Geometry and stratigraphic relationships of lower Oligocene coral reefs in Lumignano (Berici Hills, northern Italy)

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ABSTRACT

The Cliffs of Lumignano (Northern Italy) are a renowned climbing area, set on the steep walls of lower Oligocene limestones of the Castelgomberto formation which are made mainly of coral boundstone. Lumignano lies approximately on the south-eastern margin of a Cenozoic carbonate platform known as the Lessini Shelf, but the depositional environment of coral reefs is still debated, and it is unclear whether it was a Caribbean-type carbonate platform with a lagoon and steep slope, or a carbonate ramp with coral reefs on the mid ramp. We produced a geological map of the Lumignano area, in which five lithofacies are distinguished and mapped within the Castelgomberto formation. Their spatial distribution and main sedimentological characters outline that landward of coral reefs, a high-energy environment was present and was shallower than the reefs. Seaward of coral reefs, coralline algae and marlstones with bryozoans occur, while no evidence of a slope made of coral rubble was found. Hence, the detailed geological mapping and the documentation of the stratigraphic relationships between lithofacies provided a valuable contribution to the understanding of depositional environments of the lower Oligocene Lessini Shelf. This work also suggests elements for a better definition of the Castelgomberto formation, which could be split in members or lithofacies that can be mapped at a reasonably large scale (1:10000). The coralline algal lithofacies of the Castelgomberto formation is locally indistinguishable from the analogous facies of the underlying Priabona formation, but the boundary between these two units is always marked by an unconformity, which is easy to identify and may be used for the lithostratigraphic definition of the Castelgomberto formation.

KEY-WORDS: Southern Alps, Oligocene, carbonate ramp, coral reef, geological mapping.

INTRODUCTION

The main carbonate unit of the Berici Hills in the Province of Vicenza is the lower Oligocene Castelgomberto formation, a limestone deposited in shallow-water marine environments. In Italy, lithostratigraphic units are being re-defined as they are met in a new geological map at scale 1:50000, and a entry is then added, with a full description of the unit based on literature and new field observations, in a specific publication of ISPRA (I Quaderni, Serie III, downloadable for free at https://www.isprambiente.gov.it/it/pubblicazioni/periodici-tecnici/i-quaderni-serie-iii-del-sgi). The outcrop area of this unit is included in four sheets of the Geological Map of Italy at scale 1:50000: 102-Valdagno, 103-Schio, 125-Vicenza and 146-Este. None of these has been realised yet, and, as a consequence, no formal description of the Castelgomberto formation is available to date.

Overall, the lower Oligocene Castelgomberto formation is made of limestones, but it is far from being uniform, and in fact, it has been found to include a variety of facies (e.g., Frost, 1981; Bosellini & Trevisani, 1992; Pomar et al., 2017). One facies stands out however, for having often been the object of palaeontological and palaeoenvironmental studies: coral boundstones, which mostly occur in Lumignano but are also found extensively in all the Berici

Hills and Eastern Lessini Mountains (e.g., Geister & Ungaro, 1977; Ungaro, 1978; Frost, 1981; Bosellini et al., 2020). The outcrops with fossil corals at Lumignano are considered to be at the south-eastern margin of a Cenozoic structural high and carbonate platform known as the "*Lessini Shelf*" (Bosellini, 1989).

There is a debate about the palaeoenvironmental significance of these lower Oligocene coral reefs, and about the depositional geometry of the carbonate platform that hosted it.

According to Geister & Ungaro (1977), coral colonies in the boundstone outcrops of Lumignano seldom form a rigid framework, and they found no evidence of a significant relief above the surrounding sediments. The depositional environment in the early Oligocene at Lumignano did not include a barrier reef, but rather implied a gently inclined surface – a ramp – on which coral reefs formed sparse patch reefs or mounds. This interpretation implies that the area beneath the coral reefs was not protected from the action of waves, and that there should not be a slope in front of the coral reefs.

Similar conclusions were reached independently by analysing the palaeoecology of larger foraminifera and coralline algae in the nearby section of Longare, which is located some hundred metres seaward with respect to the outcrops with *in situ* corals at Lumignano. According to Nebelsick et al. (2013), all facies associations along this ca. 100-m-thick section were deposited within the photic zone, and should be interpreted as being formed on a homoclinal ramp rather than a rimmed shelf.

Pomar & Haq (2016) and Pomar et al. (2017) studied a coeval, ca. 50 m thick section near Castelgomberto, around 20 km to the NW of Lumignano, on the Lessini Shelf. Also in this case, the lower Oligocene deposits were interpreted as being formed on a homoclinal ramp, based on the integrative analysis of biotic associations and lithofacies.

Instead, Frost (1981) suggested that the coral reefs of Lumignano formed a relatively continuous barrier, which was enclosing a protected lagoon on the north-west. The depositional system was compared to that of present-day Caribbean Islands, which implies relatively low water energy north-west of the barrier, and the existence of a slope on the south-east, ideally made of gravel derived from the wave erosion of the barrier coral reefs.

A major fault is known to be present at the foot of the hills of Lumignano (Benvenuti & Norinelli, 1967). It is a high angle tectonic lineament with a ca. NNE-SSW direction, known as "*Faglia della Riviera Berica*". It was likely a normal fault in the Cenozoic, subsiding the block east of Lumignano, while its last activity was inverted and uplifted the eastern block. Frost (1981) observed that slope facies were indeed not found in the field, but explained their absence with physical erosion, for the portion on the western block of the fault, and elision by tectonics for the eastern block, which is now mostly covered by alluvial and colluvial deposits of the Venetian plain. This palaeoenvironmental reconstruction was later considered valid by several authors, including Club Speleologico Proteo (2003) and Bosellini et al. (2020).

These competing hypotheses should imply major differences in palaeoenvironment, and hence, in mappable facies associations and their arrangement in space. If a barrier reef existed in a Caribbean-type setting, then a (relatively) low-energy lagoon should have formed landward of the reefs, and a slope, made of coral rubble, should have been present seaward. If instead the depositional setting was that of a carbonate ramp with coral mounds, the deposits beneath the reefs should have been exposed to wave energy, and seaward of the reef, no slopes should be observed, but rather a succession of facies belts with decreasing proportions of light-dependent organisms should be found. In this work, we put these competing hypotheses to the test with geological mapping.

We present a geological map, at 1:10000 scale, of the most seaward portion of the lower Oligocene Lessini Shelf, which crops out at Lumignano and Costozza. In this map, those lithofacies that could be readily distinguished in the field were separated, and their lateral stratigraphic relationships were used to provide an interpretation of the depositional profile at the south-eastern margin of the Lessini Shelf.

STUDY AREA

The area of Lumignano is located in North-eastern Italy (Fig. 1), on the eastern flanks of an isolated group of hills topped by a karst plateau with maximum elevations of slightly more than 400 m a.s.l., the Berici Hills, that is surrounded by alluvial plains (Sauro in Club Speleologico Proteo, 2003, p. 25). It is best known as a climbing area, where climbing has been performed for decades on natural cliffs up to 60 m tall. Both Lumignano and Costozza villages belong to the municipality of Longare, which has a population of less than 10000.

The area has a long record of geological studies (e.g., Arduino, 1760; Catullo, 1841; Fabiani, 1902; 1908; 1911a, b; 1915). Costozza and Lumignano were also referred to in the treatise of architect Vincenzo Scamozzi "*L'idea dell'architettura universale*" (Scamozzi, 1615), because of the occurrence of quarries of Vicenza stone. In its Four Books of Architecture, Palladio (1570) used the term "*pietra tenera*" (i.e., soft stone) for dimension stones quarried in Oligocene limestones near Vicenza, and identified the building stones of bridges in the city of Vicenza as being from "*Costoza*". The underground limestone quarries in Costozza have been active since before the Roman times (Gleria, in Club Speleologico Proteo, 2005, p. 129). Vicenza stone has been mapped for this work (see geological map in the supplementary materials).

STRATIGRAPHIC SUCCESSION

The stratigraphic succession cropping out in the area is shown in Fig. 2. A upper Eocene to lower Oligocene shallow water carbonate succession crops out in the region, which is terminated by a major karst unconformity, probably of late Oligocene age; scanty and discontinuous quartz sand and gravel, possibly late Oligocene to Pliocene in age, occur locally above the unconformity (e.g., Fabiani, 1911b; Mietto, 2006; Rasser et al., 2008); layered volcanic tuff deposits are interbedded with the Oligocene limestones, and the upper Eocene-lower Oligocene carbonate succession is cut by volcanic dikes and eruption conduits, filled with basalts and intradiatremic breccia.

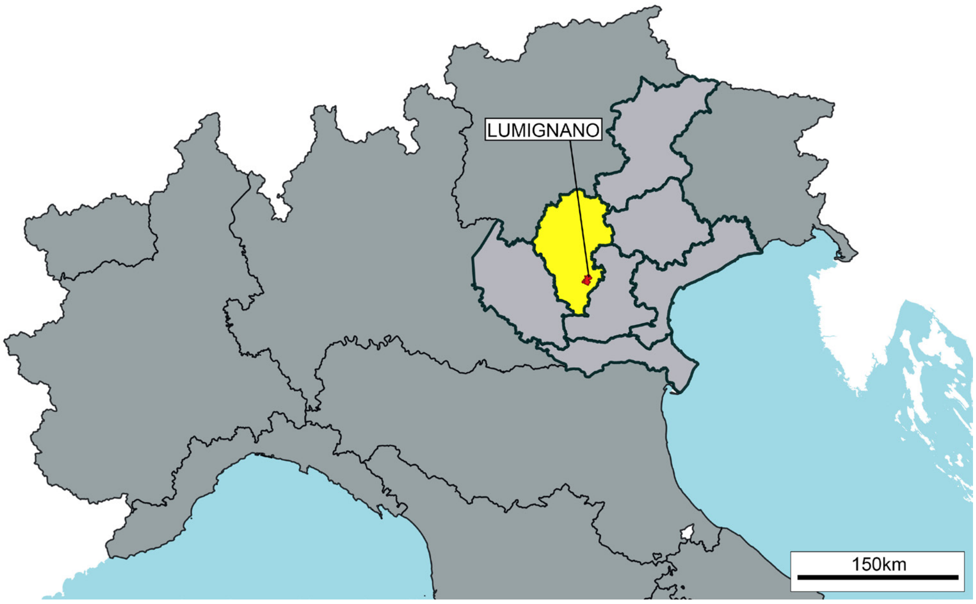

Fig. 1 - location of Lumignano in Northern Italy.

The lowest unit cropping out in the area is the late Eocene Priabona formation (Prm), which is likely lowest Oligocene at its top. It is made of poorly layered marls and marly limestones, blue-grey in colour, or yellowish on the weathered surface, with larger foraminifera, bryozoans and coralline algae (Fig. 3). Clay content decreases upwards. The lower boundary is sharp over nummulitic limestones, but it is not exposed in the mapped area. This unit crops out mostly at the foot of the hills and corresponds to relatively gentle slopes, covered with bush or wood (Fig. 4).

The lower Oligocene Castelgomberto formation (CC) lies above the Priabona formation, and is made of whitish to yellowish limestones with corals, coralline algae and foraminifera. Clay content is minimal in most of the outcrop area. Skeletal associations and bedding vary greatly (Fig. 5), but the lower boundary is always a sharp bedding joint (paraconformity) with the Priabona formation (Fig. 6 C, D). In the area around the village of Lumignano, the base of the Castelgomberto formation corresponds to the base of the cliffs. At Costozza, the base of the formation corresponds with a ca. 25 m thick horizon of porous, massive grainstone (Vicenza stone).

Within the Castelgomberto formation, horizons of volcanic tuff (VBt) are found at various stratigraphic positions (e.g., Mietto, 2006). These tuffs may reach some tens of m in thickness and are deeply altered, but their original fabric is still visible: they are made of altered basalt clasts (lapilli) from ca. 1 mm to 1 cm in size, forming fining upward beds with lamination. Limestone clasts, likely ripped up from the walls of volcanic conduits, are rare.

The sedimentary sequence is cut by volcanic conduits, the largest being ca. 400 m in diameter, filled by volcanic breccia (VBd). The elements of these breccias are fragments of vesicular basalt, and of limestone tear off from conduit walls, from less than 1 cm up to > 10 cm large. Breccias are cemented by calcite.

A few volcanic dikes, 2 m thick or less, also cut through the stratigraphic succession and are filled with deeply altered basalt (Fig. 6 B).

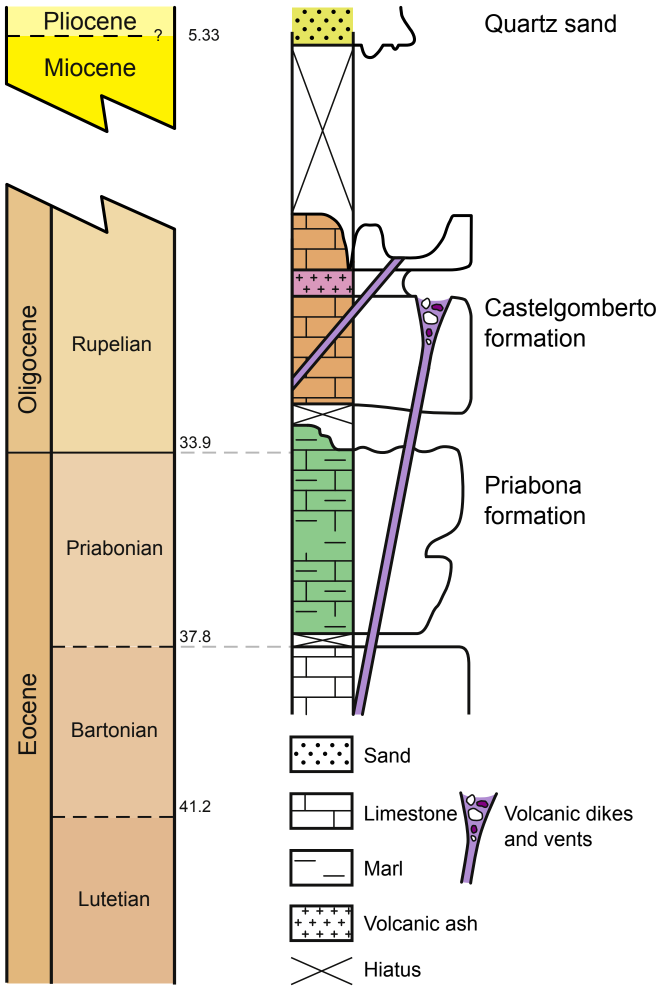

Fig. 2 - Stratigraphic scheme of the substrate units cropping out in the area. The age of quartz sands is speculative.

Quartz sand (Qs) is the youngest unit of the substrate, and it is only found in one outcrop at the bottom of a deeply incised doline in the upper corner of the map, above a karst unconformity. Here,

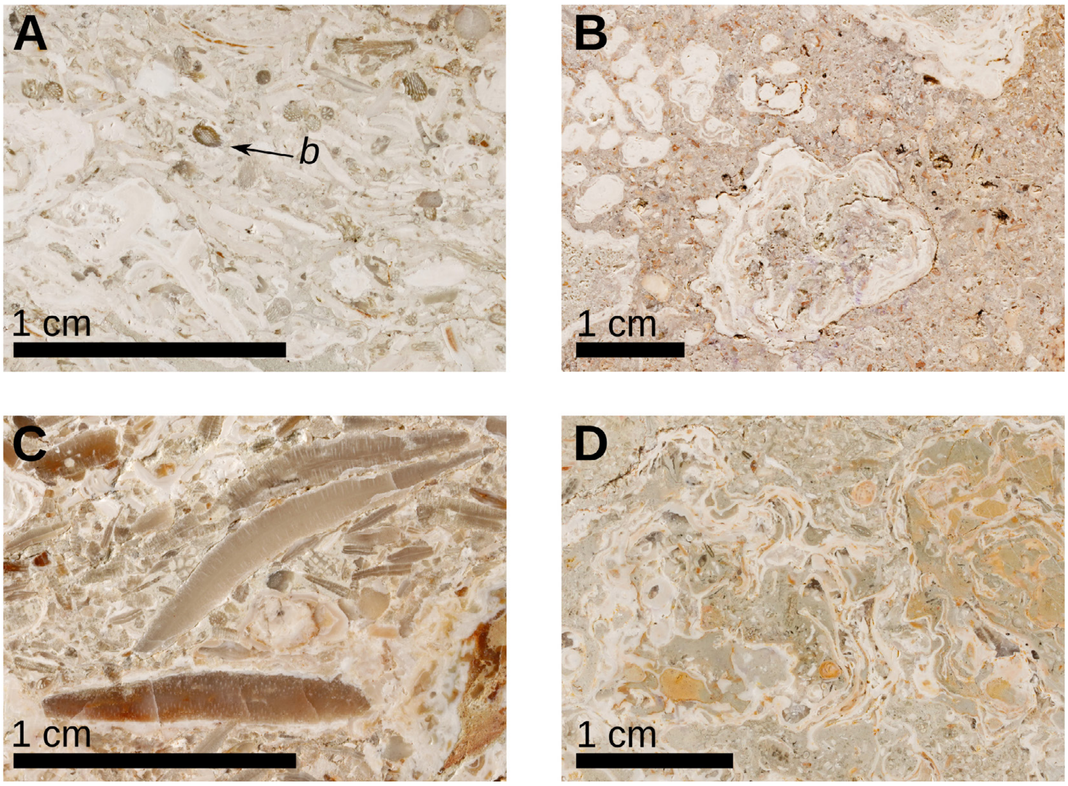

Fig. 3 - Lithofacies of the Priabona formation (Prm) in hand sample (polished slabs). A: Coralline algal packstone-rudstone with bryozoans (b). Sample Pvb 15 e. B: Floatstone with cm-scale rhodoliths. Sample Pg 26. C: Rudstone with larger foraminifera, mostly orthophragmininae. Sample Pg 14. D: Rhodolith rudstone. Sample Pg 16 g.

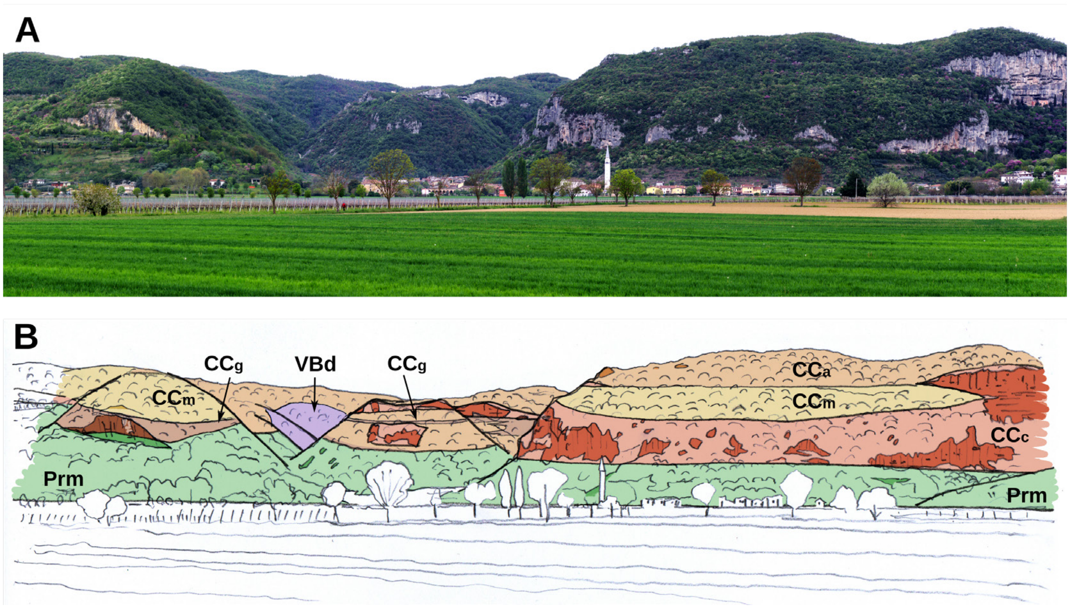

Fig. 4 - View of the eastern face of Berici Hills around Lumignano (A), with interpretation of the lithological boundaries (B). In the interpreted image (B), colours and abbreviations are the same as in Figure 2, main text and map (supplementary materials).

quartz sand has been the object of mining and has been almost totally removed. Quartz pebbles, which diameter is only seldom exceeding a few cm, are found sparse in soils all over the area and are probably residual remains derived from this unit.

Quaternary deposits were identified both on the karst plateau and on the plains. The main Quaternary unit on the plateau is made of *terra rossa* soil (TR) and colluvial deposits (CD) filling the dolines. A soil cover is present also on less inclined slopes, but it is seldom thicker than a metre and was not mapped. A few rockfall accumulations (Rf), at the base of some of the cliffs, could be instead mapped.

On the plains, most of the area is covered by colluvial deposits, made either by reworked *terra rossa* soil and/or poorly sorted gravel (Giandon et al., 2018). From the analysis of the micro-relief map (https://gaia.arpa.veneto.it/layers/territorio:geonode:microrilievopianura, accessed on September, 2022), a small portion of the area was detected, the farthest from the hills in the south-eastern side of the map, which lies at the foot of a small, blunt scarp. This part of the plain is made of deeply weathered alluvial deposits (AL), and the scarp was interpreted as a erosional fluvial scarp, bordering the most external boundary of the floodplain.

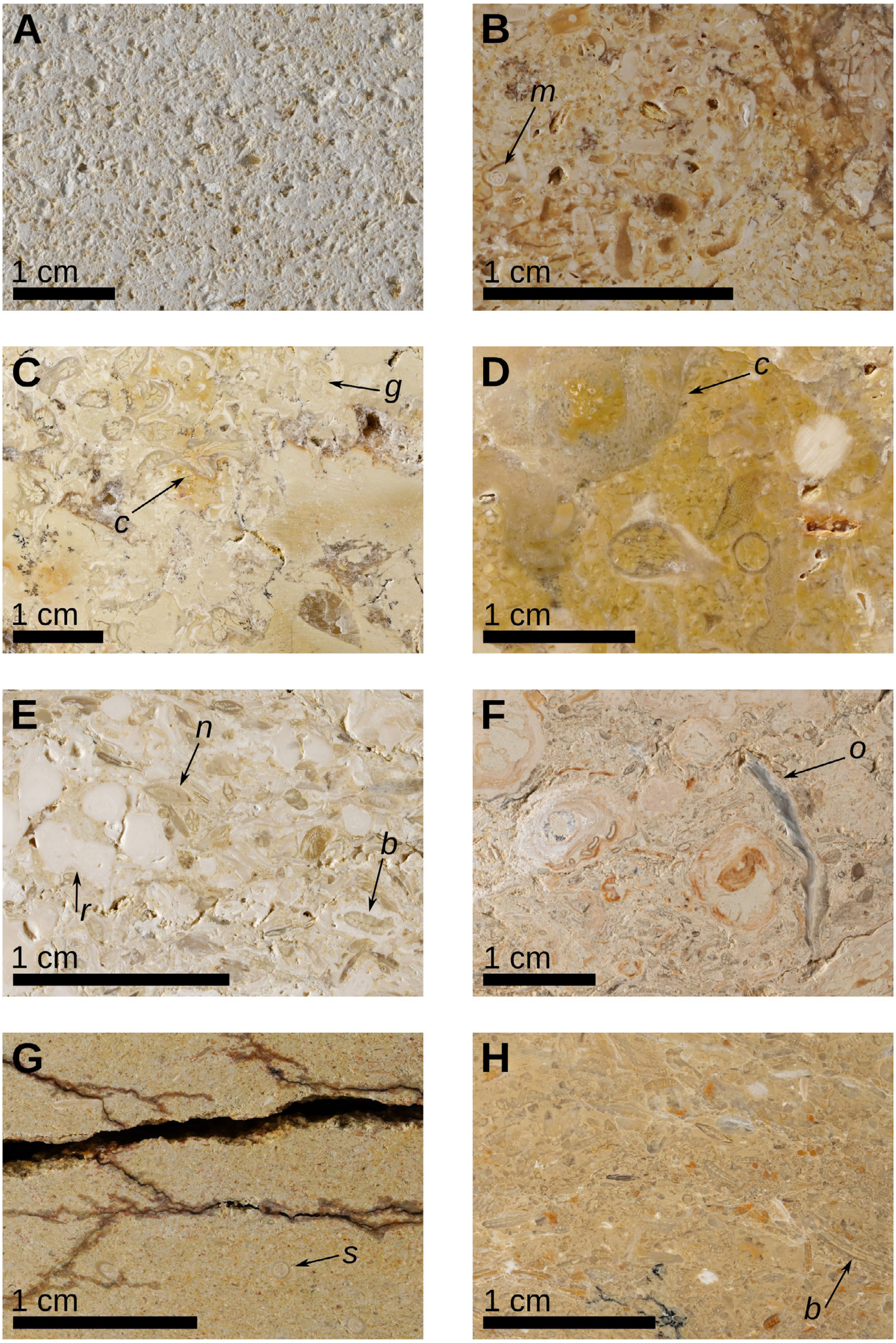

Fig. 5 - Lithofacies of the Castelgomberto formation in hand sample (polished slabs). A: Vicenza stone, CCg, (porous grainstone) from Ciole Quarry. B: layered grainstone – rudstone lithofacies, CCa: grainstone with poorly sorted fragmented skeletal grains and common miliolid foraminifera (m). Sample Pg 62. C: coral boundstone lithofacies, CCc: coral (c) boundstone with a wackestone matrix, which includes gastropods (g). Sample Gs 02. D: coral boundstone lithofacies, CCc: coral boundstone with a packstone matrix, which includes some massive corals (c). Sample Gs 13. E: coralline algal lithofacies, CCm: rudstone with branches of coralline algae (r), nummulitid larger foraminifera (n) and bryozoans (b). Sample Fcstb 42. F: coralline algal lithofacies, CCm: rhodolithic rudstone with a oyster shell (o). Sample Pg 69. G: marl and fine packstone lithofacies, CCo: fine packstone with serpulids (s). Sample Pg 57. H: marl and fine packstone lithofacies, CCo: packstone with dominant bryozoans (b). Sample Pg 66.

Fig. 6 - Some outcrop views of the study area. A: The interior of one of many caves around Lumignano (Grotta delle colonne, inventory n° 588 V Vi). B: The altered, subvertical basaltic dike of Cava Olivari, cut by a small high-angle fault in the middle. C: Cave and spring at the discontinuous boundary between the Priabona and Castelgomberto formations (Covolo and Sorgente Copacan). D: Close-up of the discomformable boundary between the Priabona and Castelgomberto formations at Covolo Copacan (same locality as C). E: View toward the South of the steep slopes of the Berici Hills. The village in the centre of the view is Lumignano; on the left, the Euganean Hills in the background are mostly intermediate and acidic subvolcanic bodies emplaced during the Oligocene.

METHODS

Geological mapping was conducted between fall 2021 and summer 2022, using as topographic base the technical cartography of the Veneto Region (1:5000 CTR, https://www.regione.veneto.it/web/ambiente-e-territorio/carta-tecnica-regionale). Surveys were conducted by collecting observations on lithology, bedding and rock components and annotating the position and extension of outcrops in a Qgis 3.16 project. Mapping was supported in the field by the use of the GNSS systems of mobile devices, on which annotated topographic maps were uploaded on Avenza Maps. The accuracy of surveys is thus that of average GNSS devices, i.e., ca. 5 m.

We also produced digital photogrammetric 3D models of the natural walls and quarry fronts, by using the structure-from-motion software Metashape. We acquired the images we used to generate models with a UAV Dji Phantom 4 rtk (1'' CMOS, 20 Mpx), driven by using DJI pilot for the vertical manual survey and UGCS for the automatic horizontal one. Those 3D models were then uploaded on Virtual Reality Geological Studio. We used this software to extract the lithological boundaries of the represented areas and use them to refine their contacts directly on the Qgis project (Fig. 7).

The output map was generated also by using Mappy plug-in of QGIS (Penasa et al., 2020), whereas the topographic profiles were carried out from Regional Digital Elevation Model and the Profile tool plug-in of QGIS.

The lithological determinations in the field were confirmed by observations on 250 samples, prepared as polished slabs (e.g., Fig. 3, 5) and thin sections. Polished slabs were then photographed with a macro lens, to obtain images with spatial resolution better than 0.1 mm, in which all major components are clearly visible.

RESULTS

Lithofacies of the Castelgomberto formation

Five lithofacies could be distinguished in the field, and mapped, within the Castelgomberto formation. These lithofacies hare described as follows:

- Vicenza stone lithofacies (CCg, Fig. 5 A): it is made of porous, well-sorted grainstones with mostly fragmented coralline algal thalli, miliolids and other benthic foraminifera. It occurs in massive, or badly bedded intervals 10 to 25 m in thickness. Locally, larger benthic foraminifera (including *Nummulites* spp.) and fragmented echinoid plates and spines may be common. The thickest horizon is found at the base of the Castelgomberto formation in the south-eastern parts of the hills (Costozza), where it has been historically quarried.
This lithofacies does not have a unique microfacies or skeletal association. Horizons of Vicenza stone are formed by a combination of deposition under high-energy conditions washing away the fine sediment component, and an incomplete lithification that leaves open most of the intergranular pores.
- Bedded grainstone – rudstone lithofacies (CCa, Fig. 5 B): it is made of well bedded grainstones with fragmented coralline algal thalli and benthic foraminifera, mostly miliolids; floatstones and rudstones are also common, and contain coral fragments, echinoid fragments and large molluscs. Beds are generally 20-100 cm thick and wavy bedded. This unit actually corresponds to several facies which cannot be mapped individually. Locally, coral colonies in life position occur (see also Geister & Ungaro, 1977), as well as beds of layered tuffs and tuffites.
In thin section, a great variety of grains occurs, among which miliolid foraminifera are ubiquitous. Fragments of articulated coralline algae are the most abundant grain type on average, and encrusting organisms (foraminifera and coralline algae) are common. In the grainstone facies, grains are usually worn and well sorted: this variety of the Bedded grainstone – rudstone lithofacies should correspond to the Smaller Miliolid Facies (MFT-10) of Nebelsick et al. (2005).
This lithofacies occurs north-west of the coral reef system, which means it was behind (i.e., landward of) the reefs at the time of deposition. It is interpreted as deposited in a shallow water environment with seagrass meadows, as suggested by the abundance of miliolid foraminifera and common encrusting organisms, which were likely epiphytic.

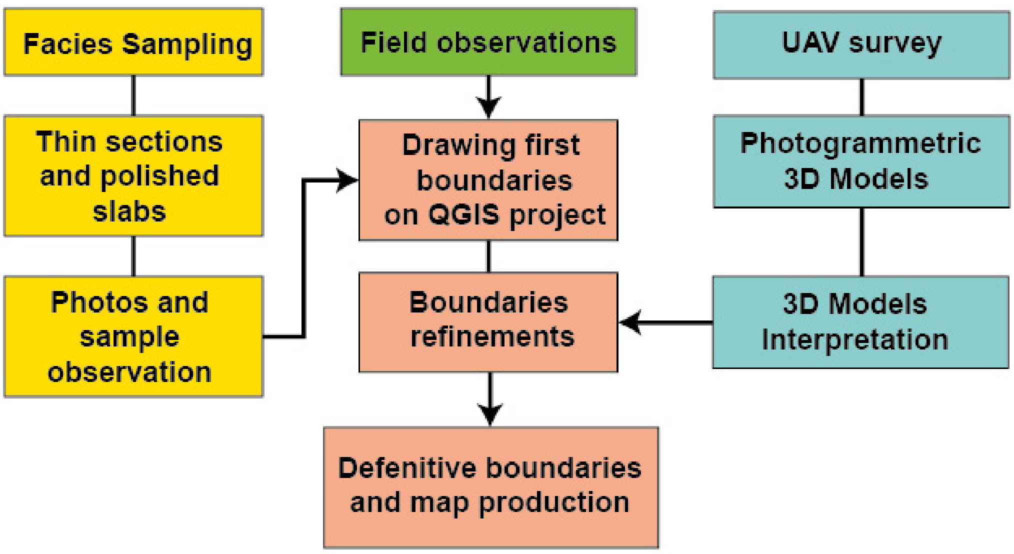

Fig. 7 - Workflow for the production of the geological map, which clarifies the use of photogrammetric 3D models for mapping. Links to 3D models of natural walls are found in Chimento et al. (2023).

- Coral boundstone lithofacies (CCc, Fig. 5 C, D): it is characterised by laterally limited bodies of massive limestone, up to 60 m thick, which often form cliffs. Sparse to dense platestones to sheetstones occur mostly at the base, while dense mixstones (*sensu* Insalaco, 1998), locally frame-building, are more typical at the cores (see also Bosellini et al., 2020). Corals are usually found in living position. At peripheral positions within the lithofacies bodies, corals are immersed in grainstones, otherwise at the cores, matrix of boundstones is a wackestone-packstone. Wackestone to grainstones are chiefly made of fragmented coralline algal thalli. It corresponds to the Coral Facies (MFT-13) of Nebelsick et al. (2005).
- Coralline algal lithofacies (CCm, Fig. 5 E, F): it is made of marly limestones and rudstones with coralline algae, small *Nummulites* and bryozoans. Marly interlayers may occur. Large oysters and echinoids may also occur, as well as fragments of corals, which often form the nuclei of rhodoliths. Coralline algae may occur as branched forms, or as rhodoliths, and rhodolithic rudstones locally develop. This lithofacies occupies a position seaward of the coral reefs, and rhodolith rudstones have been found to form a slope with inclination of about 10°, dipping south-east (i.e., seaward).

  Due to the ubiquitous presence of fine sediment, this lithofacies must be interpreted as deposited below the fair weather wave base. It is similar to the Maerl (MFT-1) and Rhodolith (MFT-2) Facies of Nebelsick et al. (2005), but never have a grainstone matrix.
- Marl and fine packstone lithofacies (CCo, Fig. 5 G, H): this lithofacies is made of fossiliferous marls and marly limestones (fine-grained packstones with fragmented skeletal grains) with dominant bryozoans, rare rhodoliths, benthic foraminifera, echinoderms and some planktic foraminifera. Brachiopods, molluscs, serpulids and decapod fragments are also found. Laterally discontinuous intercalations of rhodolith rudstones and floatstones occur, in which rhodoliths are embedded either in marls or in fine-grained skeletal packstones dominated by bryozoans. These rhodolith beds are interpreted as reworked, because the skeletal elements at their nuclei are inconsistent with the embedding sediment, and because it is often found that these beds have a sharp and irregular (erosive) base. This lithofacies occupies the most distal (i.e., south-eastern) part of the mapped area. Due to the prevalence of the fine sediment component, and the substantial absence of photic biota, with the exception of resedimented rhodoliths, this lithofacies is interpreted as deposited below the photic zone, and it is the one in the area that formed in the deepest environment. It is very similar to the Bryozoan Facies (MFT-14) of Nebelsick et al. (2005), which has also been interpreted to have deposited in the outer ramp in the Oligocene of the Circumalpine domain.

STRATIGRAPHIC RELATIONSHIPS

The stratigraphic relationships between the mapped lithofacies and formations are locally visible in the field (e.g., at Brojon, Fig. 8), and could be inferred from mapping where contacts are not exposed. Overall, the geological cross section of figure 9 illustrates the whole range of stratigraphic relationships between lithological units on the map.

The contact between the Priabona and Castelgomberto formations is well exposed in several localities, and is always a sharp surface. At Costozza, a thick deposit of the Vicenza stone lithofacies overlies the Priabona Formation, and is initially roughly bedded, to become massive upwards. At Cava Olivari, on the southern part of the map, such contact is exposed on a long stretch of the quarry walls, but here the Vicenza stone lithofacies appears massive throughout, i.e., it does not show a roughly bedded interval at its base. Under all cliffs surrounding Lumignano, it is instead the coral boundstone lithofacies that lies on the Priabona formation, still with a sharp contact (Fig. 6 A).

At Brojon (Fig. 8), massive beds of the coral boundstone lithofacies are still lying on the Priabona formation. On the western side of Brojon, beds are amalgamated and form cliffs. These beds, however, become thinner on the eastern side, where they are interfingering with the coralline algal lithofacies which, being richer in clay and hence more erodible, is recessive and corresponds to ledges. The facies interfingering at Brojon can be appreciated on the three-dimensional model of Chimento et al. (2023). In the woods more to the east, coral boundstones are completely substituted by rudstones of the coralline algal lithofacies, which can be traced laterally and correspond to the Longare section of Nebelsick et al. (2013). The Longare section is thus the lateral equivalent of coral reefs at Brojon, is made mostly of the coralline algal lithofacies, and lies above the Vicenza stone of the quarries of Costozza, which in turn sit on the Priabona formation. The Vicenza stone lithofacies, thus, has no equivalent under the cliffs made of coral boundstone lithofacies, which must be in contact with the Priabona formation through an unconformity. The sedimentary body made of Vicenza stone lithofacies at Costozza ends abruptly toward the north-west, where it is laterally replaced by outcrops of the Priabona formation. We interpreted this sharp lateral contact as a palaeo-fault, sealed by the Castelgomberto formation (Fig. 9 and geological map in the supplementary materials).

DISCUSSION

Spatial distribution of lithofacies in the field, and in particular, the occurrence of Castelgomberto formation around Costozza, at lower elevations than the base of cliffs at Lumignano, could only be resolved by hypothesizing a normal fault, active in the Eocene and now sealed by the Castelgomberto formation, which lowered the block on the south-east, and thus identifying a Oligocene high (on the north-west) and low, on the south-east, on which different Oligocene lithofacies deposited. Localised evidences of sealed faults were mapped in the area, and also imply the lowering of south-eastern blocks.

With respect to the debate on the nature of the coral reefs in Lumignano, our mapping revealed a clear facies transition that comprises, from shallow depositional environments at the north-west to deep depositional environments to the south-east: high-energy shallow water facies, the coral reefs, coralline algal

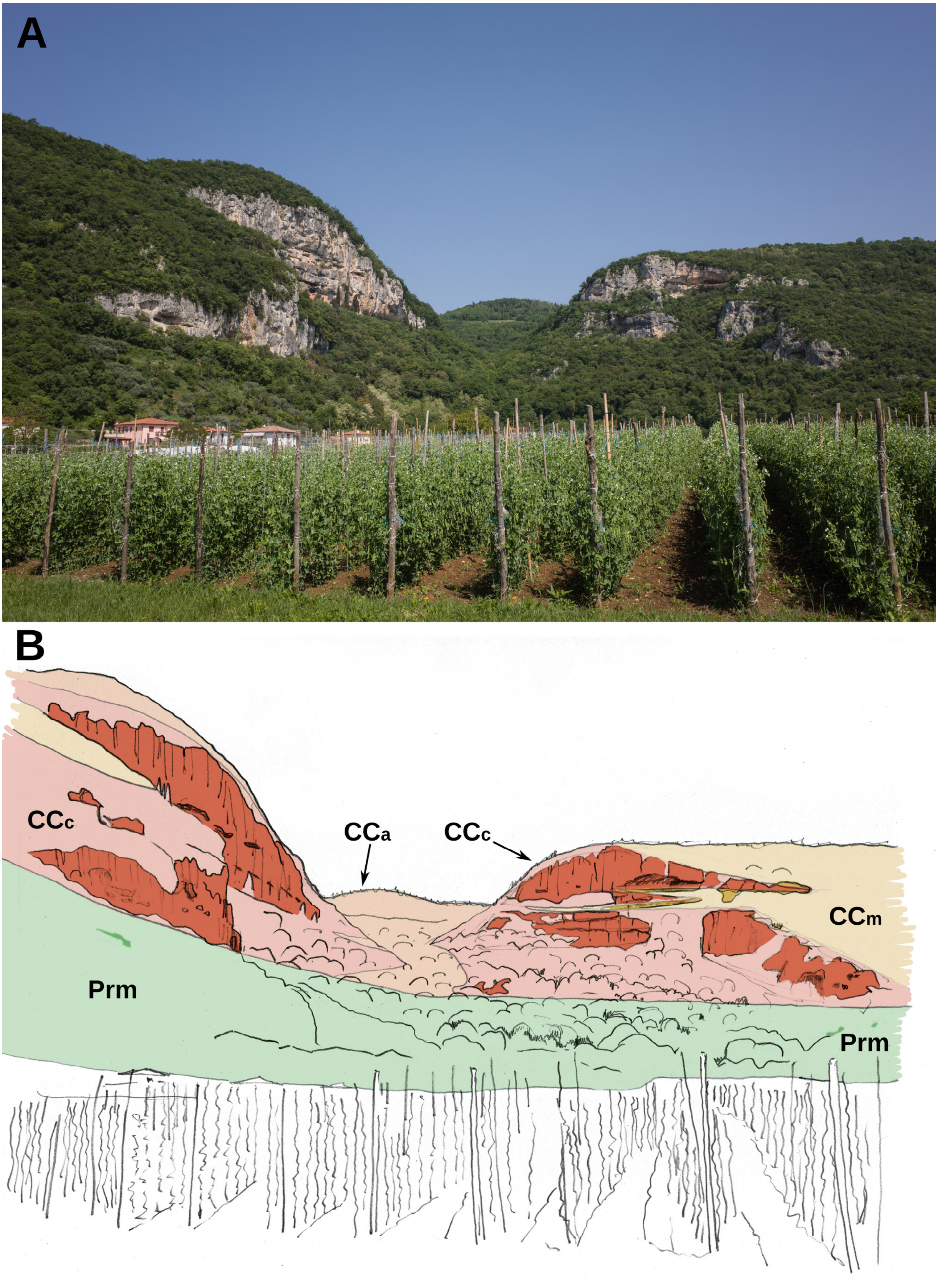

Fig. 8 - View of the walls of San Cassiano and Brojon from the south (A), with interpretation of the lithological boundaries (B). In the interpreted image (B), colours and abbreviations are the same as in Figure 2, main text and map (supplementary materials).

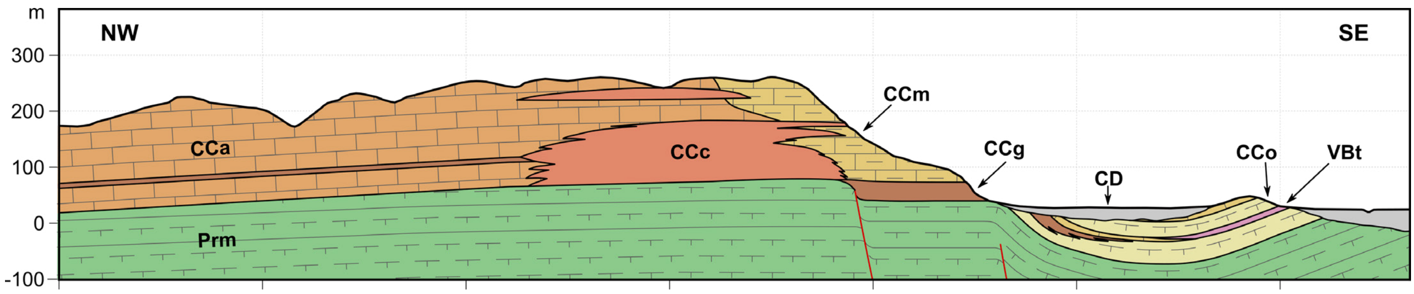

Fig. 9 - Geological cross-section. Colours and abbreviations are the same as in Figure 2, main text and map (supplementary materials). See trace on the map, supplementary materials.

lithofacies, and marlstones with aphotic associations on the most external position. While the coral boundstone lithofacies includes large portions made of framestones, i.e, coral colonies are in touch one each other and not dispersed in the sediment, clear evidence exists that the Lessini Shelf at Lumignano did not terminate basinward with a slope, but it rather faded towards shallow basinal facies of the marl and fine packstone lithofacies without major breaks on the depositional profile. If a slope existed, it was unrelated to coral reefs, and was related to the progradation of rhodolith rudstone with low-angle (10-15°) clinoforms, similarly to the Miocene distally steepened ramp of the Balearic Islands (e.g., Pomar et al., 2002; Mateu-Vicens et al., 2008).

Field mapping also permitted to unequivocally locate rhodolith or mäerl beds offshore of coral reefs, and adjacent to marls with an aphotic biotic association (i.e., the marl and fine packstone lithofacies) in the early Oligocene carbonate ramp of the Lessini shelf. While the conditions for the deposition of similar rhodolith or mäerl beds are most commonly met, in the present Mediterranean Sea, at water depths of 30-75 m (e.g., Basso et al., 2017), it is unclear where they might have been occurring in the past, under different climatic and palaeoceanographic conditions. In fact, mäerl and rhodolith facies occurred landward of coral facies and in the inner shelf during the Oligocene, according to Nebelsick et al. (2005).

Coralline algal facies of Nebelsick et al. (2013) was also attributed to a distal portion of the inner ramp.

Instead, Brandano et al. (2017) depicts a standard Mediterranean Oligocene ramp with mäerl and rhodoliths accumulating in a middle, oligophotic facies belt, in contact with bryozoan facies in the seaward direction. The ubiquitous presence of fine carbonate or clay matrix in the coralline algal lithofacies of Lumignano and Costozza implies deposition below the fair weather wave base, which is consistent with the position of the coralline algal facies belt offshore of the coral reefs, and in contact with a deeper marl and fine packstone facies that is consistently interpreted as representing the outer ramp in the literature (see the reviews of Nebelsick et al., 2005; Brandano et al., 2017). We must conclude that the coralline algal lithofacies deposited in a middle ramp position, as for the model late Eocene-Miocene carbonate ramp of Brandano et al. (2017) and similarly to mäerl and rhodolith beds of the recent Mediterranean Sea.

With this mapping work, a better definition of the boundary between the upper Eocene – lower Oligocene Priabona formation, and the lower Oligocene Castelgomberto formation can be proposed. These two units are somehow defined in the explanatory notes of the Geological Map of Italy, 1:100000 (Bosellini et al., 1967), where the Priabona formation ("*Marne di Priabona*") is described essentially on the base of the outcrops in its type locality, Priabona in the Lessini mountains. The overlying "*Calcarenite di Castelgomberto*" (Castelgomberto formation in this work) comprises a basal marly interval with abundant larger foraminifera. This basal marly interval of Bosellini et al. (1967) is here included in the Priabona formation. This definition of the Castelgomberto formation substantially overlaps with the description of the lower Oligocene interval in Fabiani (1911b; 1915) and in fact, in Bosellini et al. (1967), the Priabona formation was considered fully Priabonian in age, and the Castelgomberto formation, fully Oligocene in age.

At Priabona, the type locality of the Priabona formation, a sharp boundary between marls with bryozoans and the overlying limestones with larger benthic foraminifera and coralline algae, is observed at the base of the so-called "small *Nummulites* bed" (Trevisani, 1997). This sharp boundary between terrigenous and carbonate beds is the base of the Castelgomberto formation at Priabona (Mietto, 2000), and corresponds to a major sea level drop, coinciding with the stable isotopic event OI-1 in Miller et al. (2008) and Houben et al. (2012).

Positioning this boundary would be all but trivial if we were to maintain the definition of the Geological Map of Italy, 1:100000, because the coralline algal lithofacies of the Castelgomberto formation is identical to the analogous lithofacies of the Priabona formation (Coralline algal facies in Bassi, 2005). Possibly, coralline algae of the two units may be distinguished taxonomically, but such distinction would be impossible to use in geological mapping. In fact, the typical Priabona formation is easily distinguished because it contains abundant orthophragmind larger foraminifera and *Nummulites* spp. However, these larger benthic foraminifera decrease gradually in abundance towards the top of the formation, to disappear completely (at least according to our observations in the field and on hand samples) before the first occurrence of the typical facies of the Castelgomberto formation. There is thus a ca. 20-30 m thick interval of coralline algal rudstone, in continuity with firmly identified beds of the Priabona formation, in which late Eocene larger benthic foraminifera are rare or missing. This interval likely corresponds to the lower marly beds with larger benthic foraminifera attributed to the Oligocene, and hence to the Castelbomberto formation (Ungaro, 1978; Bosellini et al., 1967; Fabiani, 1911b, 1915).

We suggest that the base of the Castelgomberto formation should be more conveniently placed where coral boundstones and/or rudstones are overlying rhodolith rudstones, while seaward of the coral reefs, the base of the Castelgomberto formation is the sharp base of Vicenza stone lithofacies. According to this criterion, landward of the reefs, the Castelgomberto formation is also in sharp contact above the Priabona formation, and starts either with a horizon of Vicenza stone, or with layers of the bedded grainstone – rudstone lithofacies. Defined in this way, the base of the Castelgomberto formation at Lumignano should be an unconformity (paraconformity), correlated with the base of the small *Nummulites* bed and, hence, to the base of the Castelgomberto formation also at Priabona (e.g., Trevisani, 1997; Mietto, 2000).

CONCLUSIONS

Detailed geological mapping of the distal portion of the Lessini Shelf at Lumignano and Costozza allowed to identify geological features that can contribute significantly to the interpretation of the depositional system of the lower Oligocene carbonate platform. A sealed fault was identified beneath the lower Oligocene coral reef lithofacies, which we interpreted as a topographic threshold on which coral reefs nucleated. At the foot of the fault scarp, a thick package of massive grainstones of the Vicenza stone lithofacies deposited. This horizon of Vicenza stone has been quarried in Costozza since Roman times at least.

It was also possible to identify and map five lithofacies of the Castelgomberto formation, which correspond to different depositional environments with palaeo-water depth increasing towards the south-east. On the landward side, the bedded grainstone – rudstone lithofacies does not suggest the existence of a low energy lagoon, protected from the action of waves from a reef barrier. Instead, common grainstones and rudstones suggest deposition under continuous wave action. On the seaward side with respect to coral reefs, we couldn't identify a slope facies made of coral rubble. A low-angle slope may have existed, but it was formed by the progradation of rhodolith rudstones, i.e., a carbonate factory unrelated to the coral reefs.

These observations can contribute to the resolution of the current debate about the nature of the lower Oligocene carbonate platform of the Lessini Shelf, and in particular, on whether coral reefs formed a barrier protecting a lagoon, or they were instead growing on a carbonate ramp.

ELECTRONIC SUPPLEMENTARY MATERIAL

This article contains electronic supplementary material which is available to authorised users.

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Declaration of interest statement

The authors declare no conflicts of interest.

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