</i> Linnaeus (1758) ^a	<i>Chama gryphoides</i>
<i>Coralliophaga lithophagella</i> (de Lamarck 1819)	<i>Coralliophaga lithophagella</i>
<i>Costellamussiopecten badense</i> (Fontannes 1875–1892)	<i>Pecten cristatus</i>
<i>Costellamussiopecten haueri</i> (Michelotti 1847)	<i>Pecten haueri/northamptoni</i>
<i>Costellamussiopecten koheni</i> (Fuchs 1876) ^a	<i>Pecten koheni</i>
<i>Dosinia exoleta</i> (Linnaeus 1758)	<i>Dosinia exoleta</i>
<i>Glossus humanus</i> (Linnaeus 1758)	<i>Isocardia cor</i>
<i>Glycymeris nummaria</i> (Linnaeus 1758)	<i>Pectunculus insubricus</i>
<i>Gonimyrtea meneghinii</i> (De Stefani and Pantanelli 1878)	<i>Lucina spinifera</i> var. <i>meneghinii</i>
<i>Meiocardia deshayesi</i> (Michelotti 1847)	<i>Meiocardia deshayesi</i>
<i>Meiocardia moltkianoides</i> (Michelotti 1847)	<i>Meiocardia moltkianoides</i>
<i>Neopycnodonte navicularis</i> (Brocchi 1814)	<i>Ostrea cochlear</i>
<i>Spondylus concentricus</i> (Bronn 1831)	<i>Spondylus concentricus</i>
<i>Thracia convexa</i> (W. Wood 1815)	<i>Thracia convexa</i>
<i>Venus nux</i> (Gmelin 1791) ^a	<i>Venus multilamella</i>

In the right column, the identifications by Dainelli (1901) and Gianelli et al. (1965) are listed, in the left column their taxonomic update is provided

Taxa present in studied material are marked by (a)

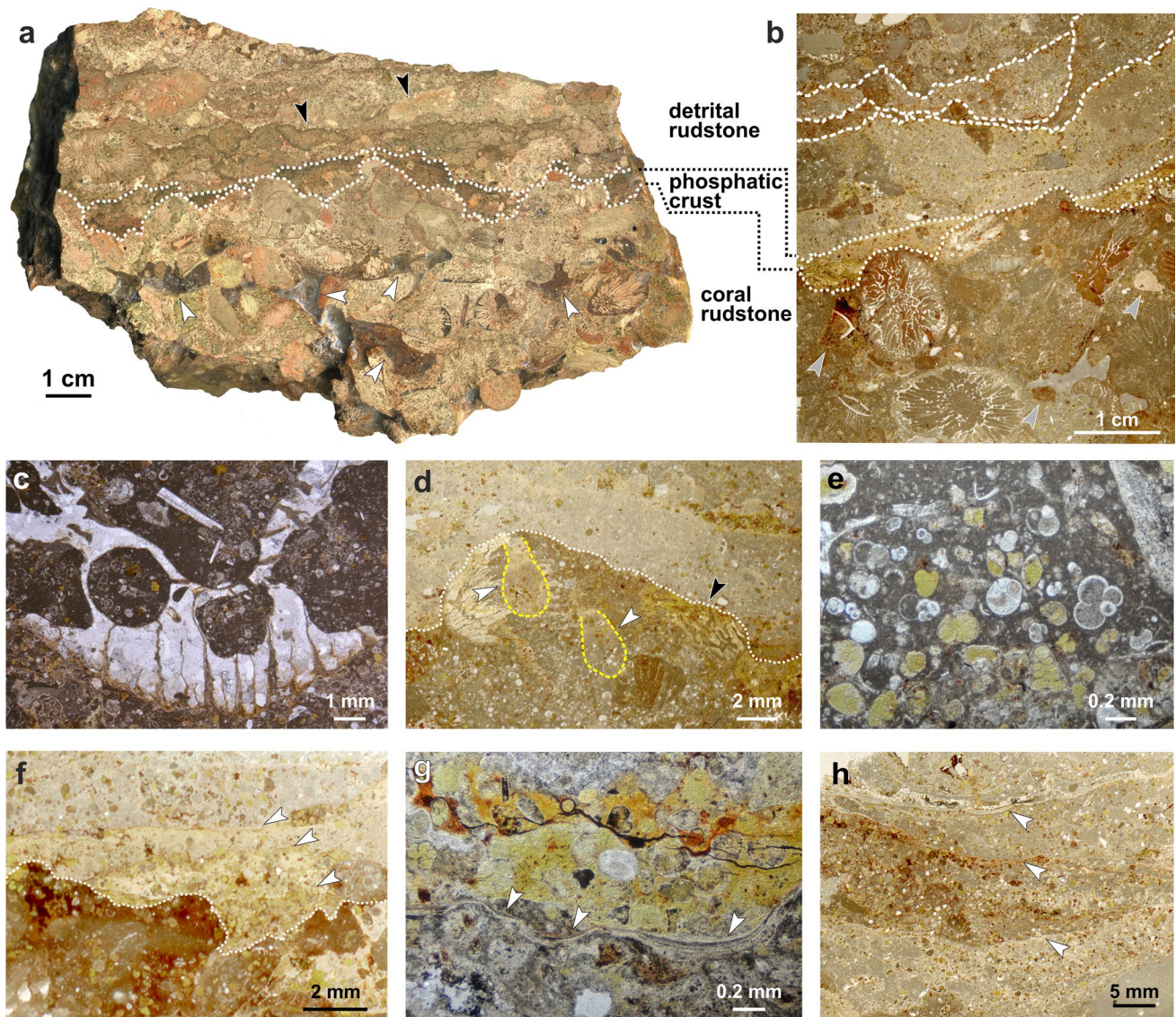


Fig. 5 **a** Polished sample and **b** thin-section showing the superimposition of the Aturia level facies: the basal coral rudstone is separated from the topmost detrital rudstone by a thick phosphatic crust (white dotted lines). In the coral rudstone, white arrows indicate empty cavities within the macrofossil accumulation and gray arrows show the presence of hardground fragments. In the detrital rudstone, black arrows indicate clasts with different degrees of phosphatization and white dashed lines separate the thin, discontinuous layers that are typical of this facies. **c** Coral rudstone: detail of a coral wall showing boring traces by clionid sponges. **d** Erosion surface on the top of

the coral rudstone (white dotted line); white arrows indicate traces of bioperforation, black arrow shows the pervasive glauconitization of a coral fragment. **e** Packstone-wackestone matrix within the coral rudstone, note the abundance of glauconitized foraminifera. **f** Phosphatic crust on the top of the coral rudstone (white dotted line), white arrows underline its different growth phases. **g** Close-up of the phosphatic crust on the top of the coral rudstone; white arrows indicate a thin micritic coating of microbial origin. **h** Layered deposits forming the detrital rudstone; white arrows underline the surfaces separating each level and associated to extremely thin micritic coatings

Macrofossils are mainly represented by corals, associated with molluscs and to a lesser amount of brachiopods, echinoderms, celleporiform bryozoans, serpulids and fish teeth. Aragonitic skeletons are mostly dissolved, and only calcitic shells of pectinid bivalves and of terebratulid brachiopods partially maintain their original structure. Even so, the largest part of the observed specimens was well preserved

before dissolution, showing a moderate degree of fragmentation prior to sedimentation and no significant traces of mechanical and chemical abrasion. Macrofossils show also boring traces mostly made by clionid sponges (Figs. 5c, 6g) and glauconitization, the latter mainly concentrated on the periphery of their skeletal structures, and particularly

pervasive on those specimens lying next to the top of the coral rudstone (Fig. 5d).

Beside the macrofossils, abundant is the presence of reworked hardground fragments (from few mm up to some cm large) characterized by different degrees of phosphatization (Fig. 5b). The accumulation of large, centimetric skeletal remains and of phosphatic pebbles allowed the formation of wide cavities within the coral rudstone. Some of these cavities have been preserved as empty (Figs. 4, 5a), but frequently they are filled with a fine-grained packstone-wackestone with abundant planktonic and benthic foraminifera, associated with a large amount of phosphatic grains mainly represented by glauconitized foraminifera (Fig. 5e). On the top of this facies there is a distinct erosion surface, often showing the presence of boring traces (Fig. 5d).

The phosphatic crust The erosion surface on the top of the coral rudstone is covered by a discontinuous, phosphatic/glauconitic crust up to 8 mm in thickness (Fig. 5a, b). This crust may exhibit different growth phases and includes small phosphatized fragments and glauconitized foraminifera (Fig. 5f). A thin, sub-millimetric micritic coating, characterized by a laminated appearance, is sometimes associated with the phosphatic crust (Fig. 5g). These micritic crusts also envelope most of the phosphatic fragments within both identified facies types.

The detrital rudstone The detrital rudstone on the top of the hardground differs from the coral rudstone by its layered nature, the absence of cavities, and by the reduced amount of skeletal components (Fig. 5a). The superimposition of several layers has been recognized, some of them extremely discontinuous, with a thickness ranging from few millimeters up to 2 cm (Fig. 5b, h). They usually exhibit a compact texture and consist of small hardground fragments with different degrees of phosphatization and roundness, associated with variable amounts of a fine-grained phosphatic packstone. The latter is rich in planktonic and benthic foraminifera, associated with abundant glauconitic grains (Fig. 5h) and sparse peloids. Scattered macrofossils can also be observed, mainly represented by solitary corals and celleporiform bryozoan colonies. On the top of each layer there is an erosive surface (Fig. 5b, h), sometimes showing traces of bioperforation, and usually covered by a thin micritic coating (Fig. 5h) or, more rarely, by a thin glauconitic crust. An erosion surface with large boring traces constitutes the upper boundary of the *Aturia* level (Fig. 3f).

Coral assemblage

Scleractinian specimens are densely packed in the coral rudstone facies. The elongate ones are mostly oriented parallel to the stratigraphic surface (Fig. 6a) while other growth forms do not show any preferential orientation. At least 17 distinct taxa, belonging to four families (in order

of abundance Dendrophylliidae, Caryophylliidae, Flabellidae, Micrabaciidae), can be clearly distinguished (Table 1). With the exception of two colonial forms, one rather common (*Dendrophyllia* cf. *cornigera*, Fig. 6a–d) and the other rare undetermined Caryophylliidae 2, all identified corals are solitary scleractinians. In most samples, over half of the scleractinian specimens are represented by dendrophylliid genera (*Dendrophyllia* and *Balanophyllia*), however caryophylliids can be rather common.

Corals belonging to the family Dendrophylliidae are mostly specimens of *Dendrophyllia* cf. *cornigera* and consist of long subcylindrical corallites, locally showing evidences of coloniality (Fig. 6b–d). The other dendrophylliid corals are ascribed to the solitary *Balanophyllia* (*Balanophyllia*) cf. *caryophylloides*, and to the free-living subgenus *Balanophyllia* (*Eupsammia*) (Fig. 6f–g). In particular, the corallum of *B. (B.)* cf. *caryophylloides* is attached to the substrate (e.g., another coral, a shell or an echinoderm fragment) through a polycyclic base and a cylindrical pedicel reaching up to 1 cm in diameter (Fig. 6e, f).

The family Caryophylliidae (Fig. 7a–f) is the most diversified one among the scleractinians examined in this study, containing at least ten distinct taxa (Table 1), some of which are extremely rare. In order of abundance: *Ceratotrochus* (*Edwardsotrochus*) cf. *duodecimcostatus*, Caryophylliidae 1, *Ceratotrochus* (*Edwardsotrochus*) cf. *pentaradiatus*,? *Acanthocyathus versicostatus*, *Caryophyllia* sp., *Deltocyathus* sp., *Trochocyathus multispinosus*,? *Stephanocyathus* sp., Caryophylliidae 2 (colonial), *Trochocyathus* (*Aplocyathus*) *armatus*.

Flabellids are relatively common and variable in size and preservation state. Most specimens, however, can be ascribed to morphotypes of the species *Flabellum avicula* (Fig. 7g),

Several caryophylliids and *Flabellum* observed in the present study, commonly show traces of boring polychaetes (ichnogenus *Sulcichnus*), so far described only for the following Mediterranean Miocene to Pliocene genera: *Caryophyllia*, *Ceratotrochus*, *Trochocyathus*, and *Flabellum* (Martinell and Domènech 2009).

With regards to the family Micrabaciidae, only two specimens belonging to the genus *Stephanophyllia* sp. (Fig. 7h) have been observed. The preservation state of these corals does not allow the identification at species level.

Mollusc assemblage

The largest part of the mollusc specimens has been collected from the coral rudstone facies. Twenty-two different species have been identified; among them 15 gastropods (e.g., *Tritia agatensis*, *Tritia simulans*, *Amalda glandiformis*, *Conilithes antidiluvianus* and *Bursa ranelloides*, Fig. 8a–e), five bivalves (e.g., *Aquiptecten* aff. *malvinae*,

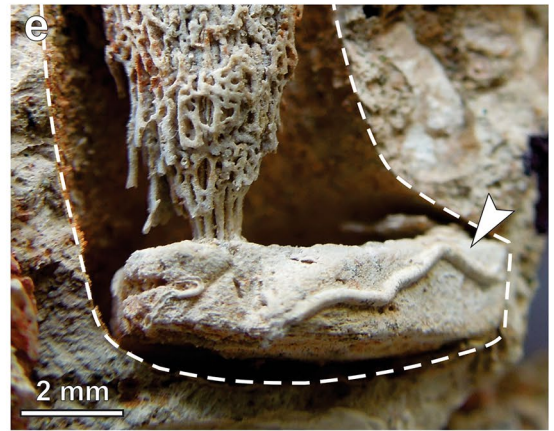
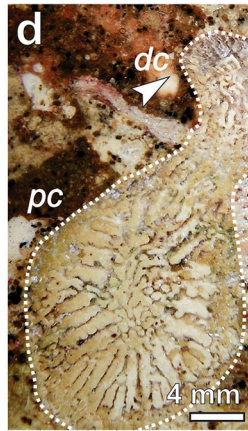
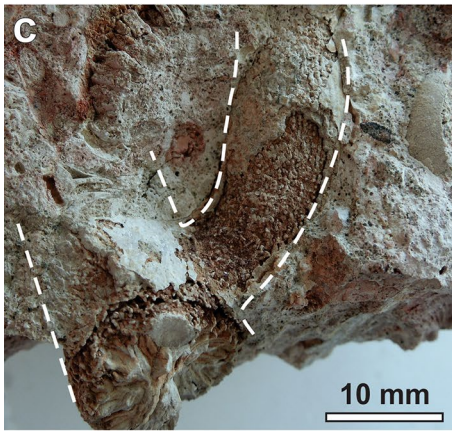


Fig. 6 **a** *Dendrophyllia* cf. *cornigera*, internal and external molds of subparallel cylindrical corallites; white arrow pointing at the internal mold of a serpulid originally encrusting the coral outer wall. **b** *Dendrophyllia* cf. *cornigera*, mold showing budding (white arrows), the imprint of well-preserved costae (gray arrow) and the mold of a large serpulid originally encrusting the outer surface of the coral (black arrow and dashed line). **c** *Dendrophyllia* cf. *cornigera*, longitudinal view of parent and budded daughter corallites. **d** *Dendrophyllia* cf. *cornigera*, transversal view, in polished section, of parent and daughter corallites (“pc” and “dc”, respectively). **e** External mold (dashed line) and partly preserved internal mold of the pedicel of **b**. cf. *caryophylloides* encrusting an echinoid plate colonized by tiny serpulids (white arrow). **f** Longitudinal view of *Balanophyllia* cf. *caryophylloides* (internal mold). **g** Longitudinal view of the internal and external mold of *Balanophyllia* (*Eupsammia*) cf. *cornu-rupicaprae*; note *Entobia* borings preserved as cast in the basal part of the corallum (white arrow)

Costellamussiopecten koheni, *Venus nux* and *Chama gryphoides*, Fig. 8f–i), and two cephalopods (*Aturia aturi* and *Aturia* sp., Fig. 8j, k). Combining these data with the lists reported by Dainelli (1901) and Giannelli et al. (1965), the total assemblage comprises about 26 gastropods, 18 bivalves, and two cephalopods species. The complete list of the mollusc association is reported in Table 2, where taxa marked with an asterisk indicate species that were identified using our own findings.

Discussion

The coral-mollusc archive: stratigraphic significance

The biostratigraphic significance of the coral and mollusc assemblages is moderate. Concerning the corals, we can assert with confidence that almost all taxa of the AL are extinct in the Mediterranean, some since the Miocene, others since the Early Pleistocene. Only the specimens ascribed to the genus *Dendrophyllia* have high affinities with the extant Mediterranean-Atlantic colonial species *Dendrophyllia cornigera*. Though Chevalier (1962) claimed the presence of this species only in post-Miocene layers of peri-Mediterranean regions, according to recent studies (Vertino et al. 2018), it seems to exist since the Early Miocene as indicated also in older literature (De Angelis 1894; Zuffardi-Comerci 1932). The other identified genera have been recurrently reported in Miocene and Pliocene deposits of the Mediterranean (overviews in Chevalier 1962; Vertino et al. 2014; Spadini 2015). Among them, *Balanophyllia* (*Eupsammia*) *cornu-rupicaprae*, *Ceratotrochus* (*Edwardsotrochus*) *pentaradiatus* and the subgenus *Acanthocyathus* have been reported so far exclusively in Upper Miocene layers (Montanaro 1929; Zuffardi-Comerci 1932; Chevalier 1962). Instead, *Stephanocyathus*, *Deltocyathus*, and the polycyclic *Balanophyllia* (*B.* cf. *caryophylloides*) have been recorded

from the Miocene until the Early Pleistocene of the Mediterranean (Vertino 2003; Vertino et al. 2014).

Concerning the molluscs, a Miocene age is indicated by the frequent occurrence of *Aturia aturi* and *Aturia formae*. Overall, the assemblage has a Middle to Late Miocene character, indicated by *Costellamussiopecten badense* and *Costellamussiopecten koheni*. The possible presence of *Xenophora deshayesi*, related to the occurrence of some poor preserved specimen, might allow narrowing the range to the Middle Miocene. Moreover, most species, for example within the nassariids, are also frequently recorded from Tortonian strata. Therefore, the mollusc fauna suggests a Serravallian to Tortonian age. Gianelli et al. (1965) listed also *Chlamys northamptoni* from the *Aturia* level, which is an Oligocene to Early Miocene species closely related to *Costellamussiopecten haueri*. As this species is apparently absent in the Middle Miocene (Mandic 2000), we consider it as an erroneous identification of *C. haueri*. Similarly, the record of the Pliocene *Pecten cristatus* by Dainelli (1901) is misleading. The species present in the AL fauna is *Costellamussiopecten badense*, which differs from *C. cristatus* in its smaller size and the presence of primary sculpture during early ontogeny (Mandic 2004).

The coral-mollusc archive: paleoenvironmental significance

Previous studies on the Early–Middle Miocene az-corals of the Mediterranean underline that many genera are morphologically indistinguishable from present-day taxa, thus making their comparison with modern analogs a reliable approach for paleoenvironmental reconstructions (Vertino et al. 2014 and references therein). Hence, the az-coral assemblage of the AL may provide useful data for estimation of the type of substrate, paleobathymetry, hydrodynamic energy, and nutrient supply that characterized their original depositional environment.

With the exception of *Dendrophyllia* cf. *cornigera* and *Balanophyllia* cf. *caryophylloides*, that are typical of hard substrates, all examined scleractinians can be compared to modern taxa living on soft bottoms, characterized by mud to fine sand-dominated sediments.

Particularly significant is the dominance of the slender and mostly subcylindrical corallites of *Dendrophyllia* fragments, which are morphologically comparable to deep-sea morphotypes of the extant *Dendrophyllia cornigera*. This species is known to live today in circalittoral to bathyal environments of the NE Atlantic (between Ireland, Azores, and the Cape Verde Islands) and in the Mediterranean Sea where it has a wider bathymetric distribution, from around 80 to 730-m water depth and a thermal range from 11 to

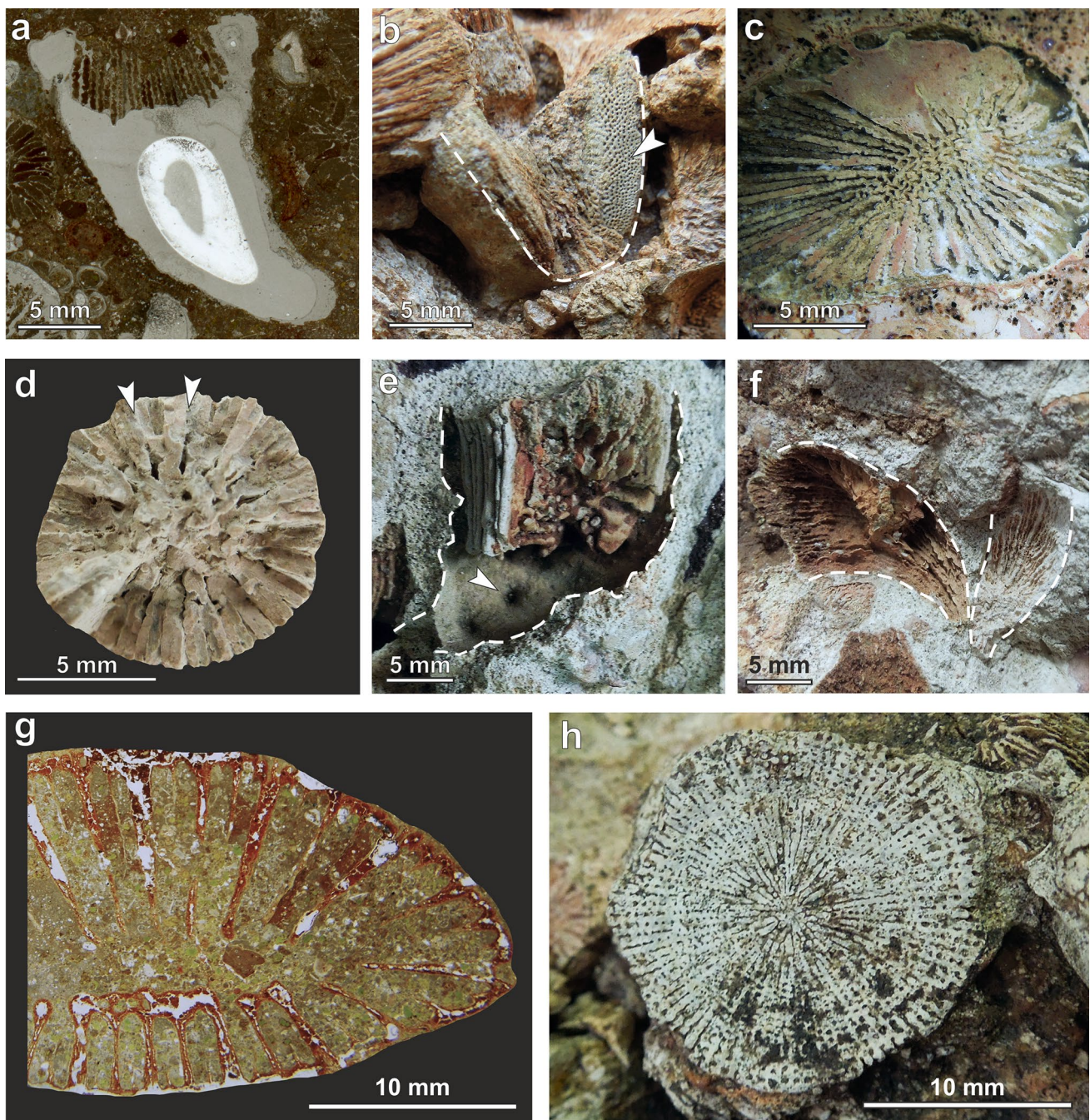


Fig. 7 **a** *Ceratrotrochus* (*Edwardsotrochus*) *duodecimcostatus*, longitudinal section showing the corallum trochoid shape and partly preserved recrystallized septa (distal part). **b** Broken specimen of the bowl-shaped *C. (E.) cf. pentaradiatus* showing a well-preserved internal mold (note the well-defined and dense septal granulation imprint, white arrow) and a partly preserved (recrystallized) outer wall. **c** Transversal polished section of *Edwardsotrochus* showing a partly bioeroded recrystallized skeleton. **d** Transversal section of mold of

Caryophyllia sp.; white arrows pointing to cavities left by the dissolution of “pali”. **e** Mold of *?Acanthocyathus versicostatus*; note the irregular outer wall profile (white dashed line) and holes presumably left by the wall spines (arrow). **f** *Caryophylliidae* sp. 2; longitudinal view of two broken ceratoid specimens with partly preserved (recrystallized) septa. **g** *Flabellum avicula*, oblique-transversal thin-section showing almost entirely dissolved, and oxidized, straight septa. **h** Basal view of *Stephanophyllia* sp

17 °C (Zibrowius 1980; Freiwald et al. 2009; Smith et al. 2009; Mastrototaro et al. 2010; Vertino et al. 2010; Salomidi et al. 2010; Gori et al. 2014 and reference therein). Bathyal

specimens of *D. cornigera* are generally less robust than the circalittoral ones and bear more elongate and slender

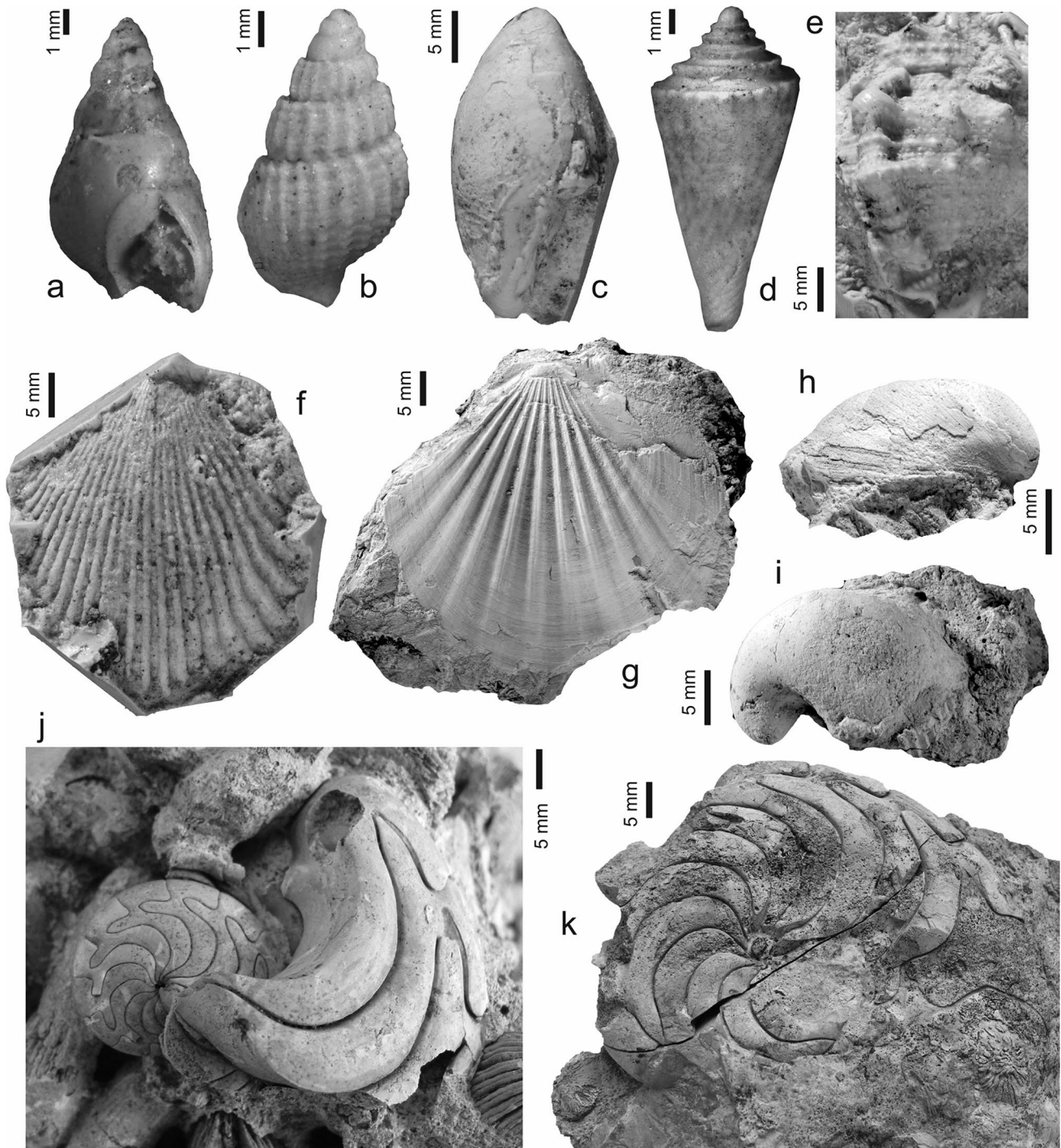


Fig. 8 **a** *Tritia agatensis* (Bellardi 1882). **b** *Tritia similans* (Bellardi 1882). **c** *Amalda glandiformis* (de Lamarck 1810). **d** *Conilithes antidiluvianus* (Bruguière 1792). **e** *Bursa ranelloides* (Reeve 1844). **f** *Aquipecten* aff. *malvinae* (Dubois de Montpéreux 1831). **g** *Costel-*

lamussiopecten koheni (Fuchs 1876). **h** *Venus nux* Gmelin 1791. **i** *Chama gryphoides* Linnaeus 1758. **j** *Aturia aturi* (De Basterot 1825). **k** *Aturia* sp. (**a–f** are silicone casts)

corallites, rather similar in shape and size to the fossil ones found in the AL (A. Vertino, pers. observ.).

In deep-water environments of the Mediterranean, the slender *D. cornigera* is generally associated with coral

buildups made up of *Madrepora oculata*, *Desmophyllum dianthus* and, secondarily, *Lophelia pertusa*. For instance, it is known along the flanks of the coral mounds located off-shore Santa Maria di Leuca (SML, southern Apulia), at

around 400–600-m water depth (Vertino et al. 2010; Rosso et al. 2010). The coral communities living on the SML morphological elevations, up to 300 m wide and 25 m high, benefit from moderate-to-strong bottom currents, partly exposed hardgrounds (mostly buried by muddy sediment) (Vertino et al. 2010; Savini et al. 2014) and food supply consisting of dense zooplankton and resuspended decayed organic matter (Carlier et al. 2009). Slender bathyal forms of *D. cornigera* have also been observed on coral mounds of the Pen Duick Escarpment (southern Gulf of Cadiz), along the Moroccan continental margin at 450–550-m depth (A. Vertino, pers. observ.), where they live on heterogeneous seafloors dominated by mud to sandy mud and patchily exposed rocky substrates, mostly consisting of rocky slabs (De Mol et al. 2012).

Aphotic and deep-water environments are also confirmed by the other az-coral species found in the AL. Though extinct in the Mediterranean, most of them are very similar to living taxa from modern oceans. For instance, *Balanophyllia* (*Balanophyllia*) *caryophylloides*, synonym of the modern NE Atlantic species *B. thalassae*, is known to live today below 350 m of depth (Zibrowius 1980). The free-living horny-shaped specimens ascribed to *Balanophyllia* (*Eupsammia*) (Fig. 7c, d) are similar to extant Indo-Pacific species living mostly between 100 and 520 m [e.g., *Balanophyllia cornu* according to Cairns and Zibrowius (1997) and Roberts et al. (2009)]. Although the genera *Caryophyllia*, *Deltocyathus* and *Flabellum* have a very wide geographic and bathymetric distribution, the specimens of *Deltocyathus* of the AL show affinities to *Deltocyathus italicus* (Michelotti 1838 = *conicus* Zibrowius 1980), a species living today below 400-m depth in the north Atlantic (Zibrowius 1980; Roberts et al. 2009 and reference therein). *Stephanophyllia*, today exclusive of Indo-Pacific regions, has been collected alive up to 700-m water depth, even if it generally lives at shallower depths (Cairns 1989; Cairns and Zibrowius 1997; Roberts et al. 2009). Finally, the association *Dendrophyllia*—*Eupsammia* (horn-like shaped)—*Flabellum*—*Deltocyathus*—*Stephanophyllia* has been commonly reported in the Philippine and Indonesian regions within the depth range of 150–350 m (Cairns and Zibrowius 1997). In the fossil record, dendrophylliid-dominated facies similar to the coral rudstone have been recorded from the Tortonian limestones of the “Calcare di Mendicino” (Calabria, southern Italy) (Mastandrea et al. 2002), and from the Lower Messinian of Carboneras (Spanish Betic Cordillera) (Barrier et al. 1991), thus making the AL as the oldest occurrence. Both of these deposits are interpreted as accumulations of coral fragments within deep-sea environments.

Similarly to corals, the composition of the mollusc assemblage (Fig. 8) suggests a mixture of hardground dwelling species with soft bottom dwellers. Taxa, such as

Chama gryphoides, *Spondylus concentricus*, *Neopycnodonte navicularis*, and *Tylacodes arenarius* are attached to rocks, corals, and shells or are nestling like *Coralliophaga lithophagella*. Other species, such as *Venus nux*, *Dosinia exoleta*, and *Glossus humanus* are buried in sediment. Similarly, several of the gastropods lived at least periodically infaunal (e.g., *Ficus*, *Semicassis*, Naticidae).

Most of the recorded mollusc species, such as *Xenophora deshayesi*, *Amalda glandiformis*, *Terebra acuminata*, and the nassariids, have wide bathymetric ranges and are frequently recorded from coastal shallow water environments down to deeper settings (Zuschin et al. 2007; Landau et al. 2013). Some taxa, however, are more restricted: the extinct *Conilithes antidiluvianus* is characteristic for Miocene and Pliocene offshore settings and rarely occurs in shallow sublittoral assemblages (Harzhauser and Landau 2016). The extant *Bursa ranelloides* prefers shelf environments and is described frequently from submarine banks and even from deep water carbonate mounds from about 100 to 500-m water depth (Okutani 1963; Gofas and Beu 2002; Foubert et al. 2008; Nascimento et al. 2012). *Coralliophaga lithophagella* is a nestling species in deeper waters down to about 360-m water depth (Morton 2014). In the Mediterranean area, the Recent gryphaeid *Neopycnodonte cochlear* occurs from sublittoral water depths of about 20 m down to bathyal settings of up to 2000 m (Parenzan 1976; Poppe and Goto 1993; Huber 2015) and is most typical in outer-shelf to upper bathyal settings (Capraro et al. 2015; Ceregato et al. 2007). *Asperarca* cf. *nodulosa* is a deep-water NE Atlantic and Mediterranean species, attached by a thin byssus on a secondary hardground of continental shelf and bathyal zones (20–4000 m; Krylova et al. 2006). It is common on seamounts in front of Portugal, Spain, and Morocco (Krylova et al. 2006), as well as on coral mounds at 300–1100-m depth off Apulia in southern Italy (Mastrototaro et al. 2010; Negri and Corselli 2016). It is also known from NE Atlantic coral mounds off-shore Ireland (Henry et al. 2007). Similarly, *Chama gryphoides* lives cemented on hardgrounds in intertidal and offshore environments but is also part of the seamount fauna of the NE Atlantic occurring there down to 1250-m depth (Krylova 2006). *Glossus humanus* lives offshore on the continental shelf down to 3660-m water depth as a shallow burrower in muddy bottoms (Rodríguez and Sanchez 1997; Oliver et al. 2016). *Venus nux* lives from the infralittoral zone down to 700-m depth, being most frequent on the continental shelf (Poppe and Goto 1993). Finally, the free-swimming cephalopod *Aturia* was interpreted by Schlögl et al. (2011), based on geochemical data, to have lived in outer-shelf environments in about 200–350-m water depth. Of course, the shells from the AL might have been transported post-mortem and the depositional environment is

not necessarily identical with the original habitat (see Luke-neder and Harzhauser 2002). Nevertheless, the estimates by Schlögl et al. (2011) might serve as realistic minimum depth boundary, which fits well to the estimates interpreted for the benthic species. Hence, the depositional environment of the AL might have been on outer shelf in about 200–300-m water depth.

Depositional model

By combining the paleoecological information from the coral and mollusc assemblages with microstratigraphic and microfacies data, it is possible to trace back the AL depositional history and to reconstruct the main factors that controlled its evolution. In particular, four different steps can be recognized (Fig. 9):

1. *Growth of the coral-mollusc association* We can assume that the first phase in the formation of the basal coral rudstone might be related to the development of a biotic association comparable to present-day frame-building cold-water coral communities.

Corals and molluscs were probably thriving on a heterogeneous seafloor, composed of well-lithified substrates associated with accumulations of mobile sediments. Hard substrates were presumably represented by exposed portions of the older Cretaceous and Oligocene formations, while loose sediments were constituted of skeletal grains and micrite accumulated within seafloor depressions and/or trapped by the coral colonies (Fig. 9a). These areas were swept by moderate to relatively intense bottom currents, providing corals with food supply and preventing them from being smothered.

The dominance of az-corals, as well as the absence of any light-dependent organism, hint at the development of AL biotic association under aphotic and deep water, also ruling out any significant downslope transport of the biotic assemblage from shallower, photic settings. By the reliable comparison of most of the identified coral taxa with their very close present-day analogues, a depth down to some hundreds of meters can be further inferred. In particular, the strong similarity between the taxonomic composition of the AL coral assemblage with the Indo-Pacific *Dendrophyllia*—*Eupsammia*—*Flabellum*—*Deltocyathus*—*Stephanophyllia* association suggests a paleodepth restricted to a range of about 100–350 m. This reconstruction is in agreement with paleobathymetric information from the mollusc association, in particular with the depth range assumed to be typical of the *Aturia* cephalopod (Schlögl et al. 2011).

Analogous deep-sea communities, dominated by the coral genus *Dendrophyllia*, have not been reported so far in phosphate-rich environments. However, Mazzini et al. (2012)

describe the finding of Early Pliocene authigenic phosphatic hardgrounds, at around 650–700-m depth, along the western flank of the Porcupine Bank (off-shore west Ireland), where present-day *Lophelia-Madrepora* carbonate mounds occur. These authors impute the formation of Pliocene phosphatic crusts to peculiar and long-lasting environmental conditions, similar to the ones occurring in the present-day Porcupine Bank and supporting the coral community. The water stratification and circulation pattern of this region allow “trapping and concentration” of large amount of organic material that provide food for coral growth and, through bacterial decay, liberate phosphates. Additionally, these conditions favor the formation of hardground crusts, quite common in association with cold-water coral ecosystems also in other locations of the North Atlantic and Mediterranean Sea (Alloué 1987; Freiwald et al. 2002; Noé et al. 2006; Rosso et al. 2010; Vertino et al. 2010; Taviani et al. 2011). Mazzini et al. (2012) propose the combination of upwelling events and current-induced turbulence as main factors promoting nutrient fluxes needed for coral growth and phosphate crust formation. Similarly, deep-sea coral habitats associated with nutrient-rich upwelling waters have been well documented in several present-day localities (e.g., Reed 1983; Rogers et al. 2007; Davies et al. 2009; Mienis et al. 2007).

2. *Deposition of the coral rudstone facies* As previously stated, the AL macrofossil assemblage was well preserved before the diagenetic dissolution of the skeletal structures. Fragmentation occurred mainly for the thin branches of the phaceloid corals, but even in this case the delicate skeletal structures rarely display evidences of abrasion and very few fragments are heavily bioeroded. These data provide some important information on the post-mortem history of the AL biotic association, that most probably involved changes in the intensity of the bottom currents. One or more high-energy episodes could have favored the breaking of the thin coral branches, causing the transport of the entire association that accumulated within a relatively short distance (Fig. 9b). These moderate transport events were most probably followed by the almost immediate burial of the skeletal remains. The well preserved micromorphology of the coral specimens and the bio-erosion often restricted to the basal part of their skeletons (e.g., Fig. 9b), presumably acting when the corals were still alive (Beuck et al. 2007), actually support the occurrence of fast burial episodes. This interpretation is consistent with previous studies on the Salento AL, that on the base of the good preservation of the macrofossil assemblage also suggested a sudden burial scenario (Föllmi et al. 2015). Part of the matrix enclosing the macrofossils, a fine-grained packstone-wackestone (Fig. 5e), probably derived from in situ accumulation of

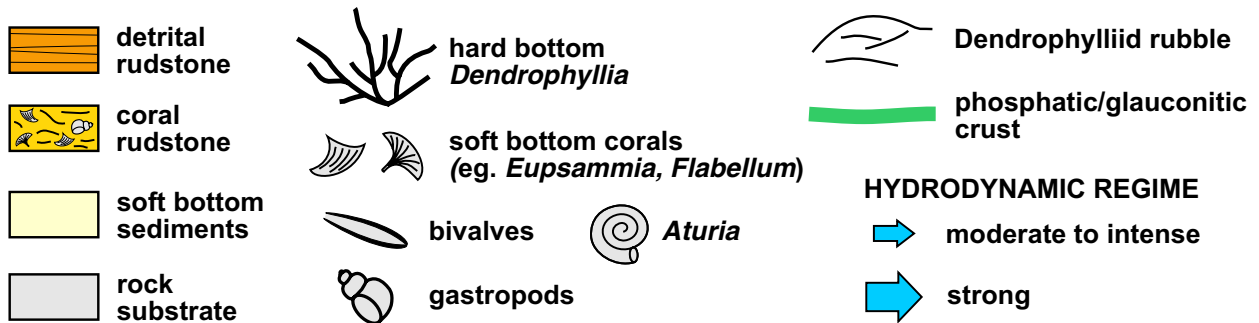
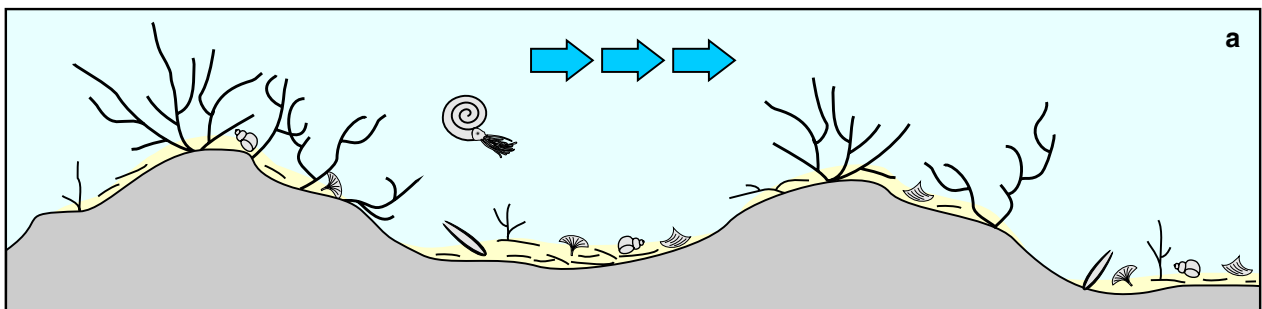
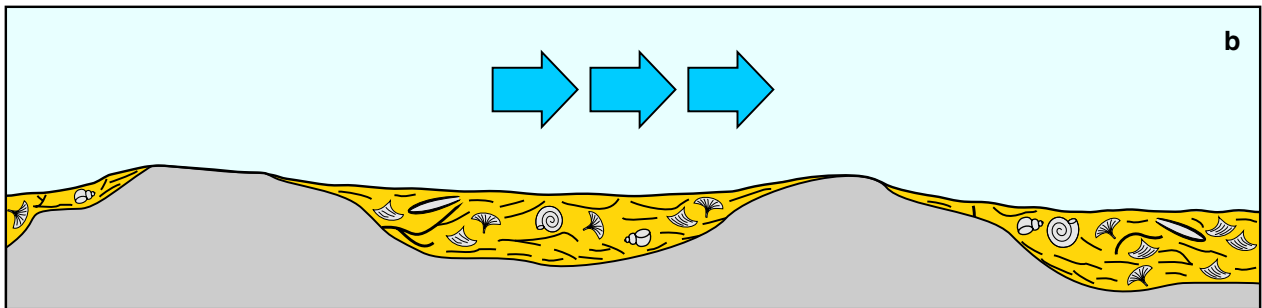
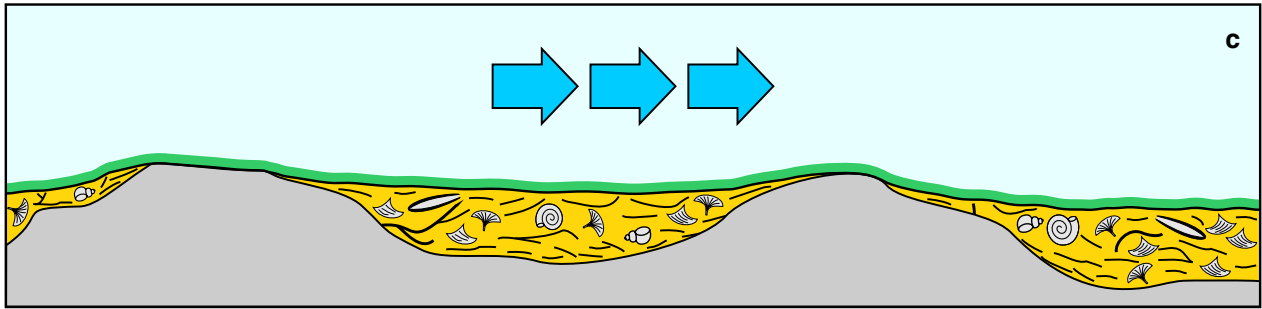
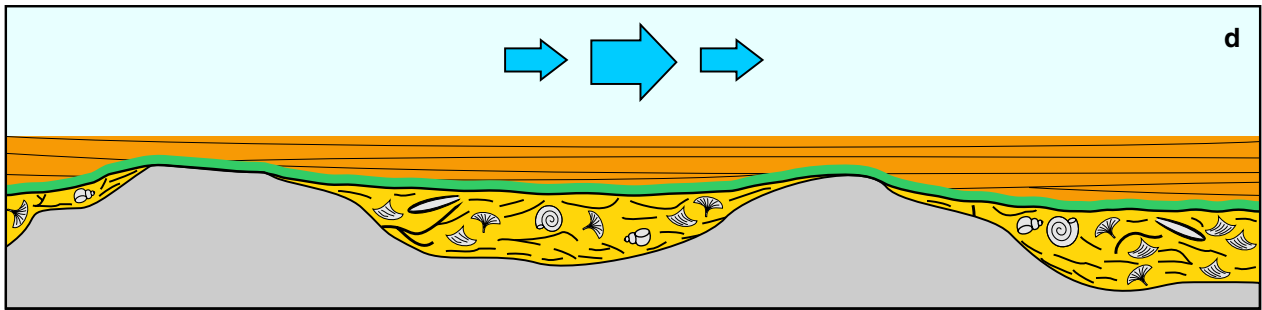


Fig. 9 Succession of the AL depositional phases: **a** Growth of the coral-mollusc association: the biotic assemblage suggests the occurrence of a heterogeneous seafloor, with hard substrates interspersed by accumulations of soft sediment, at about 100–350 m of depth and under the influence of moderate to strong bottom currents, rich in resuspended organic matter. **b** Deposition of the coral rudstone facies: one or more high-energy episodes could have swept the biotic assemblage, breaking the coral branches and causing the transport of the entire association, with its redeposition within the nearby area. **c** Formation of the phosphatic crust: the persistence of strong currents prevented the further accumulation of sediment, also triggering the erosion of the top of the coral rudstone. This phases of sediment starvation lasted for a considerable amount of time, allowing the formation of a thick phosphatic crust. **d** Deposition of the detrital rudstone facies: a general decrease in the intensity of the bottom currents allowed the restart of the sediment deposition. However, the occurrence of discontinuous layers, separated by erosion surfaces, suggests the presence of an extremely variable hydrodynamic regime, characterized by the alternation of moderate and stronger conditions

micrite and planktonic foraminifera, possibly facilitated by the trapping action of the coral frame. However, the considerable amount of phosphatized grains (Fig. 5e), as well as the occurrence of hardground fragments (Fig. 5b), indicate an important presence of reworked clasts, transported by the bottom currents from more distant areas and derived from the erosion of previously cemented hardgrounds. These sediments accumulated within the macrofossils with the decrease of the high-energy hydrodynamic conditions.

3. *Formation of the phosphatic crust* The deposition of the coral rudstone was followed by a period of stasis in sediment accumulation. This is clear from the erosion surface on the top of the coral rudstone, characterized by the presence of boring traces and glauconitized skeletal fragments (Fig. 5d), but especially by its superimposition by the thick phosphatic/glauconitic crust (Fig. 5f). Glauconitic minerals are generally assumed to develop at a depth range roughly comprised between 50 and 500 m; their formation occurs on the bottom surface and requires up to 10^5 – 10^6 years. For this reason, in situ glauconitic mineralizations are frequently used as markers of extremely slow sedimentation rate (Odin and Matter 1981; Odin and Fullagar 1988; Amorusi 1997). In Salento, this condition was most probably related to the persistence of strong currents, that triggered the erosional event on the top of the coral rudstone and kept on sweeping the sea bottom, preventing coral settlement and further accumulation of sediments (Fig. 9c). Though deep-sea coral bioconstructions are preferentially located in moderate- to high-energy environments (Roberts et al. 2006, 2009 and reference therein), too-high-flow speeds inhibit coral settlement by sweeping away floating larvae (Larsson et al. 2014) and by reducing the prey-capture efficiency of polyps (Purser et al. 2010; Orejas et al. 2016).
4. *Deposition of the detrital rudstone facies* The presence of some well-preserved corals above the phosphatic

crust hints at the temporary re-establishment of the environmental conditions that allowed the coral growth. A general decrease in the intensity of the bottom currents may have allowed the settlement of new coral larvae and triggered the restart of the sediment deposition. Nevertheless, the sparse coral occurrence and the very discontinuous layers of detrital rudstones, separated by several erosion surfaces (Fig. 5b, h), indicate the presence of an extremely variable hydrodynamic regime, unsuitable for the establishment of long-lasting coral ecosystems and characterized by relatively low-energy phases and periods of stronger hydrodynamic conditions (Fig. 9d).

The depositional model proposed herein implies the presence of a variable hydrodynamic regime that could have favored both coral growth and phosphogenesis along the Salento margin. In particular, Föllmi et al. (2015) associate the deposition of the AL to a system of nutrient-enriched currents flowing from the deeper, eastern region of the Mediterranean and characterized by changes in direction and intensity. This variable regime could have caused episodes of relatively moderate hydrodynamic conditions, which allowed the growth of the coral community, alternated with high-energy phases, with erosion, transport, and redeposition of skeletal fragments and hardground clasts. The persistence of these strong currents could have also induced protracted phases of sediment starvation with the formation of phosphatic and glauconitic mineralizations.

Temporal reconstruction of the AL formation The possibility to define the precise amount of time occupied by each of the steps in the AL depositional history is greatly hampered by the poor biostratigraphic value of the studied macrofossil association. The best resolution is provided by the molluscs, which indicate for the growth of the coral-mollusc assemblage a time period within the Serravallian/Tortonian. Although of broad stratigraphic significance, this result is in agreement with the age of the AL reported in Föllmi et al. (2015), based on strontium-isotope analyses and calcareous nannofossils biostratigraphy. These authors in fact reported an age comprised between 13.36 My (early Serravallian) and 7.55 My (late Tortonian) for the whole period of the AL formation. It is thus possible to assume that the succession of the four AL depositional phases, distinguished herein for the first time, lasted about 5.8 My. This time span was most probably characterized by an initial period of relatively stable environmental conditions that allowed the growth of the coral-mollusc community, followed by its destruction and the accumulation of the skeletal rests and leading to the formation of the coral rudstone facies. The paleontological and sedimentary features of the coral rudstone do not allow to recognize it with confidence as the product of a single event of growth/destruction/accumulation, or if it may be rather related to the succession of more episodes that created

a time-averaged, condensed macrofossil deposit (sensu Kidwell 1998). In any case, the time encompassing the first two phases of the AL depositional history might be considered as relatively short, compared to the sequence of events that followed. In particular, the evidence of several erosion surfaces (on the top of the coral rudstone and within the detrital rudstone facies), usually associated with traces of bioporation, and the thickness and number of the phosphatic and glauconitic crusts, also present within the detrital rudstone, hint to a particular importance of the time periods of erosion and sediment starvation, that could have encompassed most of the 5.8 My of deposition of the whole AL.

The condensed nature of the AL prevents a much more detailed geochronological resolution that would be necessary to establish a precise correlation of the Salento phosphogenesis with both Mediterranean and global climatic and oceanographic changes. In addition, Föllmi et al. (2015) underline a decoupling between the time of the AL formation and both the positive excursions of the carbon isotopes curve and the global changes in oceanic phosphorous burial rates (see Föllmi 1995; Zachos et al. 2001). This suggests a possible local control, over the global trends, on the intensity and direction of the upwelling currents, possibly exerted by the Miocene tectonic evolution of the Salento area (Föllmi et al. 2015).

Conclusions

The extensive deposition of phosphate-rich sediments that characterize the central Mediterranean area, from the Late Oligocene to the Late Miocene, is well represented in the Salento Peninsula by the “*Aturia level*” (AL). In this paper, for the first time, the paleontological content of phosphatic hardgrounds is analyzed in detail, in order to provide additional information for a more robust paleoenvironmental reconstruction.

We have shown that the AL consists of two main distinct facies, i.e., the coral rudstone and the detrital rudstone facies, separated by a phosphatic crust. The coral rudstone is dominated by a rich azooxanthellate coral-mollusc assemblage and its composition, compared with ecological requirements of present-day analog taxa, revealed aphotic deep-water coral habitats flourishing during the Serravallian/Tortonian at a few hundreds meters of depth along the margin of the Apulia Platform. Our data provide evidence that the seafloor was quite heterogeneous, presumably formed by hard substrates colonized mainly by dendrophylliid corals, associated with accumulations of soft sediments and swept by moderate to strong bottom currents, rich in nutrients and resuspended decayed organic matter.

Hydrodynamic variations through time did not allow the formation of long-lasting coral bioconstructions. Dendrophylliid corals were most probably present as fragile colonies

subject to breaking and local transport under very strong flow events. From this initial stage of coral growth, we reconstructed the principal steps of the depositional history of the AL, consisting in the formation of a phosphate crust under very strong hydrodynamic regime and subsequent alternating sediment starvation, deposition and erosion events.

Our paleoecological data confirm that a major driving factor for the formation of the AL was represented by the action of bottom currents. Variations in their hydrodynamic regime controlled both the develop of the biotic association and the subsequent sedimentary processes.

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