

CORAL ASSEMBLAGES AND BIOCONSTRUCTIONS ADAPTED TO THE DEPOSITIONAL DYNAMICS OF A MIXED CARBONATE-SILICICLASTIC SETTING: THE CASE STUDY OF THE BURDIGALIAN BONIFACIO BASIN (SOUTH CORSICA)

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Abstract. Coral bioconstructions associated with mixed carbonate-siliciclastic settings are known to be strongly controlled by coastal morphology and paleotopography. A striking example is represented by the different types of coral bioconstructions and coral-rich deposits of the Cala di Labra Formation deposited in the coastal environment of the Bonifacio Basin (Corsica, France) during the Early Miocene. Detailed mapping on photomosaics allowed accurate documentation of the internal organization of coral deposits as well as lateral and vertical facies relationships. Four types of coral bioconstructions (CB) and one reworked coral deposits (RCD) have been recognized. The CB are represented by sigmoidal cluster reefs, coral carpets and skeletal conglomerates rich in corals. The RCD occurs in lens-shaped bodies intercalated within clinofolds composed of bioclastic floatstones and coarse packstones. The investigated bioconstructions can be contextualised in a coastal environment. In the upper shoreface corals developed in association with the oyster *Hyothisa*, above bioclastic conglomerates sourced by ephemeral streams and erosion of the granitic coastline. In the lower shoreface corals formed sigmoidal bioconstructions interpreted as cluster reefs, whereas coral carpets developed during a relative sea-level rise related to the middle Burdigalian transgressive phase. The reworked coral deposits can be interpreted as lobe-shaped deposits of coarse-grained bioclastic submarine fans formed at the base of the depositional slope of an infralittoral prograding wedge system.

INTRODUCTION

In the Mediterranean region, during the Miocene time, a series of well-exposed carbonate platforms as well as shallow-water mixed carbonate-siliciclastic systems were commonly characterized by the occurrence of different types of coral bioconstructions, ranging from barrier reefs, fringing reefs, patch reefs and coral carpets (Santisteban & Taberner 1988; Braga et al. 1990; Pomar 1991; Esteban 1996; Pedley 1996; Bosellini 2006; Reuter et al. 2006; Brandano et al. 2010; Vigorito et al. 2010; Perrin & Bosellini 2012; Vescogni et al. 2014).

In particular, the development of coral bioconstructions in shallow water mixed carbonate-siliciclastic systems is no longer thought to be an exceptional phenomenon in the fossil record, and increasing attention to these alternative/marginal and turbid-water coral ecosystems in modern seas

makes their fossil analogs a challenging topic to explore. Studies on ancient coral communities living in marginal conditions including for example low light, high turbidity and high siliciclastic input, or high nutrients are important to understand the current structure of reefs and how they could potentially respond to global changes. Quite recently most studies investigated the response of coral assemblages to siliclastic inputs within the so-called turbid-water environments (Wilson & Lokier 2002; Sanders & Baron-Szabo 2005; Silvestri et al. 2011; Wilson 2012; Novak et al. 2013), while less common is research dedicated to understand the depositional processes, and influence of coarse terrigenous sediments and rocky substrate on the development of coral bioconstructions and biota thriving in these habitats (e.g Santisteban & Taberner 1988; Braga et al. 1990).

The Cala di Labra Fm., deposited in the small but articulated Bonifacio embayment during the Burdigalian, is characterized by a high variability

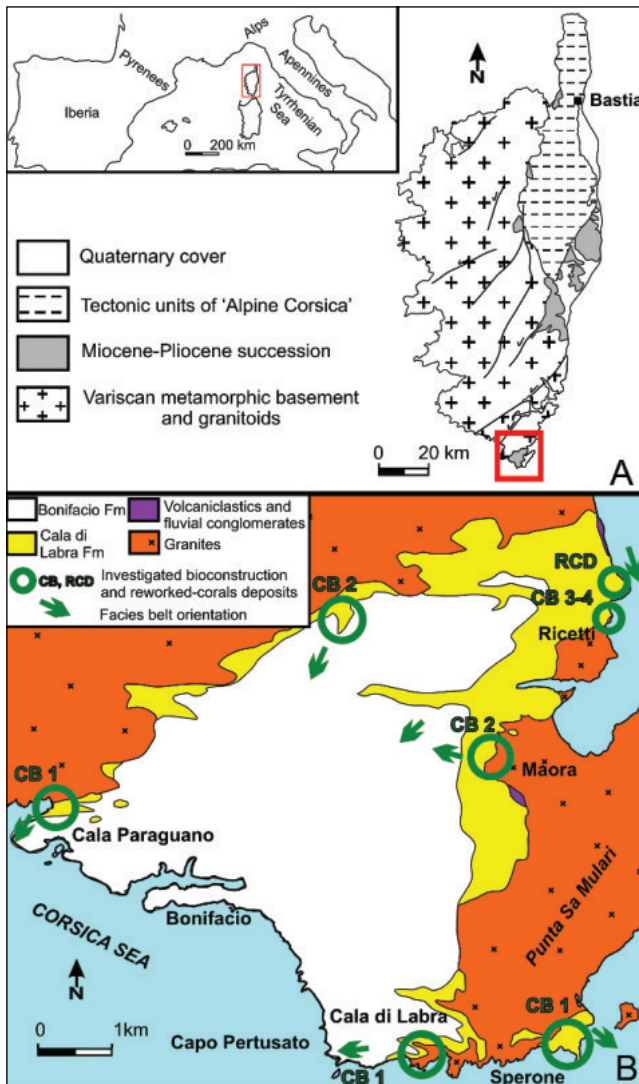


Fig. 1 - A) Schematic geological map of Corsica (Carmignani et al. 2004). B) Geological map of Bonifacio Basin and location of investigated outcrops and coral bioconstructions (modified from Reynaud et al. 2013).

of coral-rich deposits and bioconstructions. Excellent exposures provided the possibility to analyse their geometry, internal structure and facies associations in different depositional subenvironments (Reynaud et al. 2013; Tomassetti et al. 2013; Galloni et al. 2014).

In this study, we document the different types of coral bioconstructions and we aim to evaluate the control that factors such as coastal morphology, paleotopography and siliciclastic input exerted on their growth and depositional dynamics.

GEOLOGICAL SETTING

Corsica Island (France), located in the We-

Lithostratigraphy	Ferrandini et al. 2002, 2003	Brandano et al. 2009	Reynaud et al. 2013	Galloni et al. 2014
Bonifacio Formation	Early Langhian	Late Burdigalian	Serravallian to Tortonian Langhian	
Cala di Labra Formation	Late Burdigalian	Late/Middle Burdigalian	Burdigalian	R3 Late R2 Middle R1 Early
Balistra Formation	Aquitanian Oligocene		Aquitanian Oligocene	

Fig. 2 - Lithostratigraphic scheme of Oligocene-Miocene deposits of Bonifacio Basin.

stern Mediterranean, is divided in two different geological domains: “Hercynian Corsica” and “Alpine Corsica” (Fig. 1a). The “Hercynian Corsica” consists of Precambrian-middle Paleozoic metamorphic rocks and scattered Paleozoic sedimentary rocks cut by Carboniferous-Permian granitoid and volcanic rocks related to calc-alkaline and alkaline magmatism (Durand-Delga 1984; Ferré & Leake 2001). The “Alpine Corsica” consists of a complex tectonic stack including metamorphic oceanic- and continental-derived thrust sheets related to the Alpine orogeny (Durand-Delga 1984).

Up to the late Eocene, the Corsica and Sardinia micro-plate experienced a NE-SW oriented rifting followed by an Early Miocene continental drifting related to the opening of the Ligurian-Provençal Basin (Carminati & Doglioni 2005; Carminati et al. 2010). During the Aquitanian-Burdigalian, the Sardinia-Corsica block recorded the fastest counter-clockwise angular rotation and extensive pyroclastic deposits covered the central-northern part of the Sardinia Trough (Carminati et al. 2012 and reference therein). The Oligocene-Miocene sedimentary cover of Corsica consists of continental clastic deposits exposed near Ajaccio and marine mixed carbonate-siliciclastic successions cropping out in the southern (Bonifacio), eastern (Aleria) and in the northern sectors (Saint Florent, Francardo) (Ferrandini et al. 2003).

The sedimentary succession of the Bonifacio Basin is represented by three formations: the Balistra Fm., The Cala di Labra Fm. and the Bonifacio Fm. (Ferrandini et al. 2003) (Fig. 1b). The Balistra Formation (Oligocene-Aquitanian) consists of conglomerates and volcaniclastic deposits, whereas the overlying Cala di Labra Formation records the Miocene marine transgression. Based on biostra-

Tab 1 - Description of textural and compositional characteristics of the facies.

Facies	Texture, bedding and sedimentary structure	Composition
Conglomerate	Matrix-supported conglomerates.	Granitoids pebbles and cobbles.
Fine conglomerate to sandstone	Massive fine-conglomerates, crudely stratified and bioturbated (<i>Thalassinoides</i>) sandstone with skeletal elements.	Granitoids pebble, quartz and feldspars, bivalves, echinoids, gastropods, LBF, red algae and rare and reworked corals.
Hybrid sandstone	Nodular- to cross-stratified hybrid sandstones.	Quartz, feldspars, red algae and LBF (<i>Amphistegina</i>)
Skeletal conglomerate with corals	Massive to crudely stratified conglomerates.	Granitoids pebbles, isolated massive corals in growth position, oysters, gastropods, echinoids and red algae.
Coral domestone	Coral domestone with packstone to hybrid sandstone matrix.	Massive and subordinate platy corals (<i>Porites</i> , subordinate <i>Tarbellastrea</i> , rare <i>Montastrea</i> and <i>Thegioastrea</i>) in growth position. Matrix: red algae followed by LBF (<i>Miogypsina</i> and <i>Amphistegina</i>), bivalves, echinoids, small benthic foraminifera, gastropods and bryozoans.
Coral platestone	Coral platestone with hybrid sandstone matrix	Platy and subordinate massive corals (<i>Porites</i> and <i>Tarbellastrea</i>) in growth position. Matrix: predominant red algae debris and LBF (<i>Amphistegina</i> and <i>Miogypsina</i>).
Coral mixstone	Coral mixstone with packstone matrix	Massive, platy and encrusting corals (<i>Porites</i> and subordinate faviids) in growth position. Matrix: Red algae, bivalves, echinoids and benthic foraminifera.
Coral rudstone to floatstone	Coral rudstone to floatstone in a quartz-rich packstone matrix	Reworked coral colonies followed by oysters, gastropods and echinoids. Matrix: bivalve, red algae, benthic foraminifera (<i>Heterostegina</i> , cibicides and rare miliolids) and mineral grains (quartz and feldspars).
Red algae branches floatstone	Nodular-bedded and bioturbated floatstones	Red algae (free-living branches and small size rhodoliths) subordinate bryozoans, pectinids, LBF and echinoids.
Bioclastic floatstone to packstone	Poorly sorted floatstone to moderate sorted packstone with cross-bedding.	Red algae debris, small benthic and planktonic foraminifera, LBF (<i>Heterostegina</i> and <i>Operculina</i>), gastropods, bryozoans and coral fragments.

tigraphic data, Brandano et al. (2009) proposed a late-middle Burdigalian age for this formation (Fig. 2). The Bonifacio Formation (late Burdigalian-early Langhian) consists of sandstones, fine-conglomerates to cross-bedded coralline algae-rich calcarenites (Brandano et al. 2009), which are interpreted by Reynaud et al. (2013) as tidal deposits (Fig. 2).

The Cala di Labra Formation is 50 metres thick and consists, from bottom to top, of five superimposed lithofacies (Ferrandini et al. 2003; Brandano et al. 2009; Tomassetti & Brandano 2013; Galloni et al. 2014): a coral rich unit resting on boulders of a Variscan granite, a conglomeratic unit, a sandy to silty unit, and two bioclastic units showing prograding geometries. The siliciclastic facies represents deposition in the coastal environments from shoreface to upper offshore environment (Ferrandini et al. 2002; Reynaud et al. 2013; Tomassetti & Brandano 2013). Galloni et al. (2001, 2014) suggested that the coral-rich deposits actually represent three distinct superimposed, reef-building episodes: the first (R1) overlies the granitic palaeohighs; the second (R2) is coeval with the sandy deposits of shoreface environments; whereas the third (R3) episode is coeval with the prograding bioclastic unit (Fig. 2). In this work we investigate the coral-rich deposits corresponding to the R2 episode of Galloni et al. (2001, 2014), with the exception of the Rocchi Bianchi outcrop (the reworked coral deposits) that are referred to episode R3.

The limited thickness of coral bioconstructions of the Bonifacio embayment, and their relation and proximity with the granitic substrate, led Galloni et al. (2014) to interpret the coral deposits of Cala di Labra Fm. as fringing reefs and coral reefs.

MATERIAL AND METHODS

Bioconstructions and coral-rich deposits have been investigated along sea-cliffs and road cuts in six localities (Fig. 1b). Facies analysis has been carried out and four stratigraphic logs have been measured. Detailed mapping on photomosaics allowed documentation of the internal organization of coral deposits as well as lateral and vertical facies relationships. Detailed coral mapping allowed determination of coral cover (i.e. the total surface occupied by corals compared with the amount of sediment). Mapping was generally oriented with respect to the depositional dip as the paleogeography and physiography of the Bonifacio Basin has been recently reconstructed by Reynaud et al. (2013). These observations were complemented by examination of 120 thin sections.

Coral genera, growth forms and inter-coral associated fauna and sediment were characterized based on field observation and thin section analysis; coral growth fabric is defined following the nomenclature of Insalaco (1998).

RESULTS

Four types of coral bioconstructions, with associated sediments, and a reworked-coral deposit have been recognized (Tab. 1).

Coral bioconstruction 1. The first type of



Fig. 3 - Coral Bioconstruction 1: A) the coral domestone constitutes the bioconstruction core and grades landward to a platestone facies. B) Massive and subordinate platy colonies are essentially in place, close but rarely in contact.

coral bioconstruction (CB1) consists of a coral domestone, which is laterally associated with four other facies: coral platestone, hybrid sandstone, sandstone and a red algal floatstone.

The coral domestone is characterized by massive and subordinate platy colonies, which are basically in growth position, commonly close to each other but rarely in contact (Fig. 3a, b). Massive corals show domal and globular shape and generally range in size from 25 to 60 cm in diameter and from 15 to 50 cm in height. Occasionally they can show meter-size dimensions even reaching 3.5 m in length and 1 m in height. Platy corals usually range from 15 to 20 cm in diameter and 2 to 5 cm in height, although colonies up to 60 x 10 cm in size are also present. *Porites* is the dominant genus and exhibits both massive and platy growth forms (Fig. 4a). Colonies of *Tarbellastrea* (*T. chevaleri*, *T. reussiana*, *T. abditaxis*) (Fig. 4b, c, d), *Montastrea* (Fig. 4e, f), *Thegioastrea* (Fig. 4g, h) and rare *Favites* are subordinate but all characterized by a massive growth form. Bioerosion traces (*Gastrochaenolites*, *Caulostrepsis* and *Entobia*), can be common within coral colonies whereas encrustation is quite rare and represented by balanids and bryozoans.

The coral cover reaches values up to 66%, showing a moderate predominance of corals compared to the packstone matrix (Fig. 3b). Along the depositional dip more spaced colonies are separated by abundant matrix and some reworked corals occur. The matrix is a bioclastic packstone with a

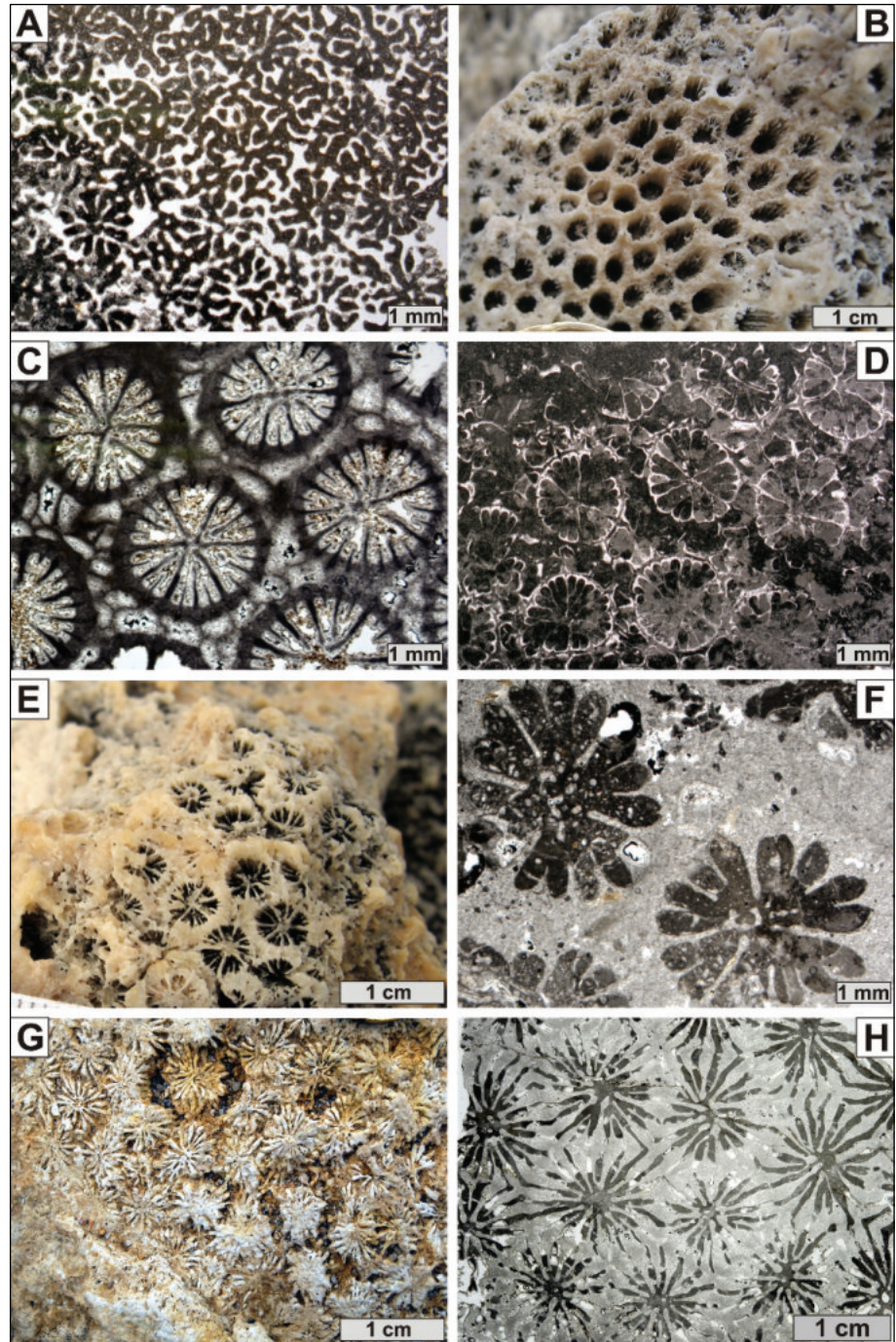
low siliciclastic fraction (Fig. 5a). Red algae are the dominant components and occur as branch fragments, small nodules and crusts together with large benthic foraminifera (LBF) such as *Miogyopsina* and *Amphistegina* (Fig. 5a). Bivalves, echinoids spines and plates, small benthic foraminifera (rotaliids, textulariids and rare cibicids), bryozoans and gastropods represent other biotic components. The downdip coral arrangement and variation of the coral/matrix ratio characterize the coral domestone beds with sigmoidal geometry up to 2-3 m thick and about 15-20 m in length. These bioconstructions extend over an area of 700 x 400 m and achieve about 12 m in thickness.

Lateral facies relationships are well exposed at the Sperone outcrop (Fig. 6). Landward, the coral domestone passes into a coral platestone, interfingering with hybrid sandstones that finally pass into sandstones.

The coral platestone is mainly composed of platy corals that occasionally constitute the substrate for the attachment of massive colonies.

Corals are in growth position, locally in contact to each other and embedded into a sandstone matrix with red algae debris and LBF (*Amphistegina* and *Miogyopsina*). The coral platestone interfingers with nodular to locally cross-bedded hybrid sandstones. Sub-rounded to sub-angular mineral grains (quartz and subordinate feldspars) represent the terrigenous fraction, whereas red algae debris, *Amphistegina*, bivalve and echinoid fragments constitu-

Fig. 4 - A) *Porites* in thin section. B) Outcrop view of massive *Tarbellastrea*. C) *Tarbellastrea chevalieri* in thin section. D) *Tarbellastrea reussiana* in thin section. E) Outcrop view of massive *Montastrea*. F) *Montastrea* in thin section. G) Outcrop view of massive *Thegioastrea*. H) *Thegioastrea* in thin section.



te the allochems (Fig. 5b). The hybrid sandstones grade into coarse- to fine-grained sandstones with skeletal elements (Fig. 5c, d). The sandstones occur as massive to crudely stratified deposits with diffuse to pervasive bioturbation (*Thalassinoides*). The poor biotic assemblage is mainly represented by fragmented bivalve shells, echinoid plates and LBF (*Amphistegina* and subordinate *Heterostegina*). Flat clypeasteroids, balanids and rare reworked coral colonies also occur.

At Cala Paraguanu, the more distal facies (red algal branches floatstones) crop out. Red algae

(*Spongites*, *Sporolithon* and melobesioids) dominate the biotic assemblage (Fig. 5e), and form free-living branches and small size rhodoliths frequently with boring traces (*Entobia*). Other constituents are bryozoans, pectinids, LBF and echinoids.

In the outcrop of Cala di Labra, Tomassetti et al. (2013) described a coral bioconstruction that colonized a granitic substrate characterized by an irregular and articulated surface. This coral buildup can be referred to the CB1. It appears as an organized lens-shaped structure, and its core consists of a relatively dense coral domestone with a moderate

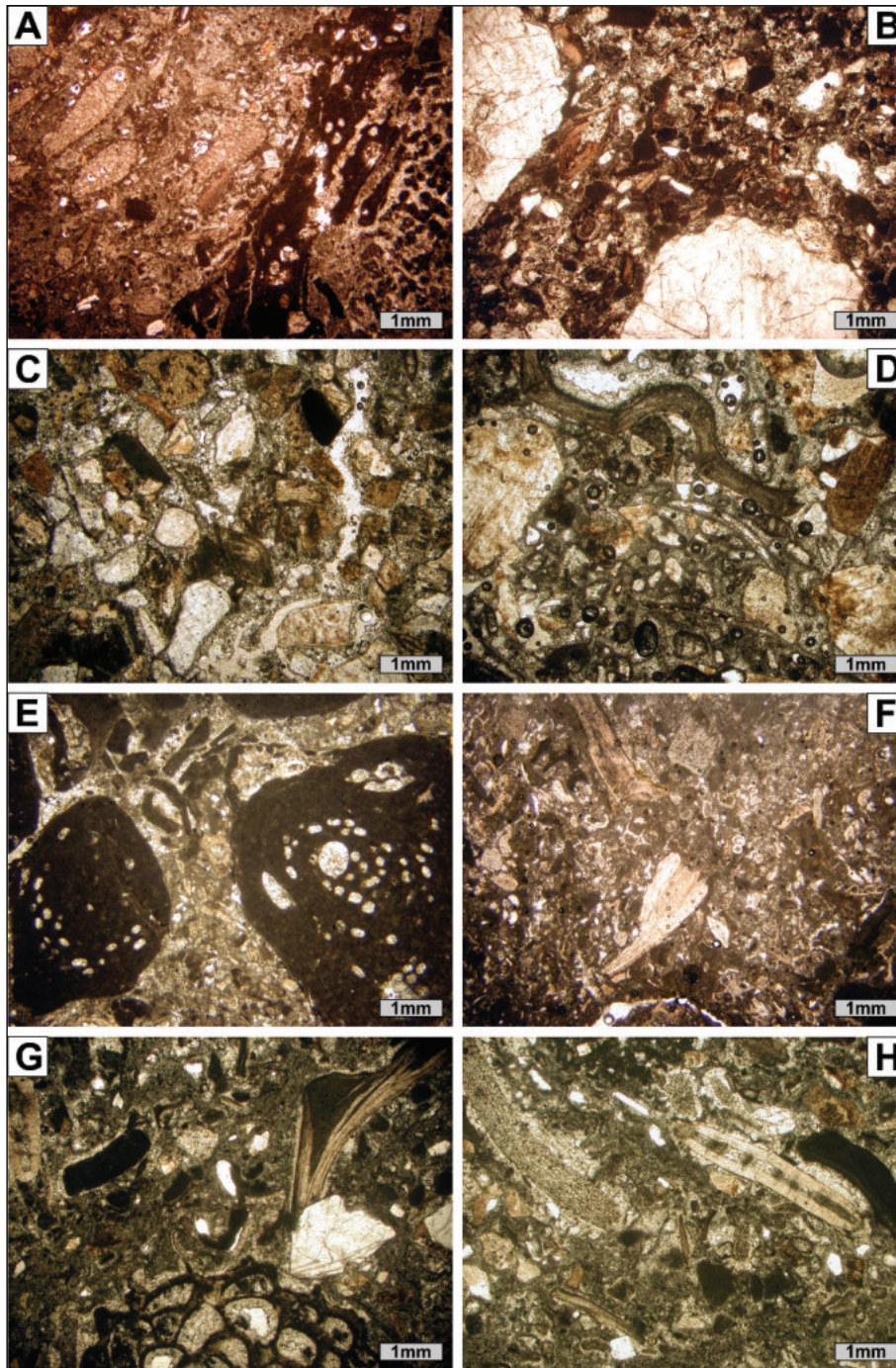


Fig. 5. - Photomicrographs of the facies. A) The main components of the coral domestone matrix are large benthic foraminifera such as *Miogypsina* and red algae. B) Terrigenous grains (quartz and feldspars) characterize the hybrid sandstones together with red algae debris and LBF (*Amphistegina*). C, D) Sandstones are composed of mineral grains (quartz, feldspars) and granitoid fragments with subordinate bioclastic fraction (bivalves, gastropods, *Amphistegina* and rare red algae). E) Red algae dominate the skeletal assemblage of the red algae branches floatstones. F) Packstone representing the matrix of the coral mixstone facies. Skeletal assemblage is characterized by red algae, bivalves, echinoids and benthic foraminifera. G) Red algae debris, bivalves, large benthic foraminifera (*Heterostegina*) and bryozoans together with subordinate mineral grains (quartz) constituting the coral rudstone matrix. H) *Heterostegina*, red algae, echinoids and bivalve fragments are the main components of the bioclastic floatstone.

increase of platy corals in the upper part. A coral rubble associated with granitic cobbles and pebbles is locally present at the base.

Interpretation. The coral domestone forms a close cluster reef (*sensu* Riding 2002) considering the arrangement of coral colonies. Coral morphology, together with sediment texture and composition, suggest well illuminated waters and relatively high hydrodynamic conditions. Recent studies in the Bonifacio Basin underlined that red algae and LBF (*Miogypsina* and *Amphistegina*), which dominate the packstone matrix, commonly characterize the

sediments of the coral bioconstructions developed within a deep part of the euphotic zone (Brandano et al. 2010; Tomassetti et al. 2013).

The coral platestone forms thin veneers following the substrate morphology. Platy corals in fact can colonize mobile loose substrates (Braga et al. 1990; Novak et al. 2013) and, locally, provide the substrate for massive corals (Reuter et al. 2012).

Facies characters of the hybrid sandstones and sandstones suggest deposition in the lower shoreface to offshore-transition, where the sediment was wave-worked but often homogenized by

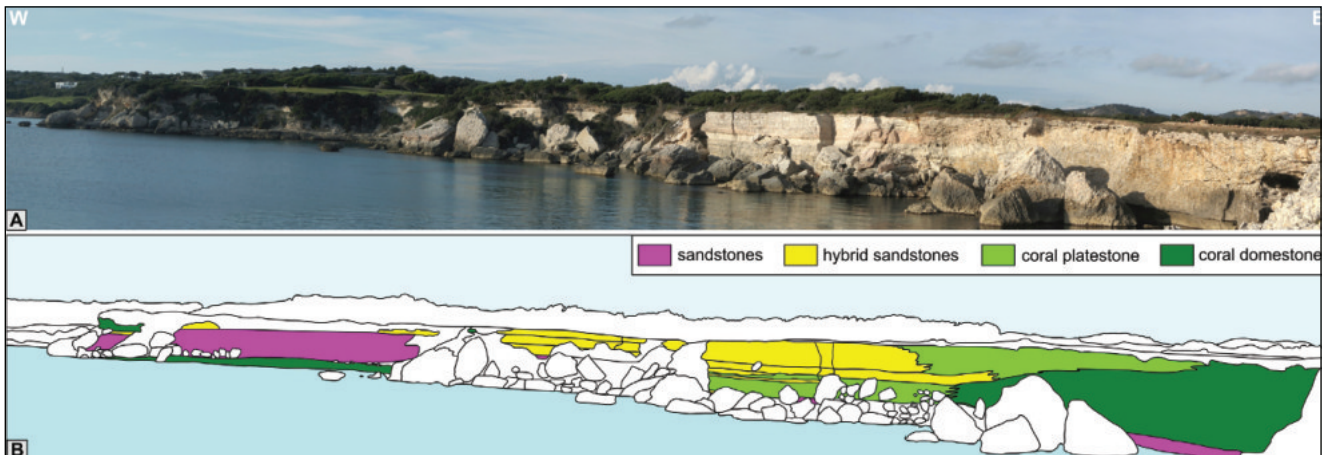


Fig. 6 - A) Photomosaic of Sperone outcrop. B) The line-drawing of this outcrop highlight facies lateral transition. Note the sandstones interfingering basinward into hybrid sandstones that pass into the coral platestone grading finally to the coral domestone.

bioturbation (Reading & Collinson 1996; Andreucci et al. 2009; Nalin et al. 2010). The presence of balanids, coralline algae nodules and fragments, thick *Amphistegina* specimens, coupled with the coarse sandsized textures, support such shallow depositional conditions. The terrigenous fraction derived from the granitic substrate is generally well sorted suggesting a high-energy environment and a proximal basement source.

Large benthic foraminifera, such as *Amphistegina*, inhabit these siliciclastic-rich sandy bottoms together with red algae according to their tolerance to the high siliciclastic input (Lokier et al. 2009). Flat clypeasteroids are shallow-burrowing endobenthic echinoids that thrived within this sandy substrate (Kroh & Nebelsick 2003).

Basinwards, the coral domestone passes into the branching red algal floatstone. This facies was deposited in the oligophotic zone as indicated by the prevalence of red algae and LBF (*Miogypsina*, *Amphistegina* and *Heterostegina*) and by the absence of coral colonies in growth position (Brandano et al. 2010).

Coral bioconstruction 2. The second type of bioconstruction (CB2) is characterized by a coral domestone fabric and is associated with fine conglomerates to sandstones and quartz-rich red algal floatstone to rudstone (Fig. 7).

Massive and subordinate platy colonies of *Porites*, *Tarbellastrea*, *Thegioastrea* and *Montastrea* constitute the coral domestone. Corals occur basically in growth position close to each other forming a small dense bioconstruction core (generally 1-2 m in

length). Moving downdip the coral coverage rapidly decreases from an average value of 50% to 40% and corals occur more spaced and embedded within the abundant matrix. Corals range in size from 10 to 90 cm in length and from 5 to 40 cm in height. Boring traces (*Caulostrepsis* and *Gastrochaenolites*) are commonly present on coral colonies. The inter-coral sediment consists of a coarse hybrid sandstone. Red algae dominate the biotic assemblage, followed by benthic foraminifera (*Miogypsina*, *Amphistegina*, cibicides and textularids), bivalves, echinoids, bryozoans and serpulids. The bioconstruction forms clinobeds with thickness ranging from 0.6 to 1.5 m with oblique-sigmoidal geometry and a few tens of meters in length. These clinobeds are characterized by a basinwards decrease in coral abundance (Fig. 7).

These types of bioconstructions develop closer to the granitic basement overlying fine conglomerates to coarse sandstones, which occur in fining upward beds (1 to 2 m thick) with crude stratification. Abraded and commonly bored fragments of bivalves represent the main bioclastic component of the siliciclastic deposits together with echinoids plates, gastropods shells, and rare red algae.

Landward, the bioconstruction interfingers with bioclastic sandy conglomerates, and sandstone. The skeletal fraction is represented by molluscs, echinoid remains, red algae and subordinate LBF (*Miogypsina* and *Amphistegina*) and bryozoans. Massive and platy coral colonies occur both in growth position and reworked. The siliciclastic fraction is represented by granitic lithoclasts, abundant quartz and feldspar grains. Traces of bioturbation (*Thalassinoides*) may occur.

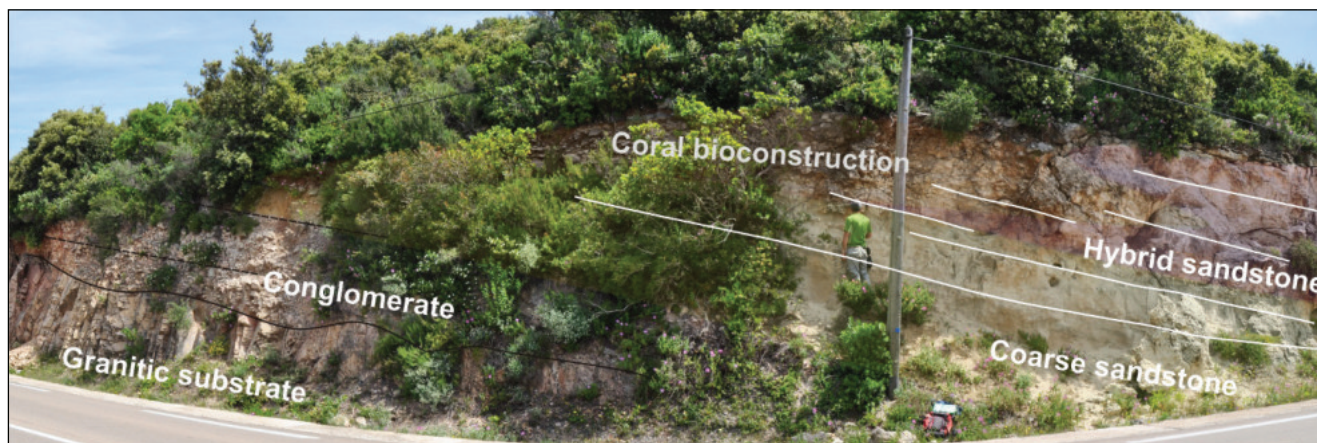


Fig. 7 - Coral Bioconstruction 2: close to the granitic basement, small coral bioconstructions developed on fine conglomerates. These are domestones consisting of massive and rare platy colonies. Basinward, coral growth is reduced, finally passing into coarse hybrid sandstones with isolated corals.

Interpretation. The coral domestone is characterized by corals close to each other in the bioconstruction core and downdip by more spaced colonies in abundant matrix. This structure is consistent with a cluster reef (*sensu* Riding 2002), which shows a close cluster in the bioconstruction core grading downdip to a more spaced structure. As suggested by the coral growth forms and the inter-coral sediment, this facies developed in a relatively high energy environment of the euphotic zone. Massive *Porites*, *Tarbellastrea* and other faviids corals formed buildups with a similar bioclastic matrix (red algae, echinoids, molluscs and benthic foraminifera) from the top down to 20 m depth in the Middle Miocene Ermenek Platform of Turkey (Janson et al. 2010).

The sandy conglomerate and sandstone deposited in a shoreface setting dominated by a high siliciclastic input derived from the proximal granitic basement source.

Molluscs and clypeasteroids, together with red algae debris predominate among the highly abraded skeletal grains of the shoreface deposits (Nalin & Massari 2009; Brandano et al. 2010). The bioerosion traces on coral colonies, with occurrence of *Gaestrochaenolites* and *Caulostrepsis*, are in agreement with the proposed environments.

Coral bioconstruction 3. The coral bioconstruction 3 (CB3) is characterized by a coral mixstone fabric associated with bioclastic packstone and hybrid sandstones.

The coral mixstone consists of massive, platy and encrusting colonies that are close to each other but mostly not in contact (Fig. 8a) *Porites* represents

the dominant genus followed by less common faviids. The sediment between the colonies is abundant and consists of a moderately/poorly sorted packstone with abundant red algae (Fig. 5e). Other bioclastic components are bivalves, echinoids and benthic foraminifera (rotaliids, textularids, rare miliolids and *Amphistegina*). Serpulids, bryozoans, balanids, encrusting and planktonic foraminifera complete the assemblage. This bioconstruction shows a lateral extension of about 20 m and a total thickness of 2 m (with beds 30 to 60 cm thick), and interfingers laterally with the skeletal sandstones.

The skeletal sandstones are thinly nodular-bedded with undulate lamination and commonly bioturbated. The bioclastic fraction is represented by the large benthic foraminifera *Heterostegina* and *Operculina*, bivalves, echinoids, corals, gastropods, subordinate small benthic foraminifera and red algae debris.

Interpretation. Corals of the mixstone facies thrived within moderate hydrodynamic conditions of the mesophotic zone, as suggested by the coral morphologies, the inter-coral sediment texture and composition. This bioconstruction, extending more laterally than in height following the siliciclastic substrate, is here interpreted as a coral carpet (*sensu* Riegl & Piller 1999). Modern faviid coral carpets representing a rigid non-uniform mixstone characterize the northern Red Sea (Riegl & Piller 1999, 2000). There, platy, massive and branching corals produce a framework up to 1 m thick at depths from 10 m down to 30-45 m.

In the Bonifacio Basin, these small bioconstructions displayed a patchy distribution within

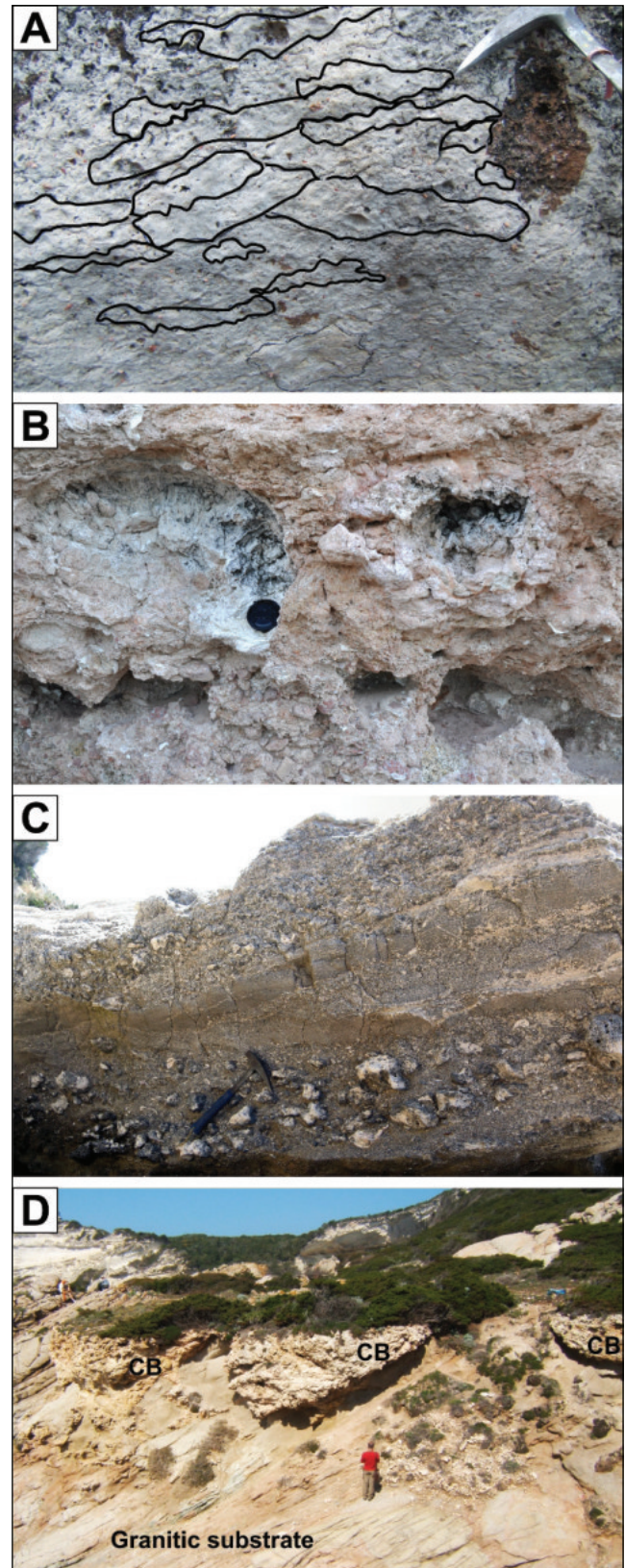
Fig. 8 - A) Coral Bioconstruction 3: biostromal beds of coral mixstone are 30 to 60 cm thick and achieve a lateral extent of about 20 m; domal, platy and encrusting coral colonies are the main growth forms; hammer for scale. B) Coral Bioconstruction 4: corals and oysters constitute a bioconstruction that develops above a layer of conglomerates. Scattered domal colonies of *Porites* and *Thegioastrea* occur in growth position, within a conglomerate with sub-rounded to sub-angular granitoid pebbles and abraded bioclasts, lens cap for scale (5 cm). C) Lenticular bodies of cross-bedded coral rudstone to floatstone are intercalated within cross-bedded bioclastic floatstone to packstone. Reworked and broken corals are associated with oyster fragments. D) In Cala di Labra outcrop lens-shaped coral bioconstructions colonized the granitic substrate. The coral fabric is represented by a coral domestone with a moderate increase of platy corals in the upper part.

coarse sandy areas represented by the skeletal sandstones. The skeletal sandstones characterized by common bioturbation were deposited in the lower shoreface environment (Nalin et al. 2010). Nummulitids inhabited the loose sandy bottom together with bivalves and clypeasteroids. Present-day *Operculina* and *Heterostegina* live from the shallow-water and high-energy environment to more quiet and deeper habitats, with major abundance between 30 and 40 m (Hohenegger et al. 1999; BouDagher-Fadel 2008).

Coral bioconstruction 4. The fourth type of bioconstruction is strictly associated with a skeletal conglomerate (Fig. 8b).

The skeletal fraction is represented by the abundant disarticulated oyster *Hyotissa hyotis* (Linnaeus, 1758) and by massive corals that are surrounded by disarticulated and intensively bored unidentified oyster shells. *Porites* and faviid (common *Thegioastrea*) colonies occur in growth position usually unbound and dispersed, commonly with *Gastrochaenolites* boring traces. Other bioclasts are represented by bivalves, serpulids, echinoids, less common red algae and small benthic foraminifera. Gastropod fragments also occur mostly as cortoids. The conglomerate consists of sub-angular to sub-rounded granitoid pebbles, mostly ranging in size between 3 and 5 cm and rarely up to 15 cm.

These deposits show an irregular lens-shaped geometry up to 1 m in thickness and about 5 m in length with a convex top and flat base. This bioconstruction lies on a fining upward matrix-supported conglomerate bed, made up of sub-rounded pebbles and cobbles of granitoids and lacking marine skeletal elements.



Interpretation. The CB4 is interpreted as a colonization of massive corals associated with oysters that developed in a high energy environment as suggested by the coral morphologies, the reworked oyster shells and the conglomerate matrix with highly

abraded bioclastic fragments. *Hyotissa* is a marine and estuarine suspension feeder usually cemented to hard subtidal substrata (Zuschin & Piller 1997; Wiedl et al. 2013) and commonly associated with corals. It is strictly stenohaline and also stenotherm (Stenzel 1971). Dense populations of *Hyotissa*, however, may also occur free-living on the substrate or attached to dead and degraded coral colonies (Slack-Smith 1998; Zuschin & Baal 2007) at water depths less of 10 m (e.g. Titschack et al. 2010). The conglomerate with sub-angular to sub-rounded pebbles and cobbles and lacking bioclasts is interpreted as a gravelly shore deposit. A double provenance for pebbles and cobbles could be assumed. They were eroded or collapsed from the near granitic cliffs and deposited by ephemeral streams.

Reworked-coral deposit (RCD). The RCD is represented by a coral rudstone to floatstone, that occurs in lens-shaped bodies intercalated within bioclastic floatstones and coarse packstones.

The coral rudstone to floatstone is characterized by corals that are not in growth position, but only occur as reworked massive colonies and fragments, commonly aligned and occasionally imbricated (Fig. 8c).

In addition to corals, oysters, gastropods (turritellids) and echinoids fragments commonly occur. Larger foraminifera (*Heterostegina*, *Operculina* and *Miogyopsina*), red algae debris and small benthic foraminifera (cibicids, textularids and rare miliolids) complete the biotic assemblage. The siliciclastic fraction is abundant and represented by quartz and feldspars grains and subordinate granitic lithoclasts.

Bioclastic floatstones and coarse packstones are commonly organized in cross-bedded sets (first order) that are 30 to 60 cm thick with bedding-plane discordant laminations and stack in 2 to 3 m thick co-sets (Fig. 8c). Coarse packstones are well to moderately sorted and composed predominantly of red algae debris, small benthic and planktonic foraminifera, bivalves and echinoids fragments (Fig. 5h). Sub-spherical rhodoliths, flat clypeasteroids and deep-burrower echinoids are also present. Floatstones are poorly sorted with an abundant siliciclastic component. Bioclasts are represented by red algae, larger foraminifera such as *Heterostegina* and *Operculina* (Fig. 5g), turritellids, bivalves, bryozoans, coral fragments and small benthic foraminifera (rotaliids, textularids and rare miliolids).

Interpretation. The RCD represents a transported and reseeded deposit as suggested by the presence of reworked and broken coral colonies within lens-shaped bodies that are embedded in a bioclastic facies. This facies is interpreted as bioclastic and calciclastic submarine fan deposits (*sensu* Payros & Pujalte 2008). Coarse-grained bioclastic and calciclastic submarine fan systems are characterized by an abundance of coarse-grained rudstones and the almost complete lack of muddy sediments. In these systems, small radial lobes develop at the base of the slope and are represented by frequently cross-bedded coarse-grained rudstones (Payros & Pujalte 2008). Payros & Pujalte (2008) underlined how the outer portion of heterozoan distally steepened ramps may supply a calciclastic sediment stock close to the slope break. In particular, part of the sediment accumulated between the middle ramp and the slope break can be transported to the slope and involved in sediment gravity flows, thus forming calciclastic sedimentary accumulations at the toe of the slope in the outer ramp. Clearly, sediment transport from the middle ramp to the ramp slope was facilitated during storm periods and downwelling high-energy currents (rip currents), with large amounts of loose bioclastic sediment transported and shed off the ramp to the slope. Paleoenvironmental and paleoclimatic conditions favoring the development of heterozoan skeletal assemblage are of course necessary to promote the development of these bioclastic fans. The bioclastic floatstones and coarse packstones in the Bonifacio Basin result from combined accumulation in the oligophotic zone of in situ-produced red algal debris and material (such as mineral grains, coral fragments and some small benthic foraminifera) swept from shallower environments and transported by wind-driven and storm currents into a depositional slope below the storm wave base level (Hernandez-Molina et al. 2000; Tomassetti & Brandano 2013). According to Tomassetti & Brandano (2013), this depositional slope can be attributed to a coastal prograding wedge system (*sensu* Hernandez-Molina et al. 2000).

DISCUSSION

Basin morphology and coral bioconstructions. A paleogeographic reconstruction of the investigated area during the Aquitanian to Burdigalian

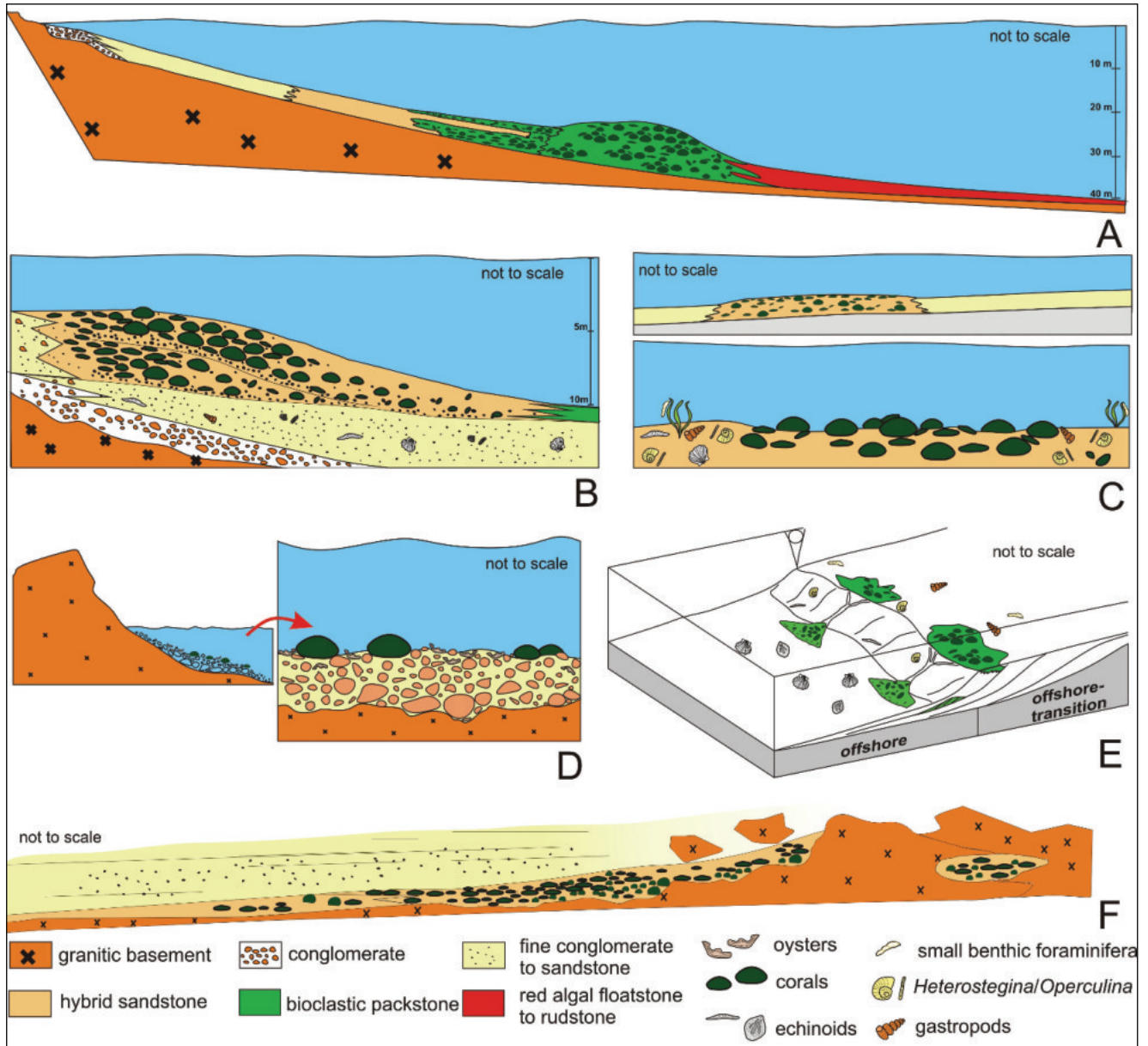


Fig. 9 - The Coral Bioconstruction 1 A) represents buildups of moderate relief that occurred in the deep euphotic zone; the Coral Bioconstruction 2 B) developed in a shallower environment, closer to the granitic basement on coastal conglomerate and was more influenced by the terrigenous input; the Coral Bioconstruction 3 C) consists of thin veneers of coral mixstone representing coral carpets that are patchily distributed within coarse skeletal sands; on the gravelly substrate of a pocket beach delimited by rocky sea cliff developed the Coral bioconstruction 4 D) characterized by sparse coral colonies associated with oysters; the cross-bedded coral rudstone to floatstone E) represents deposits of coarse-grained calciclastic submarine fans at the base of a depositional slope; in the Cala di Labra outcrop F) the coral bioconstruction settled directly on the offshore granitic substrate forming lens (after Tomassetti et al. 2013)..

interval has been recently proposed by Reynaud et al. (2013) on the basis of thickness and facies distributions of the two formations: Cala di Labra and Bonifacio Fms. According to this reconstruction, the Bonifacio Basin evolved from an embayment during the Aquitanian and early Burdigalian to a complex strait in the Late Burdigalian. This strait developed between two main islands, Corsica and Sardina, and two basins: the East Corsica Basin and the West Corsica Basin that passed westwards to the

Castel Sardo Basin (Cherchi et al. 2008; Reynaud et al. 2013). The Cala di Labra Fm. embayment was characterised by a gradual increase of water depth to the southwest and limited at southeast by a granitic ridge (Punta Sa Mulari) (Fig. 1b).

The coral bioconstructions of the first type (CB1) are located in the distal portion of the embayment, in particular in the western side of the bay, at Cala Paraguano, and in the southeast of Punta Sa Mulari ridge (Fig. 1b). The coral bioconstructions

of the distal part of the bay include also the coral buildups documented by Tomassetti et al. (2013) at the Cala di Labra locality (Fig. 8 d, 9a).

The CB2 are located at both sides of the proximal portion of the Bonifacio embayment with corals settled on sandy to conglomerate substrate close to the crystalline basement (Fig. 9b). The CB4 developed in the gravelly shoreface of the internal portion of the bay, characterized by granitic cliffs whose collapse likely supplied the gravel for the shoreface (Fig. 9d). The coral carpet CB3 overlies the CB4 and the CB1 in the Cala di Labra outcrop. The CB3 represents the gradual deepening of the shoreface environment following the progressive transgression that characterized the initial stage of the Burdigalian (Tomassetti & Brandano 2013) (Fig. 9c). However, the development of coral carpets is also controlled by bottom topography. As underlined by Riegl & Piller (2000), coral carpets prefer areas with little topographic differentiation. Consequently, in the Bonifacio Basin the CB3 may be considered also to represent the colonization by corals of flat mobile substrates when they developed in the mesophotic zone.

Depositional model. The different coral bioconstructions and coral assemblages of the Bonifacio Basin show a suite of facies associations that reflects their different position in the articulated Bonifacio embayment and consequently their connection with different depositional processes (Fig. 9a-f). However, with the exception of the CB4 that formed in a coarse clastic-dominated near-shore environment, the other bioconstructions (CB1 and 2) show a common depositional architecture that produced a sigmoidal geometry. It is represented in fact by a flat portion with platy and encrusting corals evolving to the core of the bioconstruction (i.e. cluster reef) usually dominated by corals with domal growth-forms, and by a bioclastic-dominated slope with scattered corals followed basinward by rudstone to floatstone rich in free living red algal branches (Fig. 5e, 9a,b).

Bioconstructions similar to CB 1 have been observed also in Northern Sardinia (Capo Testa), where an analogous mixed carbonate-siliciclastic system occurs (Brandano et al. 2010). The sigmoidal profile along the depositional dip direction resulted from the important nearshore siliciclastic supply, probably stabilized by seagrass meadows. The sigmoid front was stabilized by massive corals, limiting

bioclastic sedimentation along the slope and toe of the slope by the oligophotic biota.

On the basis of the bioclastic components, sediment texture and coral growth forms, a bathymetric interval between the storm-wave base (swb) and fair-weather-wave base (fwwb) may be inferred for CB1, with massive corals growing under good light conditions and relatively high hydrodynamic energy. The CB2 differs from CB1 in having increased of coarse terrigenous supply and smaller sigmoids, most likely related to their development in the more proximal and shallow shoreface environment of the Bonifacio embayment.

The coral carpet bioconstruction (CB3) is found only in the Ricetti outcrop and it overlies the CB4 following the middle Burdigalian transgressive phase (Tomassetti & Brandano 2013). Generally, coral carpets preferentially form in areas with low topographic differentiation, and in environments characterized by low sedimentation and accumulation (Riegl & Piller 2000). Considering the stratigraphic position of the CB 3 and its location in the embayment, we suggest that a small relative sea level rise and flat mobile substrates promoted the development of coral carpet bioconstructions.

The RCD form lens-shaped bodies that are embedded in the upper prograding bioclastic unit of Cala di Labra Fm. This unit has been interpreted as an infralittoral prograding wedge characterized by substantial nearshore siliciclastic supply, whereas the carbonate production is usually limited in nearshore environments, but increases with depth in the transition zone and offshore (Tomassetti & Brandano 2013). Infralittoral prograding wedge was introduced by Hernández-Molina et al. (2000) to describe Holocene seaward-prograding sedimentary bodies observed at water depth of 20-30 m in the Mediterranean Sea, and deposited below storm-wave base during stillstand of sea level. Their first outcrop counterparts have been described by Pomar & Tropeano (2001) and by Pomar et al. (2015) and interpreted as representing deposition below storm-wave base of sediment transported basinward by storm-generated currents (downwelling currents). The RCD facies represents the lobe deposits of coarse-grained bioclastic submarine fans (c.f. Payros & Pujalte 2008) occurring at the base of the depositional slope of an infralittoral prograding wedge system (Fig. 9e). Original coral bioconstructions, source of the RCD bioclastic fraction, were

probably present near the offshore-transition and topographic break into the slope (Fig. 9e). These bioconstructions may have been represented by small coral patches with a cluster reef structure (*sensu* Riding 2002). Indeed, the absence of a dense coral framework and early cementation, together with the abundance of matrix (Riding 2002), may have promoted the mobilization of corals and sediment as individual grains by storms or rip currents, which commonly affect the prograding wedge (Hernandez-Molina et al. 2000). These sediments may have been transported downslope by high-density turbidity currents, which can transport coarse sediment (coarse sand to cobble) supported by the fluid turbulence and dispersive pressure resulting from grain collision (Lowe 1982; Tucker 1992). Small bioherms placed at the platform top are recorded also in the coeval prograding flat-topped platform of Sardinia (Benisek et al. 2009).

Carbonate-siliciclastic mixing. In the geological record there are many examples where coral reef deposits are closely associated with siliciclastic sedimentary rocks (Dabrio et al. 1981; Santisteban & Taberner 1988; Braga et al. 1990; Sanders & Baron-Szabo 2005; Silvestri et al. 2011; Morsilli et al. 2012; Novak et al. 2013). In many of these examples the siliciclastic input is represented by the fine fractions of the sediments (clay or silt). Examples with coral bioconstructions also associated with coarse terrigenous sediments are documented only from fan deltas depositional settings (Santisteban & Taberner 1988; Braga et al. 1990; Wilson & Lokier 2002; Karabiyikoğlu et al. 2005). In the Bonifacio Basin, the lower Burdigalian siliciclastic deposits of Cala di Labra Fm. are represented by fluvial conglomerates, marine conglomerates and sandstones, whereas hemipelagic marls were deposited later, during the middle to late Burdigalian (Brandano et al. 2009; Reynaud et al. 2013). According to this picture, corals were most likely not affected by high turbidity levels (which results in rapid light attenuation) and by periodic smothering and burial associated with a mobile and fine siliciclastic-dominated sediment substrate (Perry 2005). On the contrary, they thrived under coarse terrigenous input derived mainly by erosional processes along the rocky shoreline and subordinately by ephemeral fluvial systems.

As in many modern coastal examples, we also observed a basinward decrease in terrigenous input associated with a simultaneous increase of

skeletal carbonate production (Mount 1984; James et al. 1992; Halfar et al. 2004). In the nearshore environments of the Bonifacio embayment, the coral colonies (CB4) are dispersed in the conglomerates of the shoreface (c.f. Dorsey 1997). In the CB2, the terrigenous fraction is still conspicuous and the bioconstruction developed above fine conglomerates to sandstones with the matrix between corals represented by hybrid sandstone. A decrease of terrigenous input and grain-size is clear in the CB1 that developed in the distal part of the embayment in more open conditions that favoured a skeletal carbonate production dominated by red algae and subordinately by benthic foraminifera and molluscs in the meso and oligophotic zones.

CONCLUSIONS

In this paper we document the occurrence of different coral bioconstructions and coral-rich deposits in the Bonifacio Basin, which was a complex and articulated embayment during the Early Miocene. Sigmoidal cluster reefs (CB1 and CB2), coral carpets (CB3) and skeletal conglomerates rich in corals (CB4) have been recognized.

These coral deposits developed within a mixed carbonate-siliciclastic setting and their depositional architecture and growth fabrics were strongly controlled by coastal morphology, paleotopography and sedimentary processes affecting the different areas of the basin.

In the upper shoreface corals, together with the oyster *Hyotissa*, represent the main component of bioclastic conglomerates alimented by ephemeral streams and erosion of the granitic coastline. Reef-building capacity took place in the lower shoreface, where corals formed small sigmoidal bioconstructions interpreted as cluster reefs. A coral carpet deposited above the CB4 following the middle Burdigalian transgressive phase and colonizing a flat mobile substrate.

The impact of siliciclastic sediments on the coral assemblages clearly reflected their position within the Bonifacio embayment. However, corals were not affected by high turbidity levels as the siliciclastic input resulted mainly from erosional processes affecting the rocky shoreline and subordinately from ephemeral fluvial systems that delivered only coarse sediments.

The suite of coral deposits of the Cala di Labra Fm. also includes the reworked coral deposits of Rocchi Bianchi (RCD), herein interpreted as lobe deposits of coarse-grained bioclastic submarine fans formed at the base of the depositional slope of an infralittoral prograding wedge system.

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