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Revisiting reef models in the Oligocene of northern Italy (Venetian Southern Alps)

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KEY WORDS - Coral reefs, early Oligocene, euphotic barrier-lagoon system, coral assemblages.

ABSTRACT - The lower Oligocene coral communities and reefs exposed in the Lessini Shelf of northern Italy may record one of the oldest well-developed barrier reef/lagoon systems of the Cenozoic. However, the rimmed-shelf interpretation has been repeatedly challenged in favour of a ramp model with scattered corals. Based upon a re-analysis of selected localities in the Lessini Shelf, we here provide support for the barrier reef model based on four key observations: 1) systematic changes of coral growth-forms from branching in the proximal areas to massive at the platform margin; 2) a progressive increase of the hydrodynamic energy from the proximal belt towards the more distal environments in the Berici Hills; 3) the occurrence of shallow-water, euphotic conditions throughout the whole depositional system; and 4) the presence of restricted circulation in the proximal environments during sea-level lowstands, with lack of coral colonies. These features, together with the evidence of coral frameworks located on the southeastern edge of the Lessini Shelf, substantiate the occurrence of a reef-rimmed margin. The reefal rim acted as an efficient barrier, with the formation of a landward, wide lagoon protected from the action of waves and currents.

INTRODUCTION

Well-developed coral reefs were globally scarce during most of the Paleogene but increased in abundance, size, and biotic diversity during the Oligocene, perhaps related to an increasing Mg/Ca ratio in ocean water facilitating coral growth (Stanley & Hardie, 1998). The Lessini Shelf is a major Cenozoic paleogeographic element of the Southern Alps (Bosellini, 1989) (Fig. 1a) with shallow marine deposits ranging from the early Eocene to the early Miocene (Bosellini et al., 1967; Bassi et al., 2007, 2008; Bassi & Nebelsick, 2010). From paleontological and geological points of view, this area is famous for the extensive collections of the 19th century describing its rich coral fauna and has long been a global landmark for the study of Oligocene reefs.

Exceptional for the Oligocene, a Rupelian (early Oligocene) barrier-reef/lagoon complex is thought to have rimmed the Lessini Shelf. According to older models, a barrier reef rim was located in the southeastern side of the Berici Hills, with a wide lagoon extending for about 30 km northwestward into the Lessini Mountains (Frost, 1981; Bosellini & Trevisani, 1992). This barrier-reef/lagoon model has been repeatedly challenged, proposing a ramp depositional system instead of a reef-rimmed platform (Nebelsick et al., 2012; Pomar et al., 2017).

Here we evaluate these alternative reconstructions providing new data, especially focusing on microfacies analysis and types of coral assemblages, from three selected key localities (Castelgomberto, Bastia, and Lumignano), placed along a NW/SE transect through the Castelgomberto Limestone Formation depositional system (Fig. 1b).

GEOLOGICAL SETTING

The Lessini Mountains and Berici Hills are located in the Southern Alps, a geological domain that resulted from the collision of the northernmost margin of the Adria Plate with the European block (Bosellini, 1989). During the Jurassic, this area was occupied by the Trento Platform, a large shallow-water area bordered to the west by the Lombard Basin and to the east by the Belluno Trough (Fig. 1a) (Bosellini et al., 1981; Winterer & Bosellini, 1981). The Trento Platform drowned in the Middle to Late Jurassic to give rise to the Trento Plateau, with deep marine sedimentation until the Paleocene. In the Paleogene, the Alpine orogeny produced a gradual uplift with the segmentation of the plateau into several blocks. During the early Eocene, some of these structures reached the photic zone, with a progressive increase of carbonate production that eventually led to the formation of a vast platform called Lessini Shelf (Fig. 1a) (Doglioni & Bosellini, 1987; Bosellini, 1989; Luciani, 1989; Bassi et al., 2008).

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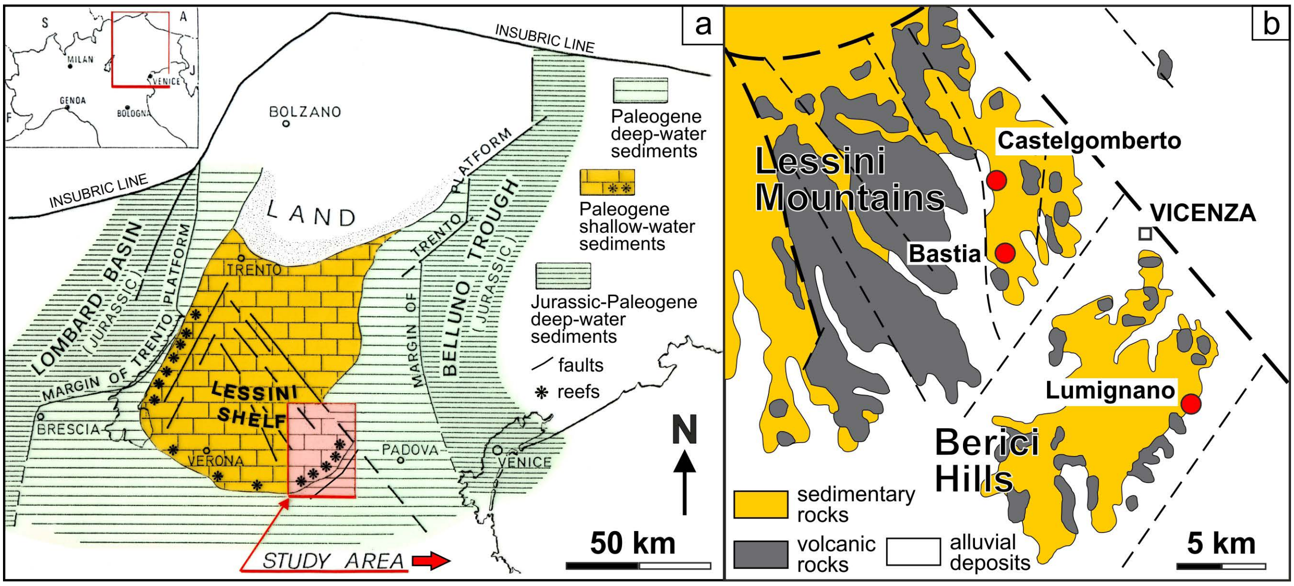

Fig. 1 - (color online) a) Paleogeographic reconstruction of the Lessini Shelf (modified from Bosellini et al., 1989). b) Simplified geological map of the south-eastern part of the Lessini Shelf (modified from De Vecchi & Sedea, 1995) showing the locations of the studied outcrops.

From the Paleocene to the Oligocene, the Lessini Shelf was limited northward by land and surrounded on the other sides by deeper marine basins (Bosellini, 1989). During this period, several pulses of volcanic activity took place, with the formation of basaltic intrusions and epiclastic horizons that interacted with the carbonate sedimentation (Barbieri et al., 1991; Barbieri & Zampieri, 1992; Zampieri, 1995). Carbonate deposits are concentrated in the eastern Lessini Shelf, initially represented by the middle Eocene "Calcari Nummulitici" (Nummulitic Limestone), an informal unit that includes a wide array of facies: larger foraminifera, coral and mollusc limestones, coralline algae breccias, and marly limestone with marine and freshwater fossils (Bosellini et al., 1967; Carraro et al., 1969; De Zanche et al., 1977; Sarti, 1980; Ungaro, 2001; Papazzoni et al., 2014, 2017; Vescogni et al., 2016). Volcanic activity over the Lessini Shelf area ceased nearly completely during the late Eocene, a phase characterised by the deposition of deep-platform, marly sediments (Barbieri et al., 1980; Mietto, 1992; Trevisani, 1997). However, volcanism started in the Euganean Hills area 42.0±1.5 Ma (Borsi et al., 1969), in the late Lutetian-Bartonian, with submarine mafic lavas, and continued until about 32-30 Ma in the early Oligocene with intermediate to felsic volcanism (Piccoli et al., 1981; Bartoli et al., 2015; Brombin et al., 2019). In the mid-Oligocene the volcanic activity started also in the Marostica Hills, east of the Lessini Shelf, reaching a peak during the early Miocene (Brombin et al., 2019).

Shallow-water carbonate sedimentation resumed in the Lessini area during the early Oligocene, with the deposition of the Castelgomberto Limestone Fm. (Geister & Ungaro, 1977; Frost, 1981; Bosellini & Trevisani, 1992; Mietto, 1992). The Castelgomberto Limestone Fm., developed in the south-eastern part of the Lessini Shelf, spans the entire Rupelian stage (Geister & Ungaro, 1977; Frost, 1981). Along the western sector, Oligocene sediments are lacking, probably due to emersion (Luciani, 1989). Lower Oligocene limestones are followed by the upper Oligocene-lowermost Miocene S. Urbano Sandstone (Bosellini et al., 1967; Bassi et al., 2007, 2008; Bassi & Nebelsick, 2010), which is further overlain by the lower Miocene Monte Costi Marlstone, a unit only a few meters thick (Bosellini & Dal Cin, 1966; Bassi et al., 2007, 2008) that represents the last marine sedimentary unit of the Lessini Shelf.

THE CASTELGOMBERTO LIMESTONE FORMATION

Known to pioneering workers as the "Strati di Castelgomberto" (Maraschini, 1824) and to modern authors as the "Calcareniti di Castelgomberto" (Bosellini et al., 1967) or "Calcare di Castelgomberto" (Coletti et al., 1973), the Castelgomberto Limestone Fm. is a 200 m thick formation made of different types of limestones (calcarenites, calcirudites, coral boundstones), marly limestones and clay horizons. This unit is mainly exposed in the south-eastern part of the Lessini Mountains and in the Berici Hills area (Fig. 1b). The number of extensive outcrops showing a luxuriant coral fauna has attracted the interest of many scientists and there were several attempts to reconstruct this lower Oligocene coral-rich depositional system (Rossi & Semenza, 1958; Geister & Ungaro, 1977; Frost, 1981; Bosellini & Russo, 1988; Bosellini & Trevisani, 1992; Nebelsick et al., 2012; Pomar et al., 2017).

Geister & Ungaro (1977) focused on the Berici Hills, where they identified two main paleoenvironmental settings and coral assemblages. In the central and NW Berici, under shallow-water, moderate hydrodynamic condition, prevalent ramose coral colonies formed low-relief patches, whereas along the SE margin, massive colonies thrived in a slightly deeper environment, rarely forming compact, wave-resistant frameworks. Taking into accounts the low-energy setting of the central-NW Berici sector, these authors postulated the presence of a coral reef barrier towards SE, acting as a protection from the open-sea. However, no certain evidence of its presence was identified, and considering that the same kind of protection could have been attained by a seaward extension of the platform, Geister & Ungaro (1977) left a detailed interpretation of the depositional paleoenvironment to future studies.

Some years later, Frost (1981) conducted a comprehensive study of the entire region where the Castelgomberto Limestone Fm. is exposed. According to Frost (1981), a shallow-water barrier reef developed in the southeastern portion of the Berici Hills, comprising a 150-200 m thick, 800-900 m wide and about 8 km long reef core mainly constructed by massive to columnar coral colonies. Corals with similar growth-forms built thickets and small patch reefs in a more protected lagoonal environment, which extended northwestward for about 30 km into the Lessini Mountains. The most proximal lagoonal areas received episodic terrigenous influxes and are characterised by ramose coral assemblages developing thicket-like structures.

Bosellini & Russo (1988) and Bosellini & Trevisani (1992) focused on the SE Lessini Mountains, in the most proximal portion of the Castelgomberto Limestone Fm. depositional system. These authors corroborated the Frost (1981) model by the recognition and interpretation of a cyclical depositional pattern. Well-bedded rhodolite-nummulitid grainstones alternate with nodular or wavy-bedded marly wackestones rich in ramose coral colonies sometimes forming thicket-like structures. Bosellini & Trevisani (1992) interpreted this cyclicity as related to alternating high-energy and low-energy hydrodynamic conditions, correlated to short-term sea-level fluctuations affecting the Lessini Shelf reef-lagoonal complex. The biocalcarenite facies represents relative highstand deposits with flooding and open circulation on the entire shelf, strong tidal currents, swells and periodic storms able to sweep the bioclastic sand masses into sand waves and subaqueous dunes. The marly facies, in contrast, was deposited during relative lowstands, when the shelf was more protected by the reefs in what is now the Berici Hills. These reefs possibly acted as a true barrier, shielding the quiet inner shelf lagoon from currents and waves and favouring colonisation by coral patches. During sea-level lowstands large inland areas were exposed to weathering, supplying fine, clay-rich detritus to the shelf-lagoon.

More recently, Nebelsick et al. (2012) studied a 100 m thick and about 280 m long section in the SE Berici Hills. They recognised a succession of coralline algal rudstones that developed within the photic zone and under relatively low hydrodynamic conditions, with corals represented only by variable amounts of fragments. Sedimentary fabrics, biofacies analysis and the lack of bioconstructions led these authors to interpret this portion of the Berici as an homoclinal ramp, with no evidence of a reef barrier.

Finally, Pomar et al. (2017), in a review of Cenozoic carbonate depositional models, considered the Castelgomberto Limestone Fm. as a low-angle ramp system, with a gradual, progressive deepening occurring from the euphotic settings of the proximal belt (present-day SE Lessini) to the oligophotic paleoenvironments in the distal areas (present-day SE Berici). According to this model corals are lacking in the shallower areas, which were instead dominated by seagrass. Isolated coral colonies were limited to the mesophotic to oligophotic paleoenvironments of the middle ramp, rarely forming small structures. In the more distal, oligophotic areas corals occur only as fragments.

A schematic summary of the different paleoenvironmental reconstructions obtained in these studies is reported in Tab. 1 and compared with the results of the present work. To facilitate the reading of the table, we replaced the terms originally used by the previous authors for the description of coral assemblages (e.g., coral carpets, biostromes, coppices) with others with similar meaning and used in this work.

MATERIALS AND METHODS

Stratigraphic, sedimentary and paleontological data have been acquired from three selected localities: Castelgomberto, Bastia and Lumignano (Fig. 1b).

The Castelgomberto section was studied along a fresh, 135 m long road cut about 1 km SW of the small town of Castelgomberto (45°34’27.6”N, 11°23’55.5”E). Here, a 27 m thick succession of Rupelian limestones and marls is exposed (Fig. 2a).

The Bastia outcrop is located about 3 km north of Montecchio Maggiore, along a small road connecting the locality of Bastia Bassa to the village of S. Urbano (45°31’26.7”N, 11°24’58.2”E). Despite a dense vegetation cover and intense faulting, this outcrop allows the observation of a 120 m long and ca. 5 m thick exposure of coral-rich limestone (Fig. 3a).

Lumignano is located in the Berici Hills at the southeastern margin of the Lessini Shelf. We studied the best exposed coral outcrop at the San Cassiano hermitage (45°27’57.1”N, 11°35’13.3”E), an antique, small monastery built on a suspended ledge carved on the cliff along the south-eastern side of the Berici Hills. There, a 100 m long and several meters thick exposure allows the characterisation of the coral facies (Fig. 4a), although intense karstification affects the assessment of primary facies patterns and prevents the measurement of a stratigraphic section.

We conducted macroscopic and microscopic observations. Coral-rich facies has been traced in the field focusing on prevalent growth-forms and dominant genera. Coral taxa have been identified directly in the field at the genus level. We also recorded growth-forms and colony size (maximum diameter and maximum height of corals in growth position). Additional data have been collected in Lumignano, where biostratinomic data (orientation, fragmentation) of 70 coral colonies were quantified from the bioconstructed portions of the outcrop. Microfacies analysis was conducted on a total of 73 thin sections (60 × 45 mm), providing data on textures and carbonate grains reported in the facies description. Rock textures were classified following Dunham (1962) and Embry & Klovan (1971). The nomenclature of Woelkerling et al. (1993), originally established for the description of coralline algae growth-forms, was slightly extended to also characterise peyssonneliancean algae.

In the Castelgomberto outcrop, some of the clay horizons have been sampled and analysed in order to ascertain their depositional origin: whether they can be

	Castelgomberto Limestone Fm.				
	SE Lessini/central-NW Berici		SE Berici		Depositional model
	Paleoenvironmental setting	Coral assemblage	Paleoenvironmental setting	Coral assemblage	
Geister & Ungaro (1977)	Within the fair weather wave base, moderate hydrodynamic conditions.	Ramose corals forming low-relief patches.	Below the fair weather wave base, close to the lower limit of the euphotic zone.	Patches of lens-shaped and massive corals, rarely forming a real framework.	Possible occurrence of a coral reef barrier in the SE of the Berici Hills protecting a lagoon towards the NW, but no direct evidence of its presence is observed.
Frost (1981)	Shallow-water environment, with marine carbonate deposition. Periodic terrigenous influxes limited to the proximal areas.	Massive corals prevail in thoroughly carbonate depositional settings, forming thickets and small patch-reefs. In proximal areas ramose corals form thicket-like structures during terrigenous/carbonate deposition.	Shallow-water conditions.	Reef framework with dominant massive-columnar corals.	A large, coral reef barrier along the SE margin of the Berici Hills protects a wide lagoon towards NE.
Bosellini & Trevisani (1992)	Shallow-water environment. Sea-level fluctuations control cyclic phases of high-energy carbonate deposition and lower-energy, mixed terrigenous/carbonate sedimentation.	Pure limestone intervals contain coral fragments and rare massive and laminar colonies. Ramose corals colonies prevail during terrigenous/carbonate deposition, forming also thicket-like structures.			The presence of a coral reef barrier in the SE of the Berici Hills is postulated, influencing the lagoon hydrodynamic conditions during sea-level variations.
Nebelsick et al. (2013)			Within the photic zone, relatively low hydrodynamic conditions.	Corals as fragments within a coralline algal rudstone.	The SE margin of the Berici Hill was represented by a homoclinal ramp. No evidence of a coral reef barrier has been identified.
Pomar et al. (2017)	Seafloor gradually downgrades from the euphotic to the meso-oligophotic zone. Presence of episodic terrigenous inputs.	Corals are absent in the shallower settings and occur as isolated colonies in the meso-oligophotic areas, where they can also form small mounds.	Oligophotic conditions.	Corals as fragments within a coralline algal rudstone.	The whole Castelgomberto Limestone Fm. depositional system is interpreted as a low-angle ramp, lacking a seaward coral reef barrier.
This study	Shallow-water, euphotic environment. In the proximal areas variations in water turbidity and terrigenous inputs are controlled by sea-level changes. Progressive seaward increase of hydrodynamic energy.	Ramose corals form thicket-like structures in the proximal areas. In more distal settings patch-reefs are made by massive and ramose colonies.	Shallow-water, euphotic setting, high-energy hydrodynamic conditions.	Massive-globose colonies form a wave-resistant framework.	A wave-resistant, shallow-water coral framework occurs at the SE margin of the Berici Hills, associated to a wide, euphotic lagoon towards the NW with scattered patch reefs.

Tab. 1 - Summary of the main interpretations of the Castelgomberto Limestone Fm. depositional models compared with the results of this study.

associated to the transport from the mainland of clays derived from the alteration of volcanic rocks, or if they can be rather related to the deposition of volcaniclastics following eruption events. Five samples (A1 to A5; Fig. 2a) have been dissolved in water and then passed through a series of sieves (1-0.5-0.25-0.125 mm) to check the presence of bioclasts and/or fragments of volcanic origin. In addition, two samples (A2 and A5) have been analysed by means of X-ray powder diffraction (XRPD), for a qualitative determination of the minerals forming the clay levels. Before the XRPD analysis both samples were air-dried and milled with an agate mortar. An aliquot of dried samples was suspended in deionised water and then casted on the aluminium sample-holder in order to obtain an oriented sample that allows a proper identification of the clay minerals (Zhou et al., 2018). Both randomly oriented samples (i.e., dry samples) and oriented samples were analysed using a conventional Bragg-Brentano Philips diffractometer (model PW-1729). A complete description of the instrumental set up is reported in Zoboli et al. (2019).

FACIES DESCRIPTION AND INTERPRETATION

Stratigraphic, sedimentary and paleontological features of the Castelgomberto Limestone Fm. facies are here reported from each of the studied localities, followed by an interpretation of the main paleoenvironmental factors controlling their deposition.

Castelgomberto

In the Castelgomberto locality, four main facies have been recognised (Fig. 2a). These are in stratigraphic order:

- Coralline rudstone: planar beds with massive to weakly stratified inner arrangement, few dm up to 3.5 m in thickness, characterised by the presence of a dense network of thin, discontinuous clay intercalations (Fig. 2b). Bioclastic components are mainly coralline algae (fragments and small rhodoliths) and small coral fragments, the latter frequently coated by coralline algae and encrusting foraminifera. The matrix is a marly wackestone/packstone (Fig. 2c) with fragments of echinoids, small concentrations of *Polystrata* sp. crusts, often showing hooked, hollow or foliose growth-forms (sensu Woelkerling et al., 1993), calcareous sponges, miliolid foraminifera, fragments of molluscs, bryozoans and rare dasycladacean algae. Within the coralline rudstone facies, the number of coral fragments increases from about 10 meters from the base of the section, with the initial appearance of scattered, ramose colonies in growth position that upward give way to more distinct, larger coral thickets.

- Bentonite layers: laterally continuous, planar clay layers of 5 to 15 cm in thickness (Fig. 2d-e). Bioclasts are mainly represented by miliolids, fragments of echinoids, ostracods and spicules. Very small fragments of volcanic glass have been also observed. XRPD analyses show that the facies contains mainly calcite, clay minerals (smectite, illite, chlorite and kaolinite) and quartz, with a minor amount of pyrite (Fig. 5a). XRPD patterns (Fig. 5b) reveal that smectite is the main group of clay minerals that characterises these deposits.

- Marly mudstone: planar beds up to 1.8 m in thickness (Fig. 2e) made of a compact, sometimes finely-laminated marly mudstone (Fig. 2f) with sparse bioclasts mainly represented by miliolids and coralline algae.

- Coral thickets: the facies is characterised by in situ coral colonies arranged in discontinuous, superimposed patches, each up to 20-50 cm thick and several meters wide. Coral thickets are covered by thin clay intervals (Fig. 2g) similar to those within the coral rudstone. The coral assemblage (Fig. 2h-j) is dominated by ramose *Actinacis rollei* Reuss, 1864 and phaceloid *Caulastraea*, especially *C. tenuis* (Reuss, 1868), with colonies up to 30 cm in size. Other corals, such as *Goniopora nummulitica* (Reuss, 1864) and *Astreopora tecta* (Catullo, 1856) are present but rare. Coral sticks are often coated by thin coralline algae and foraminiferal crusts. The matrix is a fine-grained marly limestone, with a prevalent mudstone-wackestone texture (Fig. 2k). Bioclasts are fragments of echinoderms, calcareous sponges, bivalves, gastropods, miliolid foraminifera, coralline algae, bryozoans, rare dasycladacean algae, and *Gypsina*. Coral thickets pass laterally into coralline rudstones.

Interpretation - The stratigraphic arrangement of the identified facies suggests cyclical changes of controlling factors. We identified four main cycles, each starting with a marly mudstone followed by coralline rudstone and coral thickets facies (Fig. 2a). Considering the marly mudstone, the large amount of clay within this facies most probably derives from the alteration and erosion of Paleocene-Eocene volcanic rocks that cropped out in the mainland areas. Clay minerals were transported to the sea and deposited into a calm, shallow-water environment, as suggested by the occurrence of miliolids. This process must have been fully effective during lowstand phases, that controlled the periodic progradation of terrigenous-rich sediments in the Castelgomberto area. The deposition of the marly mudstone was followed by transgressive/highstand phases, accompanied by an increase of the hydrodynamic energy. This is testified by the sedimentation of the coarser, grain-supported coralline rudstone facies and by the colonisation of corals, as isolated colonies or grouped into coral thickets. In comparison to the marly mudstone, coralline rudstone and coral thickets facies may have developed in a slightly deeper setting, but always within the euphotic zone, as indicated by the presence of dasycladacean algae and by the occurrence of hollow, hooked and foliose *Polystrata* sp. crusts in the coralline rudstone. These types of growth-forms are usually associated with seagrass beds. Algal crusts develop on the surface of stems and leaves of seagrass (Beavington-Penney et al., 2004; Sola et al., 2013) that thrive in shallow-water, euphotic settings (e.g., Larkum et al., 2006; Mateu-Vicens et al., 2010). Despite the relatively high hydrodynamic conditions, coralline rudstone and coral thickets facies are associated with a considerable amount of clay, represented by thin intercalations (Fig. 2b, g) and by marly micrite that accumulate among the in situ coral colonies (Fig. 2k). This indicates how these facies were developing in a relatively proximal environment, under the influence of terrigenous inputs. The occurrence of a turbid environment is also suggested by the coral assemblage, which is dominated by *Actinacis rollei* (Fig. 2h), a pioneer, sediment resistant genus (Frost, 1981), and by the prevalent ramose growth-forms (Fig. 2i, l), interpreted as an acclimatisation to muddy, turbid-water conditions (Bosellini & Trevisani, 1992; Bosellini & Stemann, 1996; Sanders & Baron-Szabo, 2005). The clay layers covering the coral thickets (Fig.

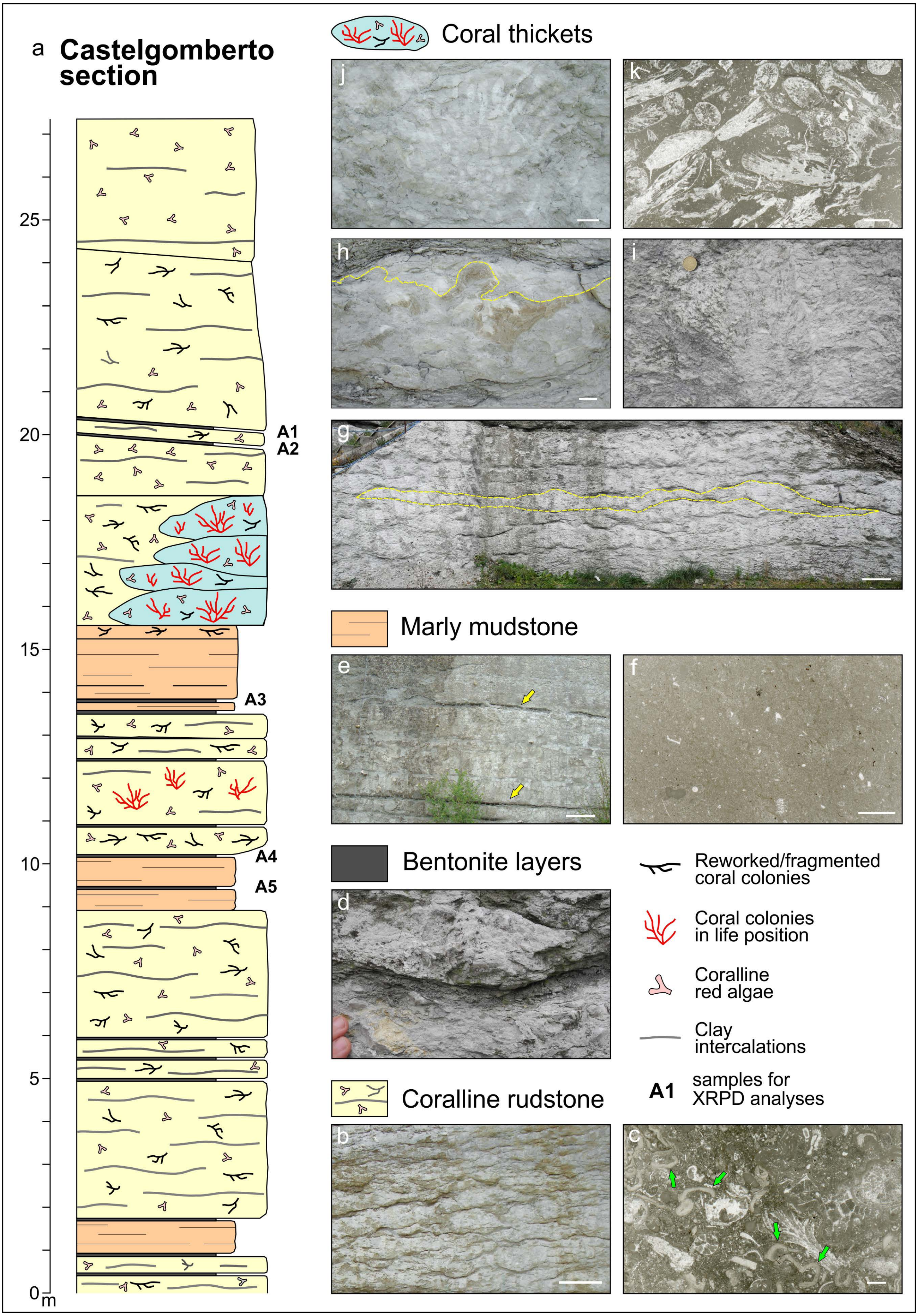
a Castelgomberto section
25
20
15
10
5
0 m
A1
A2
A3
A4
A5
Coral thickets
j
k
h
i
g
Marly mudstone
e
f
Bentonite layers
d
Coralline rudstone
b
c
Reworked/fragmented coral colonies
Coral colonies in life position
Coralline red algae
Clay intercalations
A1 samples for XRPD analyses

Fig. 2 - (color online) Castelgomberto outcrop. a) Stratigraphic column. b) Coralline rudstone facies, outcrop view showing clay intercalations among the bioclastic deposits, scale bar = 50 cm. c) Coralline rudstone facies, wackestone/packstone matrix in thin section; arrows indicate *Polystrata* sp. crusts with hooked growth form, scale bar = 2 mm. d) Bentonite layers facies, outcrop close-up. e) Marly mudstone facies with two bentonite layers (arrows), scale bar = 50 cm. f) Marly mudstone facies, mudstone texture in thin section, scale bar = 5 mm. g) Coral thickets facies, coral thickets separated by thin clay intercalations; dashed lines trace one of the coral thickets, scale bar = 50 cm. h) Coral thickets facies, *Actinacis rollei* colony with short, vertical branches (dashed line), scale bar = 1 cm. i-j) Coral thickets facies, phaceloid *Caulastraea* colonies, scale bar = 1 cm. k) Coral thickets facies, thin section showing floatstone with *Caulastraea* fragments, scale bar = 5 mm.

2g) suggest periodic mass accumulations of terrigenous sediments eventually causing the death and burial of the corals. Concerning the bentonite layers, the prevalence of smectite among the clay minerals (Fig. 5b), as well as the occurrence of fragments of volcanic glass, indicate their origin as directly related to eruption events (Cuadros et al., 1999; De la Fuente et al., 2000; Christidis & Huff, 2009). During the Rupelian, the supply of pyroclastic material in the Lessini Mountains can be associated with the volcanic activity located in the Euganei Hills, an area about 40 km SE from the Castelgomberto outcrop (Borsi et al., 1969; Brombin et al., 2019). At least 14 of these events are registered along the studied section (Fig. 2a), which probably had severe consequences for the survival of the communities. However, the presence of miliolids, ostracods and echinoids within these layers suggests a relatively fast recolonisation of the sea floor after each volcanic episode.

Bastia

Although the diverse coral assemblage of the Bastia section has been already studied, with the description of 16 genera and 20 species (Bosellini, 1988), a detailed facies analysis has never been performed. Here we identify three main facies (Fig. 3):

- Coral floatstone: stratified deposits with an overall thickness of 1.7 m, characterised by abundant fragments of *Caulastrea tenuis*, *Actinacis rollei* and *Astreopora* ramose colonies that accumulated parallel to the stratification (Fig. 3b). Fragments of coral sticks show an average diameter of about 1 cm and are frequently coated by coralline algae

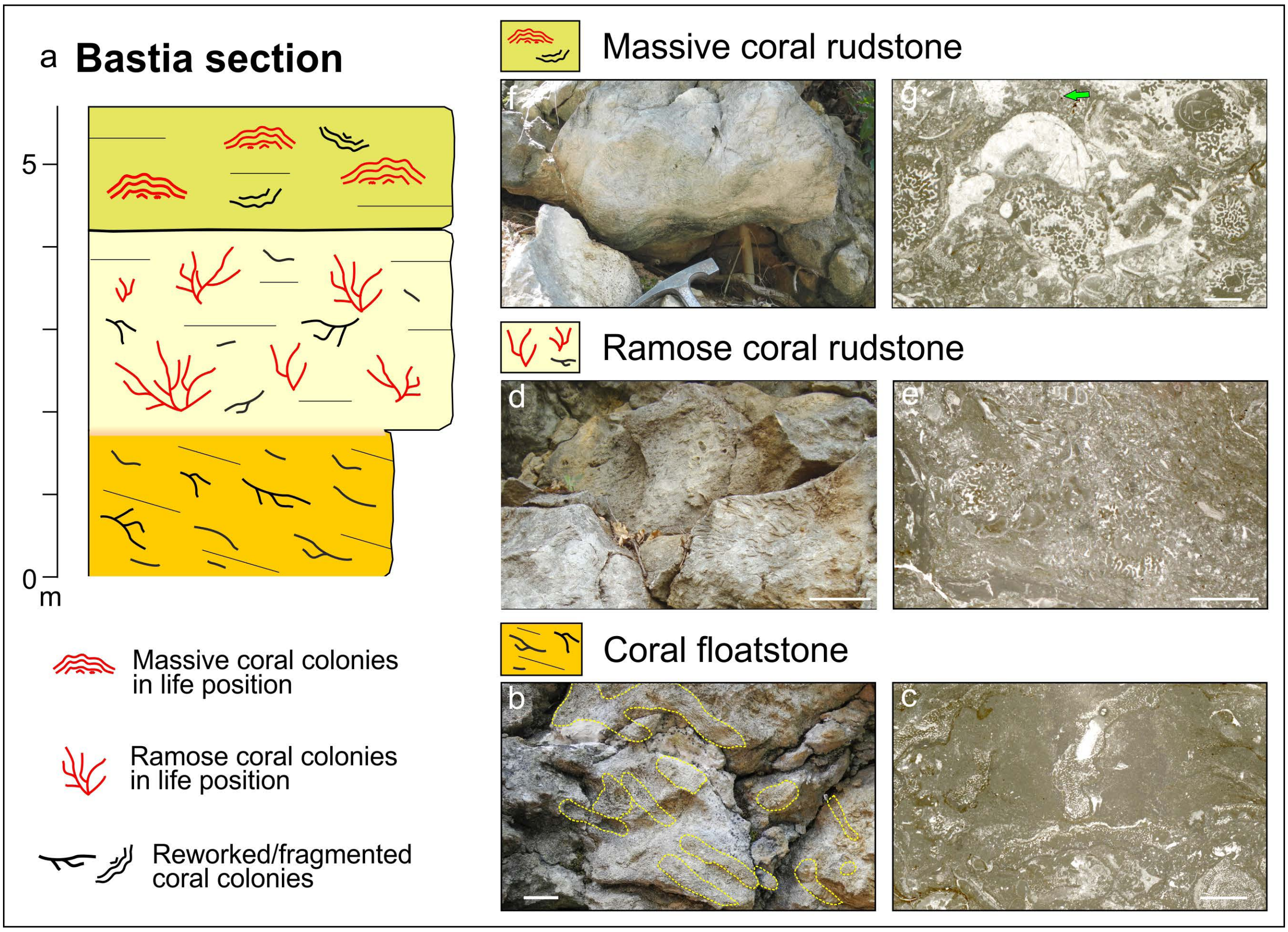

Fig. 3 - (color online) Bastia outcrop. a) Stratigraphic column. b) Coral floatstone facies, outcrop view; dashed lines outline the iso-oriented fragments of coral sticks, scale bar = 1 cm. c) Coral floatstone facies in thin section with numerous fragments of *Actinacis*, scale bar = 5 mm. d) Ramose coral rudstone facies, outcrop view with *Caulastraea* colonies in life position, scale bar = 10 cm. e) Ramose coral rudstone facies, packstone-wackestone matrix in thin section, scale bar = 5 mm. f) Massive coral rudstone facies, outcrop view with a globose *Variabilifavia* colony in life position. g) Massive coral rudstone facies in thin section; arrow indicates a dasycladacean algae, scale bar = 5 mm.

and encrusting foraminifera. The matrix is a mudstone (Fig. 3c) with fragments of coralline algae, echinoids and bryozoans.

- Ramose coral rudstone: with a gradual transition, the coral floatstone passes into an up to 2.4 m thick coral rudstone with massive appearance. Several colonies are preserved in growth position with prevailing ramose and phaceloid growth-forms (20 cm of average width and 20-35 cm in height) (Fig. 3d). *Actinacis rollei*, *Caulastrea tenuis* and other corals belonging to the genera *Acropora*, *Goniopora* and *Astreopora* are the main representatives of the coral assemblage. A minor amount of meandroid colonies, identified as *Variabilifavia,* has also been observed. In situ colonies are scattered in the sediment and associated with toppled specimens and coral rubble, thus not forming a compact framework. The rudstone matrix is a packstone-wackestone (Fig. 3e) with fragments of coralline algae, corals and minor amounts of bryozoans, miliolids, echinoids and molluscs.

- Massive coral rudstone: a sharp transition connects the ramose coral facies with coral rudstone deposits, which attain up to 1.5 m in thickness. Although mostly rudstones, massive and globose coral colonies in growth position occur in this facies (Fig. 3f). The coral assemblage, with colonies up to 50 cm in maximum diameter, is dominated by *Actinacis rollei*, associated with less common *Antiguastrea lucasiana* (Defrance, 1826) and corals belonging to the genera *Acropora, Astreopora* and *Hydnophyllia.* Although corals grew in close contact, they did not form an extensive framework. Toppled and fragmented colonies are also frequent. The matrix is a packstone (Fig. 3g) with abundant coral fragments, miliolids and rotaliid foraminifera, coralline algae, echinoids, and fragments of molluscs; *Polystrata* sp. and dasycladacean algae are also present.

Interpretation - The stratigraphic arrangement of the three Bastia facies point to a prograding, shallowing-upward depositional system. The lack of clay or marly sediments suggests development in a relatively distal setting. The basal coral floatstone can be associated with a calm, relatively deep environment, where fragments of coral sticks accumulated forming mud-supported deposits. Size and shape of these fragments, belonging to the genera *Actinacis*, *Caulastrea* and *Astreopora*, indicate their origin from the breakage of branching coral colonies that characterise the overlying ramose coral rudstone. The coral rudstone contains common miliolids, which suggests shallow water depth. Moderate wave exposure is supported by the prevalence of delicate, ramose growth forms of corals. The massive coral rudstone at the top of the section can be ascribed to very shallow water depths on the basis of an increase of miliolids and by the presence of dasycladacean algae. High-energy conditions are here indicated by the texture of the sediment and by the prevailing massive shapes of the coral colonies. In summary, the Bastia outcrop can be interpreted as a distal patch reef that grew on a topographic high in the Rupelian lagoon. In comparison to the Castelgomberto locality, this setting allowed the development of a more diverse coral fauna with larger colony sizes.

Lumignano

Despite the strong karstic overprint, two different facies could be distinguished at Lumignano:

- Coral framestone: the facies is represented by several meters wide areas occupied by a dense framework of massive-globose coral colonies (10-70 cm in width, 10-35 cm in height) (Fig. 4a, c-d), with a minor amount of branching growth-forms. Most of these corals are preserved in growth position (59%), while the rest are tilted (22%) or fragmented (19%) (Fig. 4b). The most

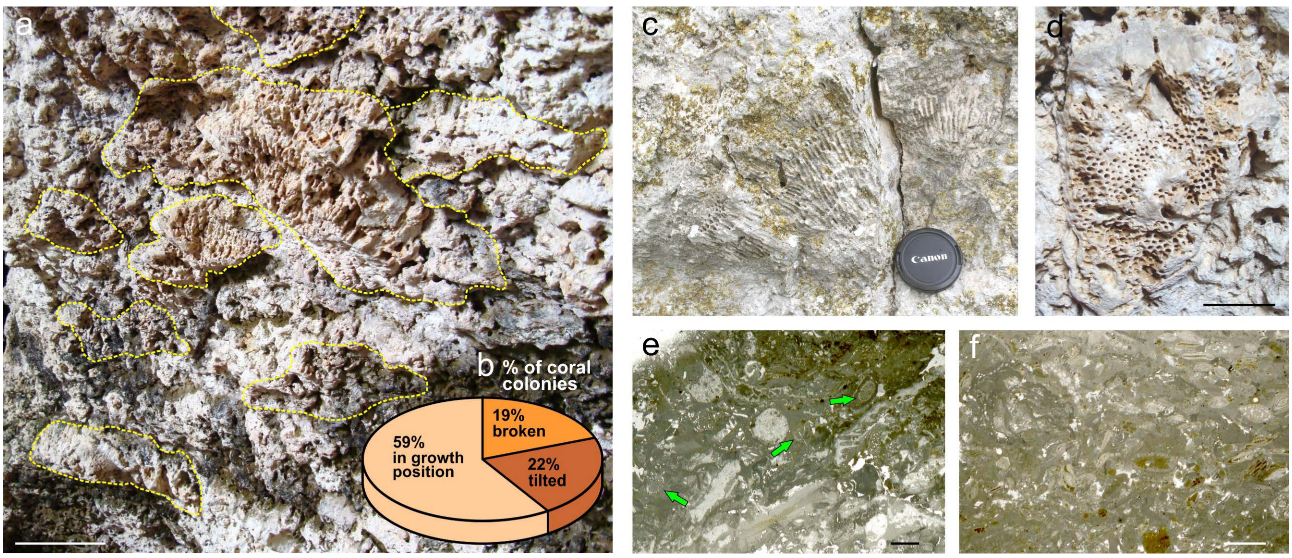

Fig. 4 - (color online) Lumignano outcrop. a) Coral framestone facies, outcrop view showing massive coral colonies in growth position, scale bar = 20 cm. b) Coral framestone facies, percentage of corals preserved as colonies in growth position, broken or tilted. c-d) Coral framestone facies, outcrop close-up of massive coral colonies, scale bar = 5 cm. e) Coral framestone facies, thin section of the rudstone deposits among the coral colonies, arrows indicate fragments of dasycladacean algae, scale bar = 2 mm. f) Coralline and bryozoan rudstone facies, microfacies assemblage in thin section, scale bar = 2 mm.

common coral taxa are *Actinacis rollei*, *Antiguastrea lucasiana* and coral colonies belonging to the genus *Montastraea.* A coarse coral rudstone can be found among the coral colonies in growth position and in close proximity of the framework. The matrix is a packstone (Fig. 4e) with abundant coral fragments associated with coralline algae, frequently represented by foliose growth-forms. Fragments of echinoids, bryozoans, molluscs, small nummulites and dasycladacean algae are also common.

- Coralline and bryozoan rudstone: the facies is found between the coral framework. Prevalent are coralline algae (foliose fragments and small rhodoliths) and bryozoans. Small nummulites, echinoids, miliolids, brachiopods, and coral fragments are associated. Micrite is present (Fig. 4f).

Interpretation - The extensive development of coral reef framework with massive corals leads us to interpret this facies as a coral reef rimming the Lessini Shelf. In situ, massive-globose colonies in close contact formed a wave-resistant framework that developed in a high-energy, euphotic environment, as testified by the abundant miliolids, the presence of dasycladacean algae and the foliose growth-forms of many coralline algae fragments. The occurrence in the nearby areas of rudstone deposits rich in coralline algae and bryozoans can be explained with the possible influx of nutrient-rich waters. The presence of a NE/SW oriented fault called Riviera dei Berici (Piccoli et al., 1976; Márton et al., 2011), bordering the southwestern side of the Berici Hills and passing close to the Lumignano locality, represented a sharp boundary during the Rupelian, which separated the southwestern margin of the Lessini Shelf from much deeper environments (Fig. 1a). Upwelling currents may have flowed from these deep areas, periodically affecting the Lumignano coral margin.

THE CASTELGOMBERTO LIMESTONE FM. DEPOSITIONAL SYSTEM

The position of the three studied localities within the Lessini Shelf (Fig. 1b) allows to trace a NE-SW oriented transect across the Castelgomberto Limestone Fm. depositional system. As already pointed out by previous authors (Geister & Ungaro, 1977; Frost, 1981), one main issue in the interpretation of the Castelgomberto Limestone Fm. is the impossibility of direct stratigraphic correlations among the different outcrops, that could not be synchronous and thus reflecting different time intervals and conditions in the depositional history of the platform. Frost (1981) however, identified a strong uniformity within the lower Oligocene carbonates of the SE Lessini and within those of the central-NW Berici. He suggested that the Castelgomberto Limestone Fm. lagoon developed within a relatively stable depositional environment throughout the existence of the barrier reef. For this reason, it seems appropriate to consider the three sections selected in the present study as representative of the environmental conditions during most of the Castelgomberto Limestone Fm. depositional history, from the innermost, proximal areas (Castelgomberto) to the most distal setting (Lumignano) (Fig. 6).

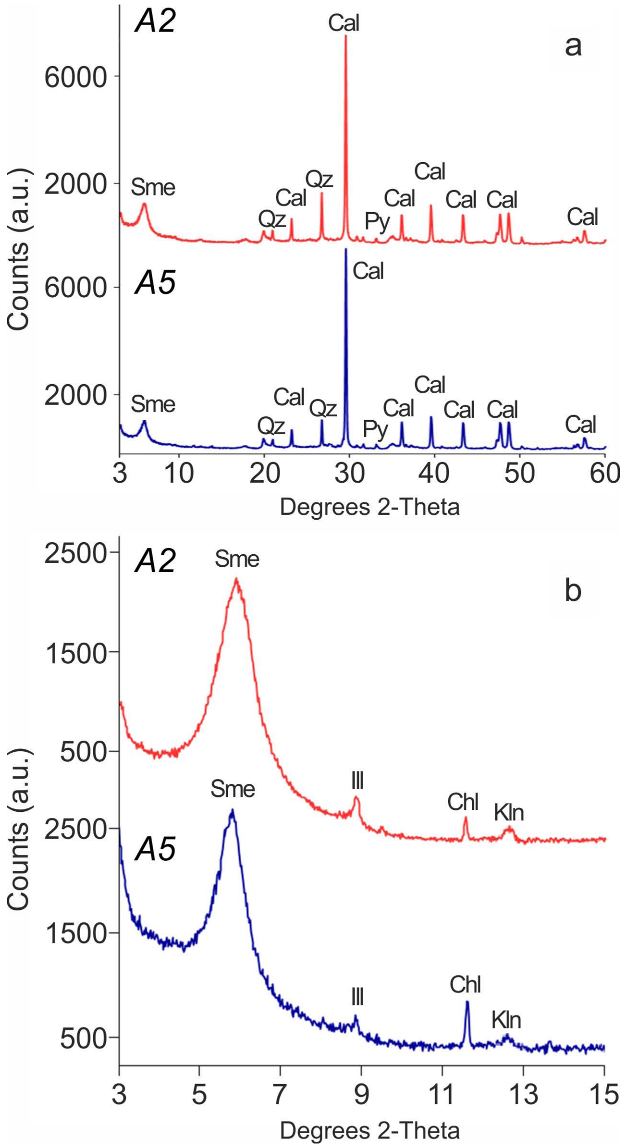

Fig. 5 - (color online) X-ray powder diffraction (XRPD) patterns of the two clay samples collected from Castelgomberto. a) XRPD patterns of the air dried and randomly oriented samples. b) Selected ranges (3-15 degrees 2-Theta) of the XRPD patterns of the orientated samples. Sme = smectite, Qz = quartz, Cal = calcite, Py = pyrite, Ill = illite, Kln= kaolinite and Chl = chlorite.

Depth

Information on the depth of the depositional system is provided by the occurrence of light-dependent organisms and porcelaneous foraminifera throughout the transect. The presence of dasycladacean algae and abundant miliolids in the coralline rudstone and coral thickets of Castelgomberto, in the massive coral rudstone of Bastia, and in the coral framestone of Lumignano, indicate a very shallow-water setting for all these facies. The same conclusion is provided by the *Polystrata* sp. crusts within the coralline rudstone of Castelgomberto, whose shapes can be associated with seagrass beds.

Turbidity

Evidence of high turbidity are limited to the Castelgomberto outcrop and can be attributed to clay influx

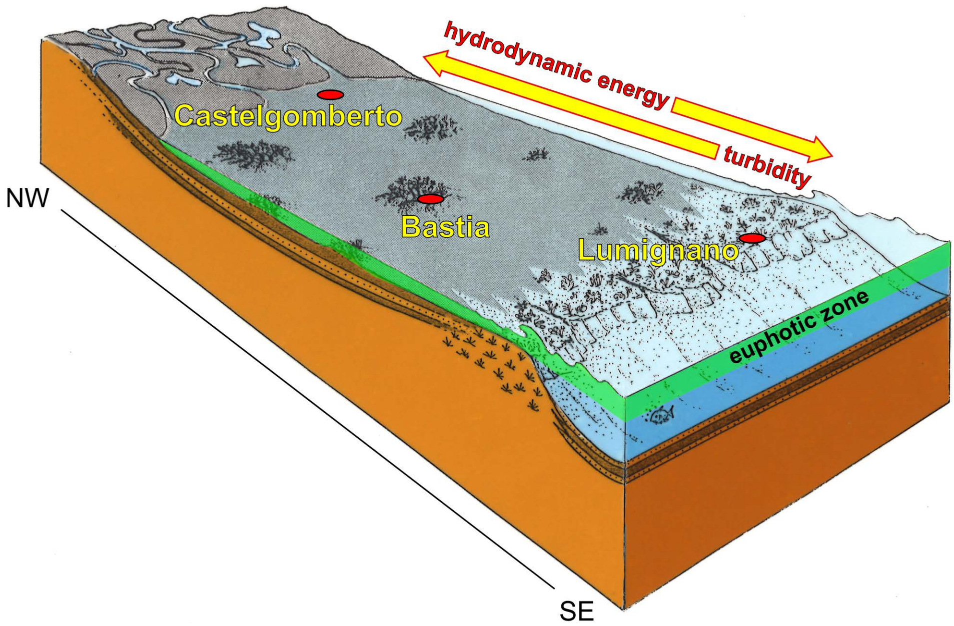

Fig. 6 - (color online) Reconstruction of the Castelgomberto Limestone Fm. depositional system with the position of the investigated sections and the variations of the main environmental stressors along the identified transect (modified from Bosellini & Trevisani, 1992).

from the mainland. These conditions were particularly strong during sea-level lowstand phases, represented by the marly mudstone facies, during which coral colonies were absent. Terrigenous sedimentation was active also during transgressive/highstand phases, affecting the coral assemblage and leading to the dominance of ramose growth-forms in the coral thickets facies. Terrigenous influx was still present but probably more episodic in the coral thickets facies. However, turbidity was not high enough to prevent coral and algal growth.

Hydrodynamic conditions

Changes in the sedimentary features indicate a progressive increase of hydrodynamic energy from the more proximal areas towards the margin of the Lessini Shelf in the Berici Hills. While the matrix of the coralline rudstone and coral thickets in Castelgomberto contains a considerable amount of clay and micrite (from wackestone/packstone to packstone/wackestone), the quantity of micrite decreases in Bastia, where the matrix of the massive coral rudstone is represented by a packstone. The sediment within the most distal coral framestone at Lumignano is characterised by a coarser rudstone with a packstone matrix. This trend in hydrodynamic conditions is also confirmed by the changes of the coral assemblages along the considered transect. In Castelgomberto, the delicate, ramose colonies are chiefly a response to high levels of turbidity but at the same time they could not have endured the impact of strong waves and currents. To the contrary, the sparse, massive colonies at the top of the Bastia patch reef are more adapted to higher energy conditions, and the Lumignano coral framestone, made of massive, in situ colonies, suggests intense hydrodynamic levels, typical of a rimmed shelf facing the open sea.

Oxygen and salinity

The highly diversified biotic assemblages that characterise all the considered outcrops indicate normal marine conditions throughout the whole depositional system. During transgressive/highstand phases, even the most proximal environment (Castelgomberto outcrop) displays a rich and diversified association that can be related to open circulation. The only exception is represented by the marly mudstone facies at Castelgomberto, which we ascribe to lowstand depositional phases, during which possible freshwater inputs may have contributed to the scarcity of fossil remains.

CONCLUSIONS

Comparing the results of the present study to the previous interpretations of the Castelgomberto Limestone Fm. (Tab. 1), three main aspects should be highlighted that improve the understanding of its depositional setting:

1. A barrier reef along the SE Berici margin. This interpretation has two issues; first, the coral framework is not particularly dense and continuous. There are larger areas with just rudstones and few corals. This observation led Geister & Ungaro (1977) to doubt the presence of a true barrier reef in Lumignano. Second, the presence of micrite, dasycladacean algae and miliolid foraminifera is not typical for a wave-swept barrier reef system. Following Geister & Ungaro (1977), we propose that the facies exposed at the Berici Hills represents the proximal back reef environment of the proper barrier reef that may have been destroyed by tectonic activity and weathering.

2. The presence of euphotic facies throughout the identified transect, from the SE Lessini to the SE Berici Hills, suggests the occurrence of a very shallow-water setting, without significant changes of the water depth.

3. Sedimentological and paleontological evidences point to a progressive increase of hydrodynamic energy from the proximal portions towards the most distal areas of the Lessini Shelf.

Features 2 and 3, as well as the presence of a distal framework, support the reef-lagoon model (Fig. 6) originally proposed by Frost (1981), whereas they are inconsistent with the interpretation of a low-angle ramp system with scattered coral colonisations limited to the meso-oligophotic zone. Considering the fundamental criteria reported in Flügel (2004) for the definition of a carbonate ramp setting, a ramp is a gently dipping sea-floor surface with progressive downslope transition from shallow-water, high-energy deposits to deeper-water, lower-energy sediments and finally to basinal, muddy deposits. A ramp geometry would thus predict for the Castelgomberto Limestone Fm. the occurrence of the shallower facies limited to the most landward portion, and a gradual deepening towards the basin, associated to a progressive decrease of the hydrodynamic conditions, which is clearly not the case.

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