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QUATERNARY BUILD-UPS AND RHODALGAL CARBONATES ALONG THE ADRIATIC AND IONIAN COASTS OF THE ITALIAN PENINSULA: A REVIEW

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*Abstract***.** In the Mediterranean, build-ups (created by coralline algae, *Cladocora caespitosa*, deep-water corals, vermetids, polychaetes and bacteria) and rhodolith beds are important hot-spots of biodiversity. Being severely threatened by anthropogenic impact and climate change, they have been included in international directives on environmental protection. This work wants to support the ongoing research on modern bioconstructions by providing further data on the long-term effects of environmental factors on these habitats. Our results are based on the analysis of the existing literature on the outcropping Quaternary successions of the Adriatic and Ionian coasts of peninsular Italy. The existing reports of build-ups and rhodalgal carbonates have been summarized in an homogeneous data-set and then studied to highlight distribution patterns in space and time. The analyses consistently outlined the importance of sedimentation rate in controlling the general distribution of build-ups and rhodalgal carbonates. The majority of the reports is concentrated south of the Gargano, where the sediment-load of the rivers is small. The majority of the reports is related to coralline algae, suggesting that they were the main carbonate producers during the period. *C. caespitosa* general distribution is mainly controlled by temperature, with most of the occurrences dating back to the warm periods of the late Ionian and of the Tarantian. Large build-ups of *Cladocora* are restricted to embayments and gulfs well-protected against storm waves. The distribution of the outcrops of deep-water corals is biased by the geological setting. A remarkable uplift is necessary to bring these corals from their original deep-water setting to elevated areas onshore. Consequently, most of the outcrops are in Southern Calabria which is characterized by a strong Quaternary uplift. Chemosynthetic build-ups, intertidal bioconstructions (made by vermetids, polychaetes or coralline algae), as well as stromatolites, are rare in the study area.

Introduction

Carbonate build-ups are limestone bodies, which had original topographic relief, produced through the direct control or the mediation of organisms (Tucker 1981). These structures offer shelter to a large number of marine species, forming local hot-spots of biodiversity (Bressan et al. 2001; Bianchi 2001; Ayata et al. 2009; Lo Iacono et al. 2017). Their preservation is a major challenge for environmental protection as these habitats are increasingly threatened by anthropogenic disturbances and climate change. This issue is particularly critical in the Mediterranean Sea, which is surrounded by heavily populated and industrialized countries. The most common Mediterranean build-ups are presently protected by European Union directives and international programs (European Habitats Directive, European Community 1992; United Nations Programme - Mediterranean Action Plan, UNEP-MAP-RAC/SPA 2008). Coralligenous build-ups, *Cladocora caespitosa* banks, deep-water coral bioconstructions, intertidal reefs created by polychaetes, vermetids or coralline algae, and bacteria-related bioconstructions, fall under these directives. Rhodolith beds are also included, since as much as carbonate build-ups, they are biodiversity hot-spots threatened by human

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activities (Bosence 1979; Steller et al. 2003; Hall-Spencer et al. 2006; Basso et al. 2017; Riosmena-Rodríguez 2017). Rhodolith beds are actually damaged by commercial fishing and exploited for the extraction of raw materials (mainly for the production of soil conditioners, but also for other applications like the production of filters; Blunden et al. 1975; Hall-Spencer et al. 2006; Coletti et al. 2017).

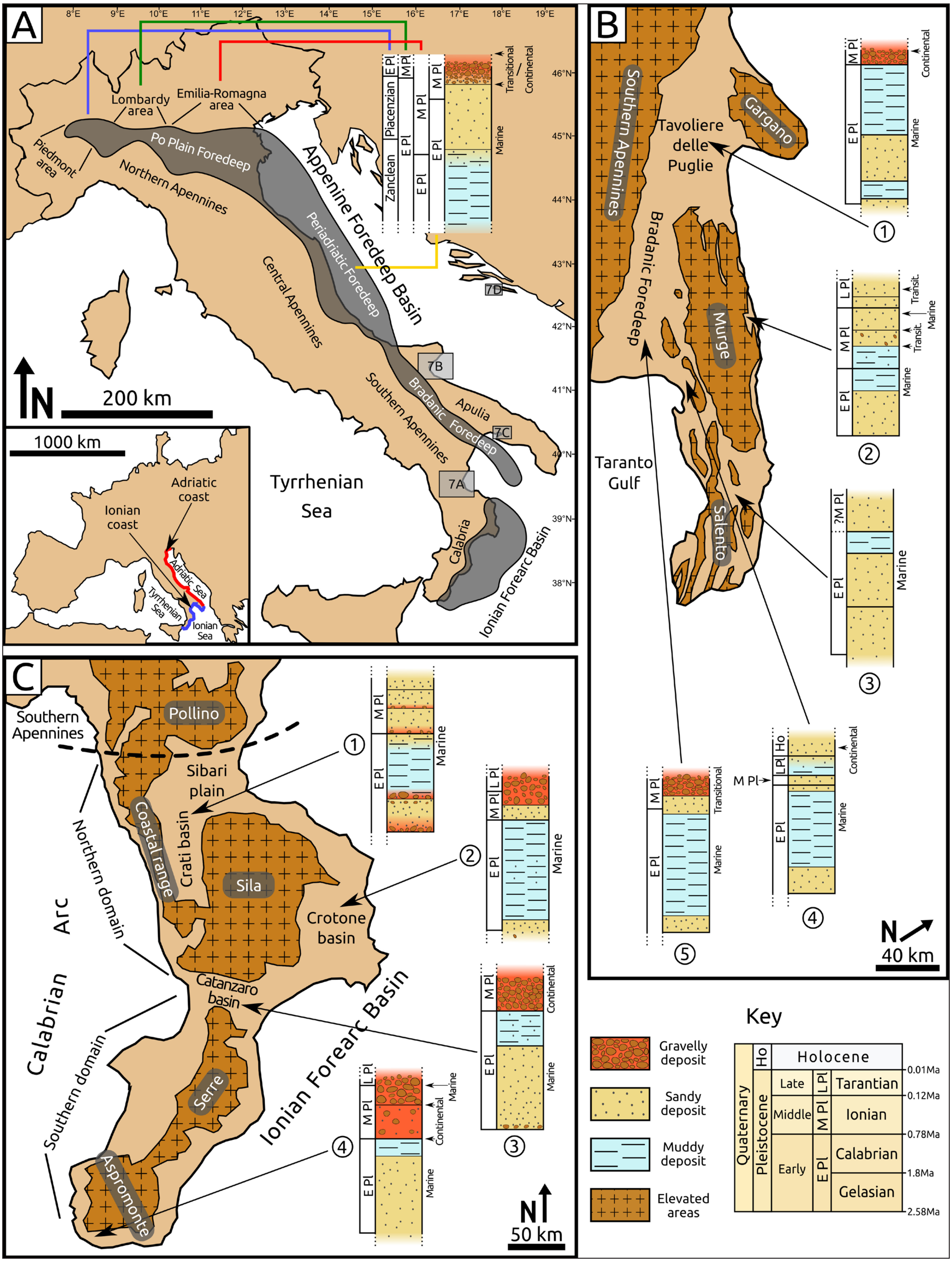
In the last decades, a remarkable effort in monitoring and mapping has significantly improved the knowledge on build-ups and rhodolith beds in the Mediterranean. This is especially true for the Adriatic and Ionian seas, which were recently investigated within RITMARE and BIOMAP projects. However, the knowledge of their response to environmental factors over the long time-scale, is still incomplete. The data extracted from the geological record can be used to assess the influence of environmental factors over a time scale longer than the one affordable from short-term monitoring alone (Wilson & Lokier 2002). This paper analyzes the geological literature on marine Quaternary successions of the Adriatic and Ionian coasts of the Italian Peninsula, investigating the distribution of carbonate build-ups and rhodolith beds. These outcrops recorded the last millions of years of glacial-interglacial cycles and thus are the ideal archive to investigate the impact of environmental factors on benthic habitats over the long time-scale.

Geological setting

The continuous northward movement of the African Plate toward the European Plate is the main driving force of the tectonic activity along the Italian Peninsula. Due to the complex nature of the boundary between the two plates, the convergence caused a variety of tectonic processes: the Apennine orogeny, the subduction of the Ionian Plate, the opening of the Tyrrhenian Sea, the formation of the Calabrian Arc and the deformation of the Apulian Swell (i.e. a ridge of continental crust connected to the African Plate, whose emerging portion constitute the Apulia; Figs 1, 2). The interplay between these processes exerted a major control over the main Quaternary basins of the study area: the Apennine Foredeep Basin and the Ionian Forearc Basin (Fig. 1).

Along the northern margin of the Northern Apennines, Quaternary sedimentation shows a general regressive trend related to the filling of the Po Plain Foredeep, caused by the onset of alpine glaciations, outpacing Apennine-related subsidence (Fig. 1A; Ricci Lucchi et al. 1982; Amorosi et al. 1998a; Muttoni et al. 2003; Garzanti et al. 2011). The succession can be subdivided into a lower part, characterized by marine sedimentation (Quaternary marine cycle, Qm, *sensu* Ricci Lucchi et al. 1982) and an upper part characterized by continental sedimentation (Quaternary continental cycle, Qc, *sensu* Ricci Lucchi et al. 1982). In the westernmost part of the basin (Fig. 1A; Piedmont area), the transition between marine and continental sedimentation occurred during the latest Pliocene (Violanti & Sassone 2008; Violanti et al. 2011; Irace et al. 2015). Eastward (Fig. 1A; Lombardy area) the shift occurred during the late Calabrian and the extent of Pleistocene marine sediments is limited (Fig. 1A; Gianolla et al. 2010). In the southeastern part of the basin (Fig. 1A; Emilia-Romagna area), the transition occurred even later (Fig. 1A; Ricci Lucchi et al. 1982).

Fig. 1 - Geological setting. A) Map of the Italian peninsula with highlighted the main geological domains and the most important quaternary basins; the simplified stratigraphic log details the characteristics of the Quaternary successions of the Eastern Po Plain Foredeep and of the Periadriatic Foredeep (the log is not to scale); information from Ricci Lucchi et al. (1982), Amorosi et al. (1998b), Gianolla et al. (2010), Irace et al. (2015), Di Celma et al. (2016); the small panels represents the panels of Fig. 7; the position of the Italian Peninsula in Europe and the Adriatic and Ionian coasts are indicated in the panel in the lower left corner. B) Representation of Apulia including Quaternary basins, elevated areas and simplified stratigraphic logs of the their successions (the logs are not to scale; general map modified from Moretti et al., 2010); 1 Tavoliere delle Puglie, information from Ispra maps and Balduzzi et al. (1982); 2 Bari area, information from Ispra maps and Spalluto et al. (2010), Transit. = transitional; 3 Salento area, information from Ispra maps and Bossio et al. (2005), ?M Pl indicates an uncertainty on the age of the upper sand-sized deposit; 4 Taranto Gulf area, information from Ispra maps, Hearty & Dai Pra (1992), Richetti (1970); 5 Bradanic Foredeep, information from Ispra maps, Pieri et al. (1996), Sabato (1996). C) Representation of Calabria, including principal tectonic domains, elevated areas, Quaternary basins and simplified stratigraphic log of the their successions (the logs are not to scale; general map modified from Milia and Torrente 2014; 1 Crati Basin, information from Bernasconi et al. (1997), Carobene et al. (1997); 2 Crotone Basin, information from Roda (1964), Massari et al. (2002); 3 Catanzaro Basin, information from Longhitano et al. (2014); 4 Aspromonte area, information from Ispra maps.


A
Lombardy area
Emilia-Romagna area
Piedmont area
Po Plain Foredeep
Northern Apennines
Appenine Foredeep Basin
Periadriatic Foredeep
Central Apennines
Southern Apennines
Bradanic Foredeep
Apulia
Calabria
Ionian Forearc Basin
Tyrrhenian Sea
200 km
1000 km
Adriatic coast
Ionian coast
Adriatic Sea
Tyrrhenian Sea
Ionian Sea
7A
7B
7C
7D
Zanclean
Piacenzian
E Pl
M Pl
Transitional
Continental
Marine
B
Southern Apennines
Tavoliere delle Puglie
Gargano
Bradanic Foredeep
Murge
Salento
Taranto Gulf
40 km
C
Southern Apennines
Pollino
Sibari plain
Coastal range
Crati basin
Sila
Crotone basin
Catanzaro basin
Northern domain
Southern domain
Calabrian Arc
Serre
Aspromonte
Ionian Forearc Basin
50 km
Key
Gravelly deposit
Sandy deposit
Muddy deposit
Elevated areas
Quaternary
Pleistocene
Holocene
Late
Middle
Early
Tarantian
Ionian
Calabrian
Gelasian
0.01Ma
0.12Ma
0.78Ma
1.8Ma
2.58Ma

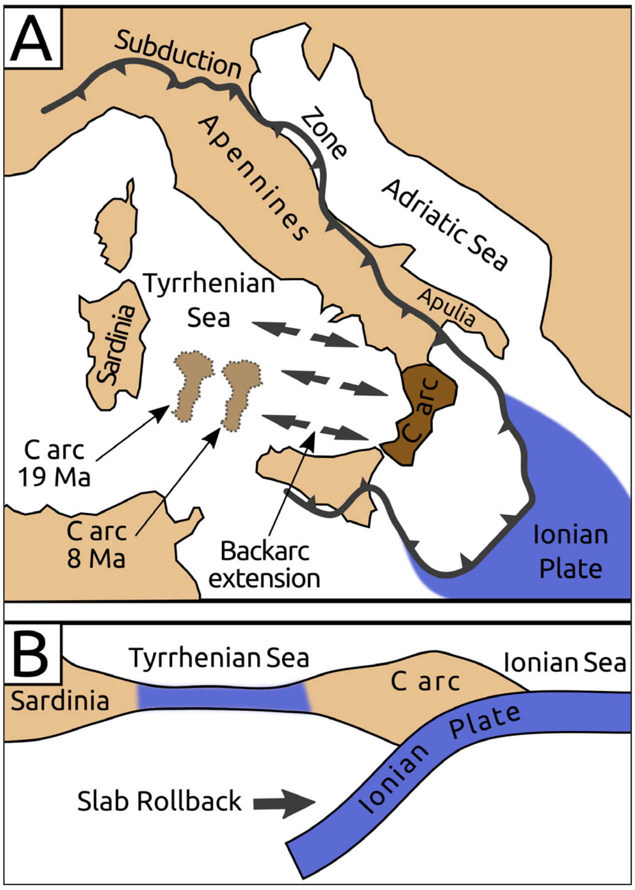


Fig. 2 - Formation of the Calabrian Arc. A) Geodynamic setting of Italy including the major tectonic process and the migration path of the Calabrian Arc, modified from Milia & Torrente (2014). B) Simplified cross section showing the lithospheric framework of the subdction, modified from Milia & Torrente (2014) and Malinverno & Ryan (1986).

In this area, the Argille Azzurre Formation (Pliocene to early middle-Pleistocene) represents the base of the Qm. The lower part of the formation is characterized by clays, but in the upper part there is an increase in grain-size with the occurrence of sands and bioclastic layers (Fig. 1A; Amorosi et al. 1998a, 1998b). The frequency and the thickness of these intercalations increase upward (Amorosi et al. 1998a). The middle-Pleistocene shallow-water sands of the Sabbie di Imola Formation, occurring at the top of the Qm cycle, represent the last episode of marine sedimentation in the area (Fig. 1A; Dondi et al. 1982; Ricci Lucchi et al. 1982; Amorosi et al. 1998b).

The Periadriatic Foredeep (Fig. 1A) is characterized by a uniform sedimentation pattern presenting the same regressive trend observed in the Po Plain Foredeep, with a Qm and a Qc cycle. The base of the Qm consists of early Pleistocene marine clays, while the upper part of the succession is characterized by shallow-water sands (Fig. 1A; Lanzafame & Tortorici 1976; Bigi et al. 1997; Coli et al. 2000; Cantalamessa & Di Celma 2004; Ragaini et al. 2006; Bracone et al. 2012; Di Celma et al. 2016). Minor and local variations to this pattern are caused by differences in subsidence rate and by the local presence of tectonic ridges created by the external thrusts of the Apennines (Bigi et al. 1997; Doglioni et al. 1994; Cantalamessa & Di Celma 2004).

Apulia structural signature differs from those of the Po Plain Foredeep and the Periadriatic Foredeep (Doglioni et al. 1994). While the latter are characterized by subsidence during the whole Pliocene-Pleistocene interval, the former is marked by a middle-Pleistocene uplift (Doglioni et al. 1994). This difference is related to subduction dynamics of the Apulian Swell. During the middle Pliocene - early Pleistocene interval, this crustal block was characterized by extensional tectonics and subsidence (Doglioni et al. 1994). At the beginning of the middle-Pleistocene, the thick continental lithosphere of the swell reached the subduction zone located under the Apennines (Fig. 2; Doglioni et al. 1994). This slowed the subduction processes, causing a new phase of extensional-tectonic, this time coupled with the uplift of the main blocks of the region: Gargano, Murge and Salento (Fig. 1B; Doglioni et al. 1994; Tropeano et al. 1994; Pieri et al. 1996; Spalluto & Moretti 2006). Quaternary sedimentation mainly occurred in the Bradanic Foredeep, the southern continuation of the Apennine Foredeep, and in the basins created during the two phases of extensional-tectonic (Fig. 1B; Doglioni et al. 1994; Tropeano et al. 1994; Pieri et al. 1996; Spalluto & Moretti 2006). The base of the Quaternary successions is represented by the Calcarenite di Gravina Formation (late Pliocene - early Pleistocene). For the purpose of this work this formation is deemed comprehensive of all the early Pleistocene calcarenites that testify the marine transgression over the Gargano, Murge and Salento highlands (Fig. 1B; Perella 1964; Pomar & Tropeano 2001; Tropeano et al. 2004; Bossio et al. 2005; Spalluto & Moretti 2006; Moretti et al. 2010). The peak of subsidence in Apulia is marked by the deposition of the early Pleistocene Argille Subappennine Formation, which overlies the Calcarenite di Gravina Formation (Fig. 1B). Middle and late Pleistocene deposits, overlying the

Argille Subappenine Formation, are influenced by the uplift of the region (Fig. 1B; Amato et al. 1997; Bordoni & Valenise 1998; Caputo et al. 2010). Along the western margin of the Bradanic Foredeep, they are mostly represented by siliciclastic regressive deposits (Pieri et al. 1996; Sabato 1996). In the rest of Apulia middle and late Pleistocene deposits are mainly composed of bioclastic material (Richetti 1970; Hearty & Dai Pra 1992; Coppa et al. 2001; Belluomini et al. 2002; Mastronuzzi et al. 2007; Moretti et al. 2010; Spalluto et al. 2010; De Santis et al. 2014).

The geological setting of Calabria is remarkably complex. In the northernmost part of the area lies the boundary between the tip of the Southern Apennines and the Calabrian Arc (Fig. 1C; Cucci & Cinti 1998). The Calabrian Arc itself is a small orogen of exotic terranes, migrated toward SE due to the roll-back of the subducting Ionian plate and emplaced upon Mesozoic carbonate units (Fig. 2; Milia & Torrente 2014). The arc can be further divided into a northern domain with the Sila Massif and a southern domain which includes Serre and Aspromonte massifs (Fig. 1C; Bonardi et al. 2001). Extensional basins (e.g. Crati Basin and Catanzaro Basin) separate these reliefs (Fig. 1C). Two major tectonic phases dominate the Quaternary. During the Pliocene - early Pleistocene the arc was dominated by extensional tectonic resulting from the underplating of the Ionian crust under the Calabrian Arc (Colella et al. 1987; Monaco et al. 1996). Since the middle Pleistocene extensional tectonic was accompanied by a strong uplift, the intensity of which decreased toward the North (Dumas & Raffy 1996; Cucci 2004; Antonioli et al. 2006). This process is thought to be related to the detachment of a subducted slab of Ionian lithosphere (Monaco et al. 1996), but is controversial (Garzanti et al. 2018). Within this setting, Quaternary sedimentation mainly occurred in the extensional basins that separated the reliefs, and in the Ionian Fore-Arc Basin. The different behavior of the various domains and blocks resulted in remarkably different sedimentary successions in the different basins, even among closely spaced areas (Fig. 1C; Barrier et al. 1996; Carobene et al. 1997; Cavazza et al. 1997). The base of the Quaternary succession is generally composed of transgressive, coarse-grained, formations of late Pliocene to early-Pleistocene age (Fig. 1C; Roda 1964; Barrier et al. 1986, 1996; Colella et al. 1987; Carobene et al. 1997; Cavazza et al. 1997; Longhitano et al. 2014). During the Calabrian, the transgression reached its peak, which is generally testified by fine-grained deposition (Fig. 1C; Roda 1964; Barrier et al. 1986, 1996; Colella et al. 1987; Carobene et al. 1997; Cavazza et al. 1997; Longhitano et al. 2014). Due to the uplift of the arc, these fine-grained sediments were overlain by regressive coarse-grained deposits and by marine and continental terraces, of middle to late-Pleistocene age (Fig. 1C; Roda 1964; Barrier et al. 1986, 1996; Colella et al. 1987; Carobene et al. 1997; Cavazza et al. 1997; Longhitano et al. 2014).

Material and methods

This review is based on the critical analysis of publications on Quaternary outcrops occurring along the Adriatic and Ionian coasts of the Italian Peninsula. We considered, as research targets, all the different kinds of build-ups that are presently common in the Mediterranean Sea. We also included rhodolith beds since they also are formed by a bioconstruction process and greatly increase the local complexity of the seafloor, fostering a high-level of biodiversity.

Unfortunately, most of the analyzed papers are not aimed at the study of fossil assemblages and the subject is often treated marginally. This makes it difficult to tell apart deposits containing only fragments of benthic builders from deposits in which an extensive biogenic structure is present. For the same reason it is also difficult to separate rhodoliths from coralline-algal fragments produced by the erosion of coralligenous build-ups. To address these problems we recognized in situ benthic builders preserved in life position, regardless of their size or abundance, as build-up, while we considered the presence of loose coralline algae as rhodalgal carbonates (i.e. a carbonate assemblage characterized by abundant coralline algae, Carannante et al. 1988). The reports are then divided into nine categories, including eight types of build-ups: rhodalgal carbonates, coralligenous build-ups, intertidal coralline-algal bioconstructions, *Cladocora caespitosa* colonies, deep-water coral colonies, chemosynthetic build-ups, stromatolites, vermetid clusters and polychaete clusters.

The subdivisions of the Quaternary period significantly changed during the last decades (Gibbard et al. 2010), and most of the reports do not present sufficient information to allow a straightforward conversion of the stratigraphy. Therefore, in order to have a homogeneous time-frame, the reports were divided into four intervals, following Gibbard et al. (2010): early Pleistocene (Gelasian and Calabrian stages; 2.58-0.78 Ma), middle Pleistocene (Ionian stage; 0.78-0.126 Ma), late Pleistocene (Tarantian stage; 0.126-0.0117 Ma) and Holocene.

All reports are provided with geographic coordinates (WGS 1984, EPSG 4326). Whenever the coordinates were not included in the original paper, an approximated position has been provided on the basis of the existing data. Large outcrops, whose extension could not be approximated by a point on the map, have been represented as areas. The extension of these areas is based on the available cartographic information provided by the analyzed papers and by the geological maps of ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale). A detailed, georeferenced, map of all the reports is also provided (Fig. S1 in Appendix 1).

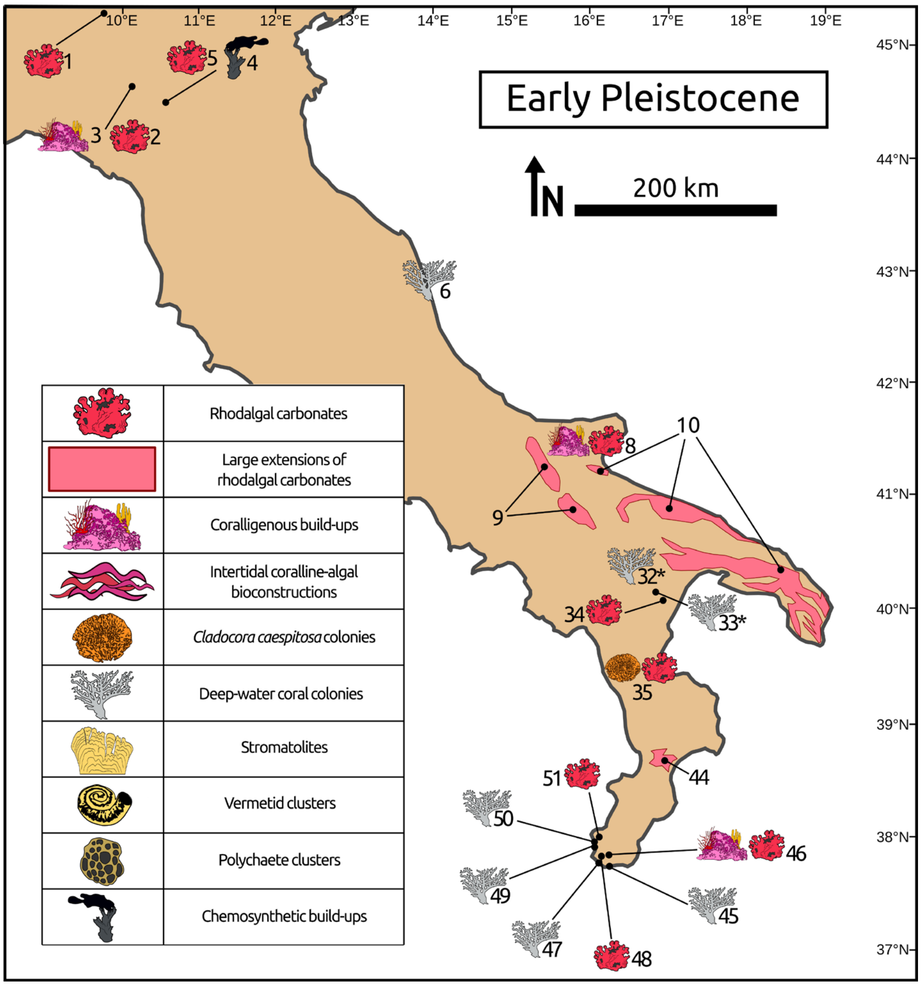


Fig. 3 - Early Pleistocene outcrops of build-ups and rhodalgal carbonates along the Adriatic and Ionian coasts of the Italian Peninsula; the numbers represents the identifiers of the reports, the same numbering is used in Tab. S1 and Fig. S1.

Results

The results of the analysis are divided into four sections, one for each interval. In each section the reports of the various categories of build-ups are presented. All the reports are summarized in Table S1 (Appendix 1) and included in the georeferenced map (Fig. S1 in Appendix 1).

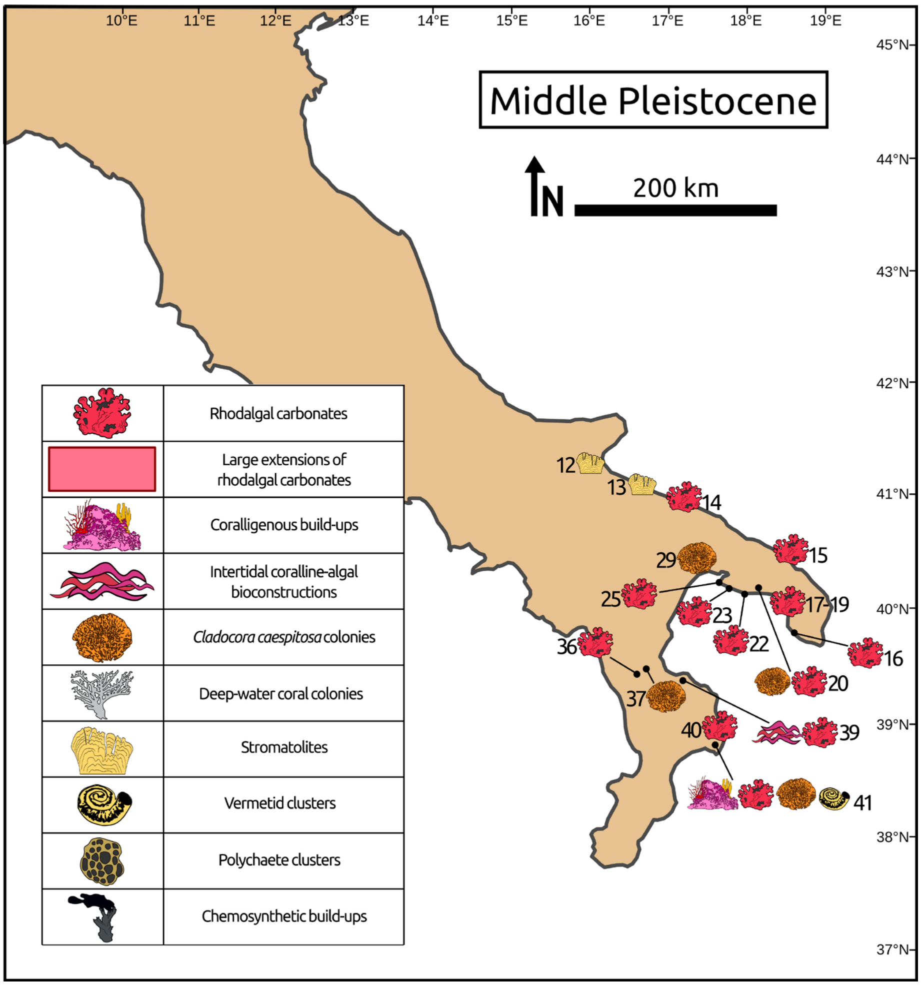
Early Pleistocene

The northernmost occurrence of rhodalgal sediments in the study area is located in Lombardy (Fig. 1A), where a borehole found a rhodolith-rich interval in the Gelasian layers of Qm (Tab. S1; Fig. 3 [1]; Gianolla et al. 2010). Along the northern margin of the Northern Apennines, in Emilia-Romagna (Fig. 1A) rhodolith-rich calcarenites occur in the late Gelasian - early Calabrian interval of the Torrente Stirone Synthem (Tab. S1; Fig. 3 [4]; Di Dio et al. 1997, 2005; Dominici 2001; Pervesler et al. 2011). Along the Stirone riverbanks a small coralligenous build-up of Calabrian age, growing over a layer of large *Arctica islandica* shells, is also reported (Tab. S1; Fig. 3 [3]). Further east, Calabrian-age methane-derived carbonates (both chimneys and crusts) occur in the upper portion of the Argille Azzurre Formation (Tab. S1; Fig 3 [4]; Gunderson et al. 2014; Oppo et al. 2015). These layers of chemosynthetic carbonates are overlain by coarse-grained, rhodolith-rich, skeletal carbonates (Tab. S1; Fig. 3 [5]; Gunderson et al. 2014; Oppo et al. 2015).

In the Calabrian part of the Qm succession of the Periadriatic Foredeep Basin (Fig. 1A), near the top of one of the trust-derived tectonic-ridges segmenting the basin, Cantalamessa et al. (1987; 1997) reported the presence of *Dendrophyllia* coral-colonies associated with a malacofauna with abundant *Lucina* (Tab. S1; Fig. 3 [6]).

Further south, the early-Pleistocene sedimentation of Apulia is dominated by the rhodalgal carbonates of the Calcarenite di Gravina Formation. (Tab. S1; Fig. 3 [10]; Pomar & Tropeano 2001; D'Alessandro et al. 2004; Tropeano et al. 2004; Spalluto & Moretti 2006; Spalluto et al. 2010). Borehole data also report

Fig. 4 - Middle Pleistocene outcrops of build-ups and rhodalgal carbonates along the Adriatic and Ionian coasts of the Italian Peninsula; the numbers represents the identifiers of the reports, the same numbering is used in Tab. S1 and Fig. S1.



the occurrence of an extensive, early Gelasian, layer of rhodalgal carbonates in the northern part of the region (Tab. S1; Fig. 3 [9]; Balduzzi et al. 1982). In the area of the Gargano (Fig. 1B), Pavia et al. (2010) reported the presence of a small, late Gelasian, coralligenous build-up developed over a rhodolith bed (Tab. S1; Fig. 3 [8]). In the area of the Bradanic Foredeep (Fig. 1B) it is noteworthy the presence of common fragments of colonies of the deep-sea frame-building species *Madrepora oculata* within clay-dominated deposits (Tab. S1; Fig. 3 [32] [33]; Placella 1980; Caldara et al. 1993). Albeit the presence of an *in situ* build-up is not clearly reported, the *Madrepora* coral-rubble may have originated from a nearby coeval bioconstruction.

In the northern part of the Calabrian Arc, in the Crati Basin (Fig. 1C), there are reports of very large *Cladocora caespitosa* build-ups, interbedded with silty sands and associated with coralline algae (Tab. S1; Fig. 3 [35]; Bernasconi et al. 1997; Carobene et al. 1997). Extensive outcrops of rhodalagal carbonates also occur in the infill of the Catanzaro Basin (Fig. 1C), which, during the early Pleistocene, was an active seaway connecting the Ionian and Tyrrhenian seas (Tab. S1; Fig. 3 [44]; Chiarella et al. 2012; Longhitano et al. 2014). Due to the remarkable uplift of the area, the southern tip of the Calabrian Arc (as well as the eastern margin of the Messina Strait) is characterized by bathyal sediments containing both soft and hard-bottom deep-water corals, including the frame-building species *Lophelia pertusa* and *Madrepora oculata* (Tab. S1; Fig. 3 [45] [47] [49] [50]; Placella 1978; Barrier et al. 1986, 1996; Taviani et al. 1990; Di Geronimo et al. 1995, 1997; Rosso & Di Geronimo 1998). These successions, firstly recognized as deep-sea sediment by the pioneering work of Giuseppe Seguenza, are dominated by clays and bioclastic sands, while *in situ* coral build-ups are a minor component (Seguenza 1875, 1880). Coral fragments are locally abundant and occur either scattered in the fine-grained embedding sediment or accumulated around boulders that represent the original substrate of the corals. *In situ*, deep-water coral colonies are rare and are mainly found on the surface of paleo-escarpments and on large boulders (Barrier 1987).

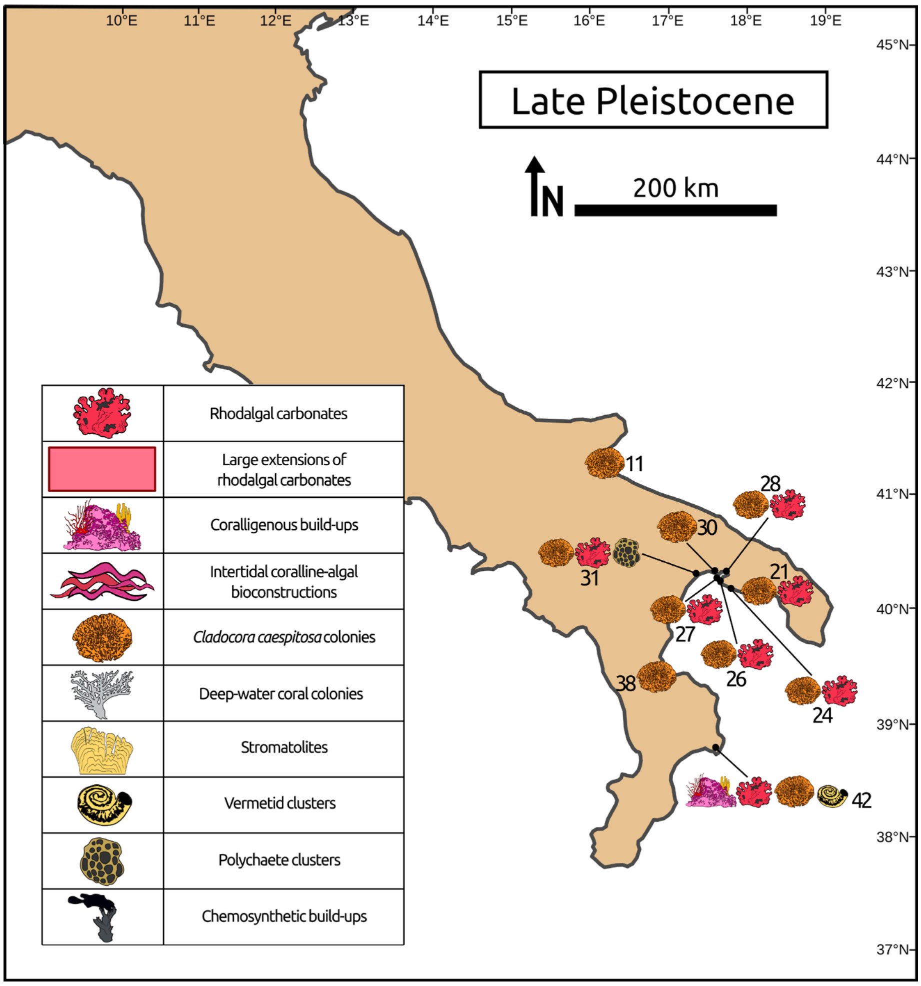


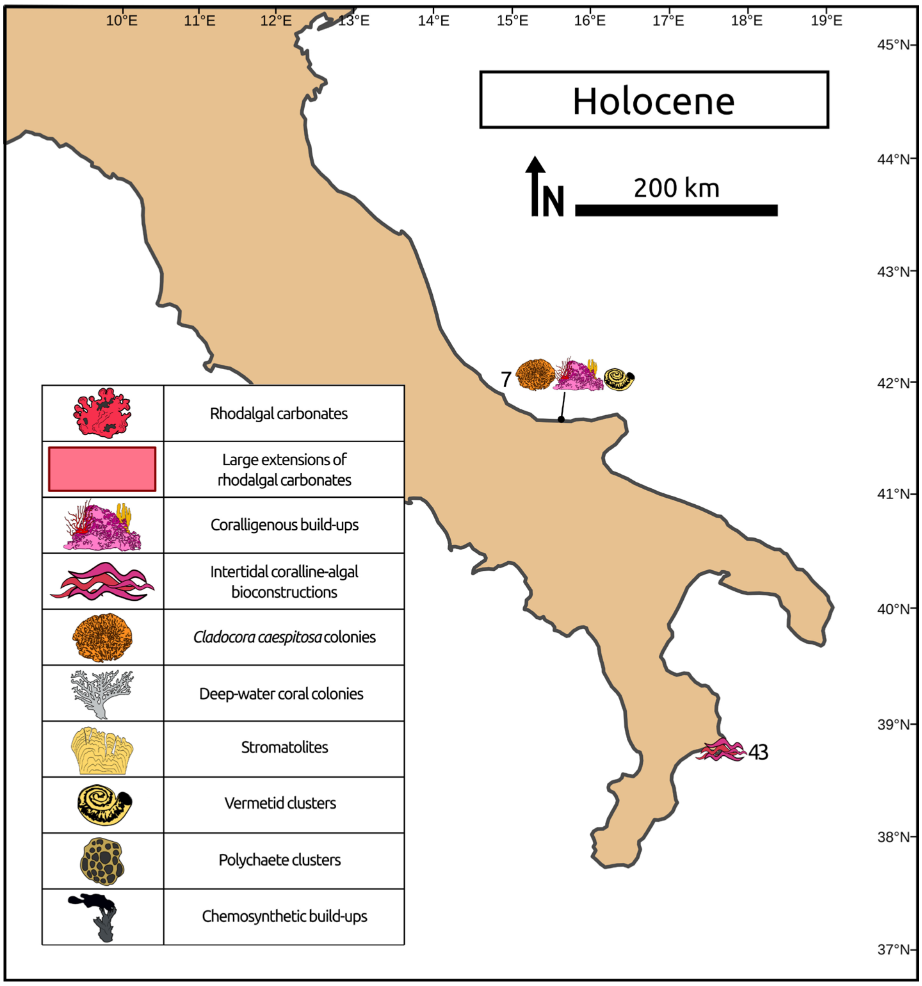
Fig. 5 - Late Pleistocene outcrops of build-ups and rhodalgal carbonates along the Adriatic and Ionian coasts of the Italian Peninsula; the numbers represents the identifiers of the reports, the same numbering is used in Tab. S1 and Fig. S1.

Middle Pleistocene

Although there are outcrops of middle-Pleistocene marine sediments all along the margins of the Apennine Foredeep Basin (Fig. 1), build-ups and rhodalgal carbonates are reported only in Southern Italy (Tab. S1; Fig. 4). Along the northern coast of Apulia there are two reports of stromatolites related to a lagoonal environment (Tab. S1; Fig. 4 [12] [13]; Caldara et al. 2013; De Santis et al. 2014). Rhodalgal carbonates are common in the region, especially along the eastern coast of the Taranto Gulf (Tab. S1; Fig. 1B; Fig. 4 [14] [15] [16] [17] [18] [19] [20] [22] [23] [25]; Dai Pra & Stearns 1977; Dai Pra & Hearty 1988; Hearty & Dai Pra 1992; Cita & Castradori 1995; Coppa et al. 2001; Belluomini et al. 2002; Mastronuzzi & Sansò 2002b; Spalluto et al. 2010). During the interglacial periods of the late Ionian, the sedimentation in this area was dominated by bioclastic production, with important contributions of coralline algae and *C. caespitosa* (Tab. S1; Fig. 4; Hearty & Dai Pra 1992; Cita & Castradori 1995; Belluomini et al. 2002).

Rhodalgal carbonates and *C. caespitosa* colonies also occur in the middle Pleistocene of the Calabrian Arc, within the Crati and Crotone basins (Tab. S1; Fig. 1C; Fig. 4 [36] [37] [40] [41]; Carobene et al. 1997; Zecchin et al. 2004; Santoro et al. 2009). The latter is an uplifted fragment of the Ionian Forearc Basin, whose middle and late-Pleistocene successions are composed of a flight of extensive marine terraces, correlated to interglacial marine transgressions (Roda 1964; Gliozzi 1987; Zecchin et al. 2004; Nalin et al. 2007; Nalin & Massari 2009; Bracchi et al. 2014, 2016). In this setting, a wide variety of middle-Pleistocene build-ups is preserved, including large coralligenous build-ups, small colonies of *C. caespitosa*, and vermetids clusters (Tab. S1; Fig. 4 [41]; Gliozzi 1987; Zecchin et al. 2004; Nalin et al. 2006; Basso et al. 2007; Bracchi et al. 2014). Intertidal coralline-algal bioconstructions occur in the marine terraces of the northern side of the Sila Massif (Tab. S1; Fig. 4 [39]; Carobene 2003). They are associated with the coarse-grained deposits (pebble to boulder

Fig. 6 - Holocene outcrops of build-ups and rhodalgal carbonates along the Adriatic and Ionian coasts of the Italian Peninsula; the numbers represents the identifiers of the reports, the same numbering is used in Tab. S1 and Fig. S1.



size) of the oldest terrace of the area, and consist of thin algal crusts, dominated by shallow-water genera *Titanoderma* and *Spongites*, with articulated coralline algae and small rhodoliths (Carobene 2003).

Late Pleistocene

Build-ups of Tarantian age are reported only in the southern part of the studied area (Tab. S1; Fig. 5). The only report along the Adriatic-coast of Apulia is of a buried, very large (> 10 km^2), *C. caespitosa* build-up, in the area of the Gulf of Manfredonia (Tab. S1; Fig. 5 [11]; De Santis et al. 2010). The build-up is composed of long-branched specimens and is associated with clayey sediments (De Santis et al. 2010). *C. caespitosa* is important also along the eastern coast of the Gulf of Taranto (Tab. S1; Fig. 1B; Fig. 5 [21] [24] [26] [27] [30] [31]; Dai Pra & Stearns 1977; Dai Pra & Hearty 1988; Hearty & Dai Pra 1992; Cita & Castradori 1995; Belluomini et al. 2002; Mastronuzzi & Sansò 2002b; Amorosi et al. 2014). In these late-Pleistocene deposits, common *Cladocora* colonies are associated with coralline algae (Tab. S1, Fig. 5 [21] [24] [26] [27] [31]; Hearty & Dai Pra 1992; Belluomini et al. 2002). In the area of the Mar Piccolo, a small and highly-restricted basin within the town of Taranto, fossil colonies of *C. caespitosa* are extremely abundant and they constitute a large bioconstruction (Fig. 5 [30]), associated with silty sands (the "Marne a *Cladocora*" of Gignoux 1913). This structure can be traced from one side to the other of the basin and is much larger than the other occurrences of *C. caespitosa* in the area of the Taranto Gulf (Dai Pra & Stearns 1977; Hearty & Dai Pra 1992; Belluomini et al. 2002).

In Calabria, small colonies of *C. caespitosa* are present in the Crati Basin, within the sandy deposits associated with MIS 5 (Tab. S1; Fig. 1C; Fig. 5 [38]; Santoro et al. 2009). In the marine terraces of the Crotone Basin related to the interglacial stages MIS 5 and MIS 3, there are complex bioconstructions composed of coralligenous build-ups, colonies of *C. caespitosa* and small vermetids clusters (Tab. S1; Fig. 5 [42]; Gliozzi 1987; Bracchi et al. 2014, 2016).

Holocene

In the study area, Holocene build-ups, outcropping above the sea-level, are rare (Tab. S1; Fig. 6). A small build-up, composed of platy encrustations of coralline algae, vermetid clusters and globular colonies of *C. caespitosa*, has been reported on the northwestern coast of Gargano Promontory (Tab. S1; Fig. 6 [7]; Mastronuzzi & Sansò 2002a; Gravina et al. 2005). This build-up was probably initiated by coralline algae and *Cladocora* about 6000-7000 yr BP, at the transition between the infralittoral and circalittoral zone (Mastronuzzi & Sansò 2002a; Gravina et al. 2005). Later, due to coseismic uplift, the build-up rose toward the surface and vermetids colonized it (Mastronuzzi & Sansò 2002a; Gravina et al. 2005). In the Crotone Basin, a beachrock with a thick crust of coralline algae was dated 3000 yr BP (Tab. S1; Fig. 6 [43]; Pirazzoli et al. 1997). The emergence of this element is probably related to the local uplift rather than to coseismic uplift (Pirazzoli et al. 1997).

Discussion

The general distribution of build-ups and rhodalgal carbonates follows a clear pattern: most of the reports are located south of the Gargano promontory (Figs 3 to 6). Sedimentation rates vary considerably between north and south of the promontory. Due to climatic, geographic and geological specificities, the sediment load of the rivers north of the Gargano is one order of magnitude higher than the one of the rivers south of the promontory (Cattaneo et al. 2003; Harris et al. 2008). This difference was probably present during the whole Quaternary. Variations in sedimentation rate definitively occurred between glacial and interglacial intervals (Garzanti et al. 2011), but the overall Pleistocene sedimentation rate was probably similar to the modern one (Bartolini et al. 1996). Siliciclastic input has a number of significant and often detrimental effects on carbonate producers (Wilson & Lokier 2002; Lokier et al. 2009). High sedimentation rate may result in death by burial, high amount of suspended matter reduces water transparency damaging autotrophs, siliciclastic particles may damage and choke the feeding apparatus of suspension feeders (Wilson & Lokier 2002; Lokier et al. 2009). Although major carbonate producers can tolerate near continuous siliciclastic input, they cannot survive sedimentation rates exceeding their growth rate (for sessile organisms) or their ability to escape burial (for mobile organisms; Wilson & Lokier 2002; Lokier et al. 2009). Coralline algae, which are the most commonly reported group of carbonate producers in the study area, according to our analysis (Tab. S1; Figs 3 to 6), generally have a slow growth rate, especially at temperate latitudes (Basso 2012). Therefore, it is likely that the sedimentation rates of the northern and central part of the Adriatic have been too high through the Quaternary to allow abundant carbonate bioconstruction. On the other hand, the low sedimentation rate of the coast of Apulia and Calabria was more favorable.

Coralline algae

Coralline algae are one of the most important carbonate-producers on a global basis; they are well adapted to a broad range of climatic conditions and can thrive even in dim light (Riosmena-Rodríguez 2017). They commonly occur in shallow-water carbonate successions since the Cretaceous and they are especially important during the Cenozoic (Braga et al. 2010).

Rhodalgal carbonates occur throughout the whole Quaternary and are particularly common in the early Pleistocene successions of Apulia and Calabria (Tab. S1; Figs 3 to 6). Only in the deposits of the Periadriatic Foredeep rhodalgal carbonates are absent (Tab. S1; Figs 3 to 6). Presently, most of the Mediterranean rhodolith beds are located around islands, capes, on the top of submarine plateaus, and in areas influenced by strong tidal currents (Basso et al. 2017). These environments, either due to the lack of clastic input or to currents clearing the sediment, are characterized by a low sedimentation rate (Basso et al. 2017). Coralline algae are restricted to areas where their growth-rate can keep-up with the sedimentation rate (Lokier et al. 2009). Therefore, during the Quaternary, much like today (Basso et al. 2017), the coast south of the Gargano was more favorable for their development than the one in the north.

Coralligenous build-ups follow the same pattern. Furthermore, the reported build-ups always develop from a hard or a very coarse-grained (pebble to cobble) substrate (Barriet et al. 1986; Nalin et al. 2006; Pavia et al. 2010; Bracchi et al. 2014, 2016). This confirms that, along with the sedimen-

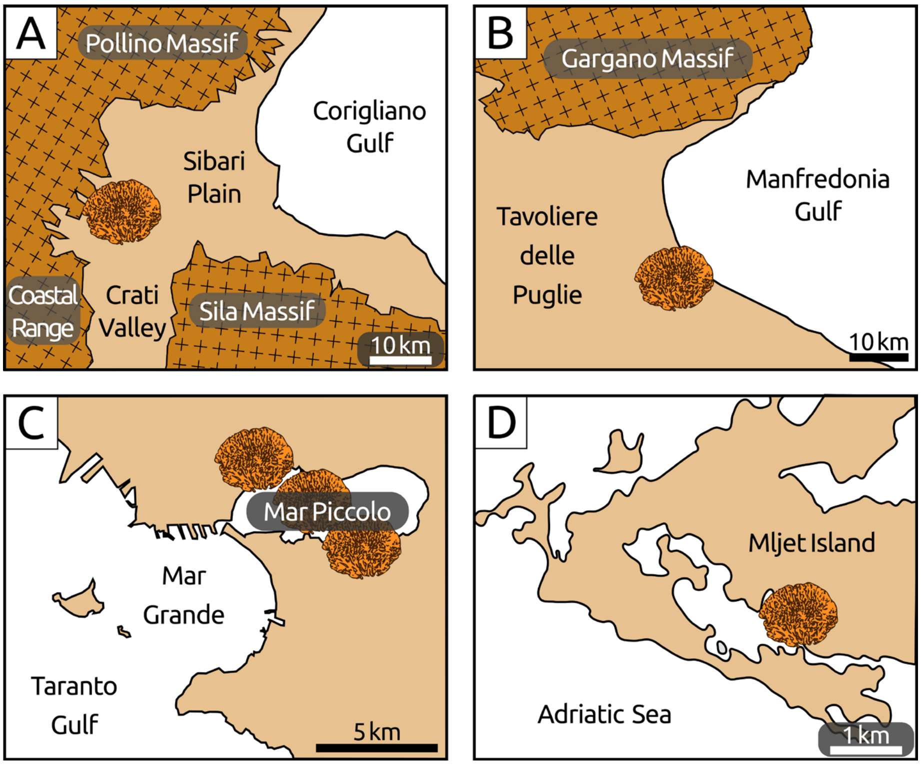


Fig. 7 - Location and general geological setting of the large build-ups of *Cladocora caespitosa*. A) Early Pleistocene, Crati Basin. B) Late Pleistocene, Manfredonia Plain. C) Late Pleistocene, Mar Piccolo. D) Present-day, Adriatic Sea.

tation rate, the occurrence of a suitable substrate is another key-factor influencing the development of these build-ups (as proposed by Bracchi et al. 2016; 2017).

Intertidal coralline-algal bioconstructions are very rare in the Quaternary succession of the study area (Tab. S1; Fig. 4 [39]; Fig. 6 [43]). However, nowadays these build-ups occur along long stretches of the southern tip of Apulia (CoNISMa 2014). Since they develop in a shallow setting, where destructive processes prevail (Doyle et al. 1997), they probably have a low preservation potential. This may be the cause of the scarcity of reports.

Cladocora caespitosa

C. caespitosa is a common Mediterranean zooxanthellate coral able to form large-sized build-ups comparable to those of tropical reefs (Zibrowius 1980; Aguirre & Jimènez 1998; Peirano et al. 1998). In the study area, fossil *Cladocora* colonies have a distinctive distribution. All the reports, except two, are related to the middle and late Pleistocene interglacial stages (Tab. S1; Figs 3 to 6), suggesting that warm temperatures are favorable to *C. caespitosa*. A second trend may be observed. While scattered colonies occur in a wide variety of situations, large build-ups (where *C. caespitosa* is basically the only organism involved in the construction) always occur in restricted basins protected from the impact of storm-waves and characterized by fine-grained sedimentation (Tab. S1; Figs 3 to 7). Therefore, while temperature seems to have a strong control on the overall geographic distribution of *C. caespitosa*, the development of large build-ups seems to be mainly controlled by the hydrodynamic setting. These hypotheses are consistent with the existing information on modern *C. caespitosa*. The growth rate of *C. caespitosa* shows a positive correlation with temperature, although high temperatures (like those of recent Mediterranean summer heat-waves) are strongly detrimental and may kill the coral (Peirano & Kružić 2004; Rodolfo-Metalpa et al. 2006; Kružić & Benković 2008; Peirano et al. 2009; Kružić et al. 2012; El Kateb et al. 2016). *C. caespitosa* benefits from continuous water motion and can adapt to moderate hydrodynamic energy, but the direct impact of storm waves is detrimental and limits the development of large bioconstructions (Zibrowius 1980; Kružić & Benković 2008; Kersting & Linares 2012). Actually the largest, living, continuous bank is located inside an inlet of the Croatian coast (Fig. 7D; Kružić & Benković 2008; Kersting & Linares 2012). High sedimentation-rate is potentially detrimental for symbiont-bearing corals, because it can negatively affect photosynthetic production and the particles may either clog or bury the polyps (e.g. Kružić & Benković 2008; Lokier et al. 2009; Peirano et al. 2009). However, *C. caespitosa* is tolerant to high input of fines (which may be common in protected basins) since its polyps are proficient in removing small particles from their oral disk (Schiller, 1993; Bernasconi et al. 1997; Peirano et al. 2004; Kružić and Benković 2008). Contrary to many other symbiont-bearing corals, *C. caespitosa* is well adapted to take advantage of suspended organic matter and therefore can survive in non-oligotrophic conditions, which may be common in restricted coastal basins (Peirano et al. 2004; Kružić & Benković 2008; Rodolfo-Metalpa et al. 2008).

Frame-building deep-water corals

Modern azooxanthellate frame-building cold-water corals live at temperatures ranging between 4 and 15°C. Their largest bioconstructions occur within a temperature range of 4-8 °C and, with the exception of the relatively shallow reefs off Norway, they develop at depth exceeding 400 m (Corselli 2001; Freiwald et al. 2004; Taviani et al. 2005; Roberts et al. 2006; Roberts et al. 2009; Vertino et al. 2014; Lo Iacono et al. 2017). The species *Madrepora oculata* is relatively common in modern Mediterranean deep-sea water, at around 13-14 °C, and is often associated with *Lophelia pertusa* (Taviani et al. 2005; Freiwald et al. 2009; Vertino et al. 2014). In the study area, the Quaternary reports of *M. oculata* and *L. pertusa* build-ups are restricted to early Pleistocene deep-water deposits cropping out in Southern Italy (Tab. S1; Figs 3). They are especially common in Calabria along the Messina Strait margins (Tab. S1; Fig. 3 [45] [47] [49] [50]), where significant uplift caused the exposure of bathyal deposits (Barrier et al, 1986, 1989; Vertino 2004; Di Geronimo et al. 2005). The two things are related: a remarkable uplift is necessary to bring these corals, from their original deep-water setting, to elevated areas onshore. In the rest of the study area, due to the lack of strong uplift, outcrops of bathyal sediments of Quaternary age are too rare to draw any further conclusion on their distribution. Deep-water corals were probably widespread in the Mediterranean during the early Pleistocene and possibly more abundant and diverse than in modern times (Vertino et al. in press). This was probably related to the lower temperature of the deep sea and different oceanographic conditions that favored an increase in food supply to bathyal invertebrates (Corselli 2001; Taviani et al. 2005).

Among deep-water coral reports, the one from the area of Porto San Giorgio is distinctive (Tab. S1; Fig. 3 [6]). The described association includes the azooxhanthellate colonial coral *Dendrophyllia* and the mollusk *Lucina* (Cantalamessa et al. 1987, 1997). The fossil association and its taphonomic signature suggest a less deep setting than the other deep-water-coral reports (Cantalamessa et al. 1987, 1997), while the presence of *Lucina* may suggest the presence of a cold seep.

Chemosynthetic build-ups

The carbonate chimneys and crusts of the Enza River are the only reported build-up of chemosynthetic origin (Tab. S1; Fig. 3 [4]). These structures are rare in the geological record, but they are relatively common in the successions of the Po Foredeep Basin. These build-ups occurred from the Miocene onwards along the margins of the Northern Apennines (Taviani 1994; Monegatti et al. 2001; Taviani et al. 2011; Gordini et al. 2012; Oppo et al. 2015). The tectonic structures of the area actually facilitate fluid migration toward the surface. The emission of fluids at the seafloor fuels bacterial communities that foster the precipitation of authigenic crusts. The crusts are then colonized by a wide variety of carbonate producing organisms. Processes, similar to those that lead to the formation of the Enza River build-ups, are also active nowadays, in the nearby area of the Northern Adriatic Sea (Gordini et al. 2012).

Polychaetes, vermetids and stromatolites

In the studied area there are very few occurrences of polychaetes and vermetid clusters (Tab. S1; Figs 4 to 6), therefore it is difficult to generalize their distribution pattern. Similarly to intertidal coralline-algal bioconstructions, the lack of reports may be caused by a preservation bias. These build-ups generally develop in the shallow littoral zone (Multer & Milliman 1967; Naylor & Viles 2000; Del Bono et al. 2003; Ayata et al. 2009; Chemello 2009). In this setting destructive processes generally prevail, hindering the preservation.

Modern stromatolites are rare in the Mediterranean Sea. Therefore, the presence of only two reports of these microbialites is not surprising (Tab. S1; Fig. 4 [12] [13]). These structures are not built by a single taxa, but rather by a microbial community, therefore, generalization of their ecological preferences may be problematic (Golubic 1991). Those reported in the late Ionian of Apulia are thought to have formed in a warm and shallow lagoonal-setting (Caldara et al. 2013; De Santis et al. 2014).

Problems and limitations

The geological setting influences the availability of the outcrops. The existence of accessible outcrops in turn fosters geological researches. The combination of uplift and arid climate granted Apulia and Calabria a wealth of Pleistocene outcrops, inspiring a number of researches on the Quaternary (especially on the late Quaternary). Notwithstanding this, the general distribution of build-ups and rhodalgal carbonates is environmentally controlled. Although early Pleistocene outcrops are not as easily accessible in the Po Plain Foredeep and in of the Periadriatic Foredeep as they are in Apulia and Calabria, they are almost as common. For example, along the Northern Apennines, almost every river cuts through early Pleistocene deposits and almost every succession is studied (e.g., Marabini et al. 1995; Taviani et al. 1998), yet the reports of build-ups and rhodalgal carbonates are rare. In the area of the Periadriatic Foredeep there are abundant bore hole data and in none rhodalgal carbonates or build-ups are mentioned (Crescenti et al. 1980). The difference is even sharper for middle Pleistocene deposits. There are outcrops of middle Pleistocene shallow-water sands in both the Po Plain and in the Periadriatic Foredeep (e.g. Amorosi et al. 1998b; Di Celma et al. 2016), and none of them present build-ups or rhodalgal carbonates. Conversely, build-ups and rhodalgal carbonates are very common in the middle-Pleistocene outcrops of Apulia and Calabria (Tab. S1, Fig. 4).

The geological setting is definitively very important for the distribution of certain types of build-ups, namely deep-water corals and chemosynthetic build-ups. The former require a remarkable uplift to be exposed, while the genesis of the latter can be favored by the presence of active tectonic structures allowing fluid seepage (Taviani 1994). Nowadays, deep-water corals and chemosynthetic build-ups are less common then coralligenous build-ups, *Cladocora* build-ups and rhodalgal carbonates in the study area (e.g. CoNISMa 2014). There is no evidence of a completely different pattern in the study area during the Quaternary. Therefore, although the influence of the geological setting is significant, it does not obscure the importance of the environmental control on the general distribution.

A small number of reports may influence the confidence of the interpretation. Intertidal build-ups made by vermetids, polychaetes, coralline algae and bacteria are quite rare in the study area. This is probably related to the fact that they develop in a setting where preservation is difficult (Doyle et al. 1997), but further researches are necessary to formulate more accurate hypotheses. Chemosynthetic build-ups are also very rare. However, their connection with the seepage of hydrocarbons (and therefore with the geological setting, Taviani 1994) is well-established and the results of our analysis are in agreement with it.

The uneven nature of the database hinders more detailed analyses. The type and the quality of the information varies depending on the scientific scope and the scale of the original papers on which the database is based. This limitation is common to every study based on data compilation. However, the database-approach has indeed a great potential in unraveling environmental controls on the large-scale distribution of marine habitats (Kiessling et al. 1999; Kiessling et al. 2001).

The lack of detailed information on coralline algae contribution may have resulted in the underestimation of coralligenous build-ups. Coralligenous build-ups are presently quite common along the coast of Apulia (CoNISMa 2014), but they are almost unreported in the Quaternary successions of the area. The rigid and thick framework of these build-ups, produced by continuous overlapping of thin crusts of coralline algae together with other organisms (bryozoans, mollusks, sponges, corals) and the coeval trapping of sediments, clearly has a high preservation potential. This discrepancy suggests that further researches are indeed necessary on this subject.

Conclusions

Most of the reported Quaternary build-ups and rhodalgal carbonates are concentrated south of the Gargano. They are more rare north of the Gargano, where sediment load from rivers is much higher. This suggests that in the study area, over the long time scale, high sedimentation rates hindered the development of build-ups and rhodalgal carbonates. Albeit carbonate producers can tolerate prolonged and significant clastic input, they cannot survive sedimentation rate exceeding their own growth rate. In the study area this is likely to occur, since carbonate production is dominated by coralline algae (which grow slowly at temperate latitudes) and the sedimentation rate can be quite high.

Rhodalgal carbonates are common south of the Gargano. Coralligenous build-ups have a similar distribution, but they are less abundant; they always grow from a hard or a very coarse-grained substrate, suggesting that the occurrence of suitable substrate is another key-factor for their development. Intertidal coralline-algal bioconstructions are quite rare, probably because the high-energy setting in which they live limits their preservation potential.

All the reports of *Cladocora caespitosa,* with just two exception, are related to the middle and late Pleistocene interglacial stages, suggesting that warm temperatures favor this coral. Large build-ups of *Cladocora caespitosa* always occur in well-protected embayments, suggesting that the development of such large bioconstructions is mainly controlled by hydrodynamics.

The distribution of the reports of deep-water coral build-ups is biased by the geological setting, because a remarkable uplift is necessary to bring these corals from their original deep-water environment to elevated areas onshore. Therefore, most of the outcrops occur in the southern tip of Calabria, which is characterized by a strong Quaternary uplift. In the remaining of the study area the outcrops of Quaternary bathyal deposits are very rare.

The formation of chemosynthetic build-ups is generally related to the presence of active tectonic structures that allow fluid seepage toward the surface. Unsurprisingly, the only report of this type of bioconstruction comes from the eastern Po Plain Foredeep, where hydrocarbon seepage is still active today.

Shallow-water bioconstructions built by polychaetes and vermetids are quite rare, probably because they grow in a setting where destructive processes prevail, hindering their preservation. Stromatolites are also uncommon, but they are equally rare in present-day Mediterranean Sea.

The results of this review, although limited by the lack of paleontological details and by the uneven nature of the database, suggest that Quaternary successions hold precious data for the study of modern marine environments over the long time-scale. Further researches are indeed necessary, since this relatively recent past represents our best model to figure out our near future.

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