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Terrestrial laser scanning, geomorphology and archaeology of a Roman gypsum quarry (Vena de Gesso area, Northern Apennines, Italy)

Stefano Fabbri [a], Veronica Chiarini [a,b,c], Massimo Ercolani [c], Garibaldi Sansavini [c], Tommaso Santagata [d], Jo De Waele [a]

[a] *Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università di Bologna, Via Zamboni 67, 40126 Bologna, Italy*
[b] *Ente di Gestione per i Parchi e la Biodiversità – Romagna, Via Aldo Moro 2, 48025 Riolo Terme, Italy*
[c] *Federazione Speleologica Regionale dell'Emilia Romagna-GAM Mezzano, Italy*
[d] *VIGEA – Virtual Geographic Agency, Reggio Emilia, Italy*

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ABSTRACT

Roman-period extractive sites in gypsum outcrops are very rare, and most have become very degraded by later weathering or quarrying activities. This paper describes, using laser scanning, photogrammetry and survey using a UAV-based survey, the uniquely well-preserved Roman-period gypsum quarry of Ca' Castellina (Northern Apennines, Italy). This site was excavated only in the last few years and the excavations have brought to light some gypsum blocks and the ancient quarry benches showing excavation marks, the remains of a rectangular building and a great number of artefacts that range between the Protohistoric Period and the modern time. The size of the extracted blocks, the extraction methodologies and the age of a charcoal fragment (361 – 178BCE) found immediately at the contact between the gypsum quarry floor and the infilling sediments date the quarry back to the Roman age. Archaeological evidences demonstrate the building to have been used for a short period of time during the XVI-XVII century. Immediately after its abandonment most of the quarry floor has been covered with a thick detrital layer, protecting it from dissolution (fossilizing this floor and leaving it as if it was abandoned very recently), whereas the naked or poorly covered floor of this quarry has been subjected to dissolution phenomena of the exposed gypsum rocks, with a lowering of the surface, the smoothening of the corners and the formation of a set of deeply carved karren features. A 3D survey using both a laser scanning instrument and a drone-mounted photo camera have allowed to get precise measures on the size of the blocks that were extracted in this quarry, the traces of pick axe marks, and on the dissolution morphologies that have developed on the bare gypsum rock. These typical gypsum landforms show how fast these solution forms can develop where concentrated runoff flows on bare gypsum. To prevent this exceptional archaeological extractive site of being further dissolved, it will be important to plan some measures to be put in place in order to protect this delicate historical landmark.

1. Introduction

Gypsum and anhydrite are easy-to-carve rocks, abundantly outcropping around the Mediterranean Sea. In some areas, this rock is the only hard material available, and despite its poor resistance to surface weathering and erosion, it was often employed for the interior of buildings. Especially the finely veined and coloured microcrystalline varieties were popular in some places. This rock has been found in the form of floor pavements, benches, and steps in different settlements of Ancient Greek, Egyptian, and Roman age (i.e. Gale et al., 1988; Chlouveraki and Lugli, 2009; Heldal et al., 2009; Harrell, 2010). The rocks were probably also used for external parts of buildings, but due to their solubility and high susceptibility to weathering, few traces have survived the centuries. The provenance of the gypsum blocks is often poorly constrained, with very general locations of possible gypsum quarries (Harrell, 2012). The origin of gypsum can also be retraced based on geochemical fingerprints, but this often does not exactly locate the extraction sites (Gale et al., 1988). Only in a few cases gypsum quarries have been clearly identified: this is the case for the Roman anhydrite-gypsum quarry of the Marsa Nakari port in Egypt (Harrell, 2010). These quarries are still well visible, with their decametric open rectangular cuts and up to 3-metre high vertical confining walls. Their surface exposure, even in this rather arid climate, has erased all traces of original cutting, and chemical weathering combined with erosion has caused the formation of a hard, secondary crust, or intense traces of natural dissolution (Harrell, 2010).

It is reasonable to think that also the Romans used gypsum blocks for the construction of different types of buildings in Emilia Romagna. Often the selenitic (macro-crystalline) gypsum rock was the easiest and cheapest building material in some areas in the northern Apennines. Messinian selenitic gypsum outcrops discontinuously in

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the northern Apennine foothills from Modena in the West to Rimini in the East. The largest outcrops form cuesta-like ridges with an over 200 m thick sequence of alternating gypsum and shale beds, and occur immediately South of Bologna, and in the Vena del Gesso Romagnola area South-West of Imola and Faenza (Columbu et al., 2017).

This soft rock might have been used for the erection of some monumental buildings in Roman Bologna. The use of gypsum rock was maintained for many centuries, and especially during the XI-XIII centuries (the golden period for the use of selenite blocks as building material), falling into disuse in the first decennia of the XIV century (Del Monte, 2005). In fact, the frequent fires in the mostly wooden-constructed Medieval Bologna made people realize that burnt gypsum (plaster) could be used as cement, moulding, casting, and protective coating material in the building industry. This "re-invention" of plaster (these properties of dried out gypsum were known since at least two millennia) caused selenite to be transformed into this much more profitable material, instead of using it as a building stone. However, the advantageous properties of selenite such as its availability close to the city, its softness (easy to be worked), its porosity close to zero and high elasticity made this stone extremely suited for its use in the construction of buildings, and especially of the lower parts of large constructions (since the impermeable selenite blocks inhibit capillary water to rise from the foundations to the surface, and its elastic behavior enables seismic shocks to be absorbed more readily). Still nowadays the large selenite blocks can be seen at the base of the leaning towers in Bologna. The quarries used during the XI-XIV centuries were located close to Bologna, in the Apennine foothills some km South of the city. From the end of the XIX century the improved communication (roads, railways) has allowed better materials (such as limestones) to be brought to Bologna and used as building stones.

Often it is not clear where the large selenite blocks used in Roman times were quarried, since many of the possible original extractive sites were used also later, erasing the traces of the Roman excavations. In Sicily, a Roman quarrying area is known in the Rocca di Entella (Palermo province), a Regional Integral Nature Reserve. Here some almost completely isolated blocks were left behind in some of the thirty extraction sites on the summit area of this gypsum ridge. At least 1800 m^3 of gypsum blocks (a largely underestimated number) would have been quarried in a period that might have started during the Hellenistic age (IV-II BC) (Guarnieri, 2019). Before the discovery of Ca' Castellina, two Roman extraction sites were known in Emilia-Romagna region: Borzano (Albinea, Reggio Emilia province), a quarrying site active in the period I-II AD, and a much more dubious one in Borgo Tossignano (Imola), a quarry that was active also during Medieval times but might be of Roman age (Guarnieri, 2019).

Many of the Roman buildings made of gypsum blocks have nowadays disappeared for several reasons: the blocks of important buildings were reused for the erection of newer constructions, or simply the gypsum blocks, if exposed to weathering, were easily brought into solution by meteoric (rain) waters. Only where these blocks were protected by overlying bricks (or rocks), or have been covered by a sufficiently thick soil, they could survive from a complete dissolution.

The discovery on Mt. Mauro (Vena del Gesso Romagnola area, 40 km South-East of Bologna) of an ancient Roman quarry where gypsum blocks were extracted has enabled to study this extractive site with a variety of scientific methods, including the traditional archaeological excavations, geomorphological studies, laser scanner acquisition and 3D photogrammetry. We published a preliminary version of this research in an Italian local book series (Santagata et al., 2019), but here we report on the final results obtained following the multidisciplinary study of this exceptional Roman quarry. This quarry was hidden below a thick soil cover, that protected the floor and walls from surface weathering and dissolution. In some parts of the quarry walls and floor the original excavation traces and tool marks are still well visible, making this Roman gypsum quarry one of the few well-preserved ones in the Mediterranean area (Guarnieri, 2019).

Over 2000-year-old quarries or quarrying areas are often studied with field methods and direct observations. These traditional surveys, accompanied by excavations and chronological studies, are often still the most efficient methods of collecting data. Laser scanning surveys are increasingly used to document archaeological sites prior to excavation, in order to get a good idea of the distribution of material at the surface, and combined with geophysical techniques (Ground Penetrating Radar), also of the subsurface (Landry et al., 2019). When the archaeological settlements are spread over very large areas, and under a dense forest cover, airborne laser scanning can have enormous advantages (Štular et al., 2012; Evans, 2016). In case of smaller areas to be covered by the surveys, photogrammetry is increasingly employed as a substitute to traditional mapping (De Reu et al., 2014; Waagen, 2019). These innovative surveying methods are especially suitable in the study of ancient quarries, enabling the study of extraction techniques, the estimation of volumes, and the morphologies accessory to the quarries with great accuracy, similar to that obtained by traditional archaeological surveys (Verhoeven et al., 2012).

Our detailed studies were aimed at making a 3D model of the quarry area, document the multiple evidences of excavation techniques, reconstructing the history of this quarry, and to allow the planning of its potential cultural and tourist exploitation and protection. Some hypotheses on the possible destination of the quarried blocks are also formulated.

2. Study site

Traces of an ancient gypsum quarry were discovered a few years ago in the location known as Ca' Castellina, around half a kilometre NW of Mt. Mauro (515 m asl) (Fig. 1). Mt. Mauro is the highest peak of the Vena del Gesso Romagnola Regional Park, dominated by a WNW-ESE oriented gypsum ridge of Messinian age. This ridge extends along the Apennine foothills, approximately 10 km south-west of the cities of Faenza and Imola in the Emilia Romagna Region (Italy).

Excavations carried out in 2017 have cleared the area, unveiling a more or less square 20-metres wide quarried area bordered to the SW and NW by 5-metre high vertical rock walls (Guarnieri and D'Amato, 2019) (Fig. 2).~~Fig. 3.~~

This area is well known for its natural and scientific interest (see Fig. 1). The Ca' Castellina gypsum cave is located at the bottom of the nearby doline immediately West of the quarry, and is an important palaeoclimatic and palaeoenvironmental site witnessing the hydrology and sedimentation occurred previous to the Last Glacial Maximum (De Waele et al., 2018). Another important archaeological cave, the Grotta dei Banditi, opens on the southern slopes of Mt. Mauro (above the locality called Ca' Toresina). This cave was used since the Chalcolithic, and extensively during the Late Bronze age, Roman and Medieval times. The thick calcite flowstones present in this cave have been dated back to the Last Interglacial (125 ka). Even older calcite speleothems, witnessing the presence of karst caves now completely dissolved away, have ages up to over 400 ka (Columbu et al., 2017).

A rural, now abandoned, building oversees the deep Ca' Castellina doline and is built in gypsum blocks quarried nearby. Several ancient mines of "*lapis specularis*" have been found close to this house, showing the area to be used during Roman times for the ex-

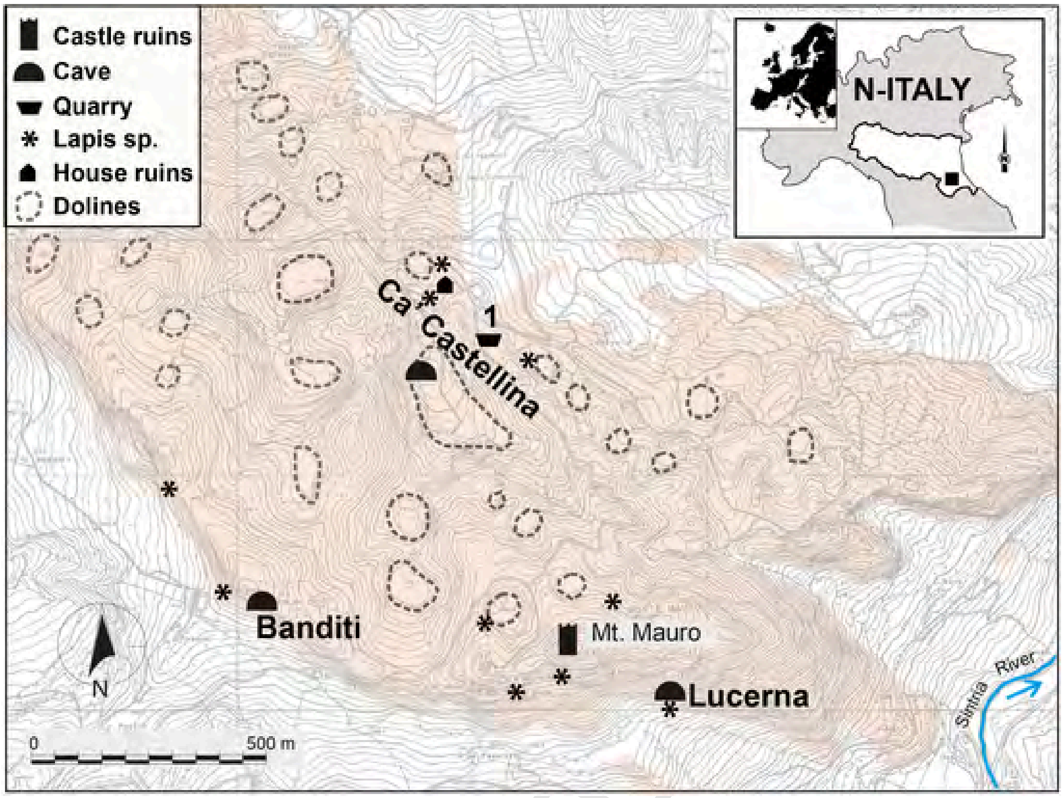

Fig. 1. Location of the Ca' Castellina Roman quarry (number 1 in figure) and the nearby historical and archaeological locations (*lapis specularis* sites and Lucerna Cave, I-V a.C.; Banditi Cave used since Chalcolithic age until Roman age, X century Castle on Mt. Mauro, Ca' Castellina ruins of uncertain age). The pink shaded area shows the limits of the Messinian gypsum outcrops, whereas the dashed circles shows locations of the main dolines. The upper right inset shows the geographic location in Italy and Europe. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

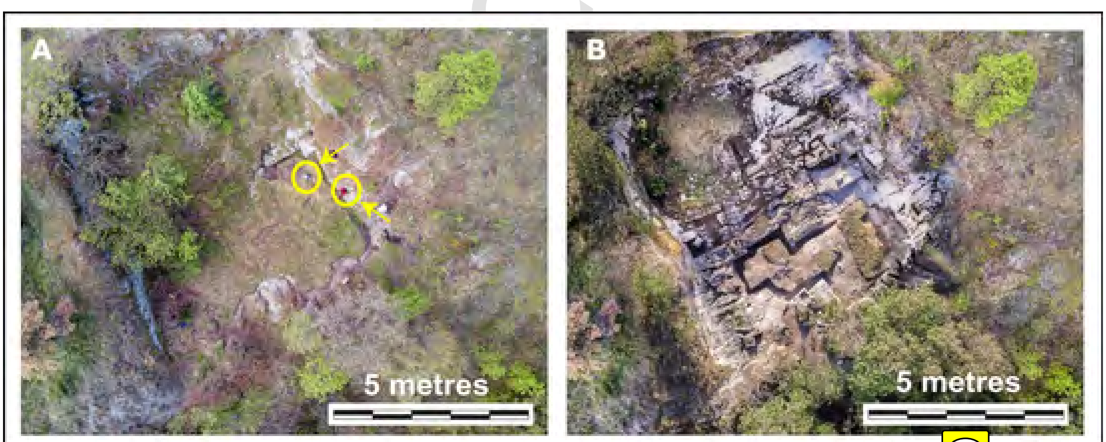

Fig. 2. Aerial drone (UAV) photographs of the site of Ca' Castellina before (A) and after (B) the excavations.

traction of this important transparent gypsum variety (Guarnieri, 2015; Guarnieri et al., 2015). These Roman excavations are coeval to the main *lapis specularis* extraction site (I-V a.C.), the Lucerna Cave, located ca. 800 SE from the Roman Ca' Castellina quarry described in this paper (Santagata et al., 2015). The remains of a castle are still visible very close to the highest peak of Mt. Mauro, with the base of a watch tower and a wall made of large gypsum blocks. This fortified settlement dates back to the VIII century and was abandoned in the XVI century, while its ruins were completely destroyed in 1945 (Guarnieri, 2019).

3. Methods

The quarry site was excavated by means of traditional hand excavation methods and recorded using manual techniques, making hand drawings of structures based on vertical and oblique photographs. A local coordinate system was used during excavations and was later transformed into absolute coordinates (WGS84). A total station was used to locate the main elements (e.g. corners of the built structure, corners of the quarry). Dry sieving was performed on all excavated sediments and all materials were collected and inventoried. Archaeological units were defined during fieldwork following lithological contacts.

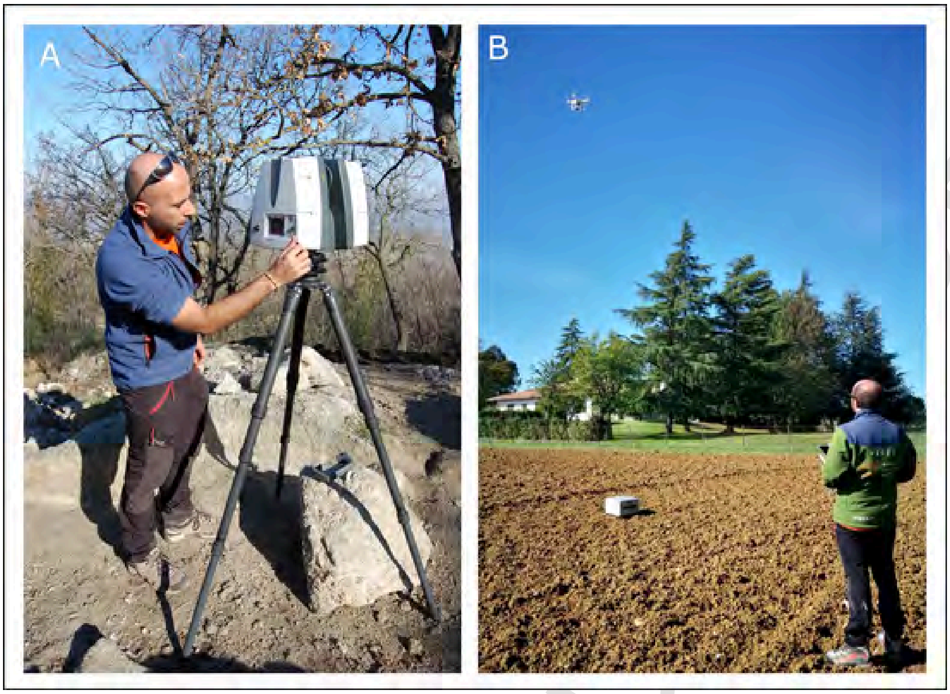

Fig. 3. A. The Leica P40 Scan Station during the survey in the Roman quarry; B. Operation of the DJI Phantom 4 Drone (circle) equipped with a digital camera for the realization of a digital model based on 147 digital images.

One fragment of charcoal was dated at Beta Analytic (Miami, USA). The sample (Beta-495854) underwent an acid/alkali/acid pretreatment before being analyzed on a NEC accelerator mass spectrometer and Thermo isotope ratio mass spectrometer. The sample ratio was compared to the ratio measured from Oxalic Acid standard (NIST SRM 4990C). Sample $^{13}C/^{12}C$ ratios were expressed as $\delta^{13}C$ with respect to VPDB-1, with an error of less than 0.1‰. The reported age is obtained using INTCAL13 (Reimer et al., 2013), is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = CE 1950, using the ^{14}C half-life of 5568 years.

For this research, a Leica P40 Terrestrial Laser Scanner (TLS) was used. This kind of device is very well suited to perform digital surveys in environments such as Ca' Castellina, because it is powerful (the theoretical maximum range is about 270 m) and manageable (12 kg), but also for its operational speed (up to 1 million points per second), reliability and accuracy of its measurements (less than 1 mm on a measuring distance of 10 m). Moreover, it is equipped with a High Definition camera, which can acquire RGB information to elaborate, in post processing, a texture, applicable to the 3D point cloud model. The scanner is mounted on a light carbon tripod equipped with a circular level; once mounted, the scanner itself has an accurate digital level to optimize the positioning; this assures a high accuracy level and a more precise alignment of adjacent scans.

To perform the whole survey of the quarry and, above all, to obtain an accurate 3D digital reproduction of the archaeology, we considered 17 scans, outdistancing scanner positions of about 5 m, taking care in avoiding shadow corners and acquire every possible detail.

Each scan was then aligned in post-processing, using reference points to anchor scans and help positioning. Once the model was completed, it was re-elaborated with the PCV ("Portion de Ciel Visible") CloudCompare plug-in, improving consistently the visibility of the whole model and its minor features.

For what concerns the Unmanned Air Vehicle (UAV) survey, the flight lasted about 30 min, performing two different gridded planes of flight, one at 20 m height above the terrain, the other about 30 m; in total the HD camera acquired about 2000 pictures. No reference targets were used to align nor to scale the model, every measure in this sense was taken directly on the surveyed environment, which made the survey quicker. In post-processing, the Structure From Motion (SfM) algorithm (used by many 3D data management softwares) automatically aligned all pictures acquired and create the related pointcloud model.

4. Results

The excavations brought to light a Roman quarry covering an area of over 300 m^2 with a difference in elevation between the highest quarry border (North) and the lowest excavated floor (South) of approximately 8 m (Fig. 4). The excavations have cleared part of the entire quarry floor, leaving a central patch of 28.5 m^2 of original infilling untouched (soil and infill in Fig. 5). Four more or less horizontal quarry floors can be recognized (quarry benches): the first (lowest) at 178.5 m asl, a second one at 179.0 m asl, a third at 179.5 m asl, and the upper one, much more irregular, at around 180.0 m asl. The lower three of these benches, located in the northern part of the quarry, were completely covered by soil, and thus protected from surface waters, whereas the upper bench was covered by a very thin layer of soil only. This upper bench is intensely carved by flutes and rills, typical of karst (i.e. karren). This bench is the floor of a built structure, positioned in the southern corner of the quarry. Despite its rather uncomfortable northward (cold) exposition, the two vertical quarry walls were used thus economizing on the use of stones.

4.1. The quarry floor

The three lower quarry benches, that were originally covered by a thick soil cover, have a rather uniform horizontal floor. The contact between the gypsum rock and the soil is very neat and devoid of dissolution traces (Fig. 6C). At a first glance the horizontal quarry benches are carved by two main morphologies: the first are com-

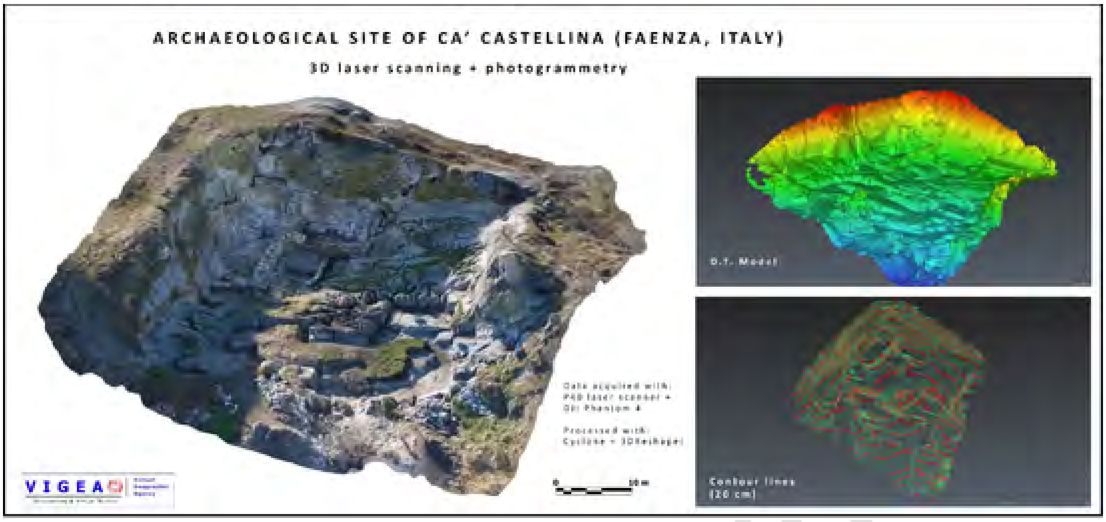

Fig. 4. Aerial photo (left), obtained using 147 drone-based photographs and digital terrain model (right up) and contour lines of the Roman quarry based on 17 laser scan station measurements.

posed of straight lines, corresponding to the extraction grooves carved by the quarry workers (Fig. 6A and D); the second are sinuous flat-floored channels, up to a couple centimeters deep, caused by the concentrated runoff and dissolution of the gypsum bedrock (Fig. 6B). These latter are always connected to a large karren channel located in the upper bench, feeding the lower ones with occasional important runoff. Such flat-floored channels are also present in the largest room of the building (Room I), adjacent to the quarry wall. These in-house channels appear to be connected to a temporary spring located inside Room I at the base of the wall, visible also because of the presence of some ceramic tiles meant to collect this water and lead it to a sort of cistern located immediately NE of the building.

4.2. The karren field

The upper quarry bench is highly irregular, mostly carved by deep incisions forming a karren field (Figs. 5 and 6A). These deep runnels developed on a soil-free gypsum surface (they were originally covered by only a few centimetres of soil). Some of these karren are aligned and closely follow the bedding of the gypsum crystals (NW-SE) (Fig. 6B and D) but others radiate from these main directions, and are often orthogonal to them. Their width can reach 20 cm, with depths of around 1 m. The best-developed karren fields are located in the central part of the quarry and on its eastern and western side, and appear to surround the building located in the southern corner. It is worth noting that karren are much less developed, or even completely absent, along the western border of the quarry.

In the northeastern corner of the quarry there is a deeper karren feature, a cone-shaped shaft, that normally maintains a certain quantity of water (Fig. 7D). Although there are no clear traces of excavation or mortar, this feature was probably plastered (since cracks in the gypsum would make this feature leak) and used as local water resource. The fact that the extraction of the blocks appears to have taken in consideration (avoided to cut) this water-containing shaft may indicate that it may also have been used by the quarry-men (Fig. 7D).

4.3. The signs of extraction

One of the most astonishing characteristics of this gypsum quarry is the preservation of excavation marks on both floor and vertical walls (Guarnieri and D'Amato, 2015). These signs are well preserved only in the lower quarry benches, which were covered by abundant soil. These are composed of rectilinear grooves on the floor, which delimit the rows of blocks to be extracted (Fig. 7A). These grooves can be retraced in all three lower quarry benches. Multiple measurements on these grooves on the laser scan model has allowed to calculate their average width (8 cm).

On the vertical walls, in some places, pick marks can be observed (Fig. 7B). These are curvilinear traces left by pick axes used to carve the soft gypsum rock.

In several parts of the quarry more or less isolated gypsum blocks and lines of blocks are still visible (Fig. 7C-E). One of these completely isolated blocks was left on the third bench, as if it were abandoned yesterday.

Observations in the field and laboratory measurements on the 3D model derived from laser scanner has shown these blocks to have different measures (Table 1 and Fig. 8). Three series of measurements on blocks (Blocks 1, 5, and 7 in Fig. 8) have given lengths of 169 (+11/-6) cm, 157 (+4/-3) cm, and 145 (+6/-4) cm, and widths of 62 (+6/-7) cm, 75 (+5/-6) cm, and 76 (+4/-5) cm respectively, block 1 having a height of 24 (+2/-2) cm and block 7 of 40 (+3/-3) cm (in block 5 height is not measurable). The areas of excavation of these blocks is located in the uppermost portion of the quarry (the higher lying areas). All four other measured blocks (2–4 and 6 in Fig. 8) have similar sizes, with lengths of 45 (+3/-3) cm, 49 (+4/-7) cm, 51 (+4/-7) cm, 44 (+4/-4) cm, and widths of 20 (+3/-2) cm, 22 (+3/-4) cm, 28 (+5/-5) cm, and 21 (+2/-4) cm respectively (Table 1). Heights could only be measured in blocks 3 and 6, being 9 (+2/-2) cm and 23 (+2/-4) cm respectively. Measures of heights were measured on four walls of the quarry (A-D in Fig. 8) and have given values of 30 (+3/-4) cm, 22 (+4/-5) cm, 44 (+8/-3) cm, and 58 (+4/-5) cm

4.4. The infilling

A 1x1 m exploration trench was dug in the central part of the quarry (for location see Fig. 5) (Guarnieri and D'Amato, 2015).

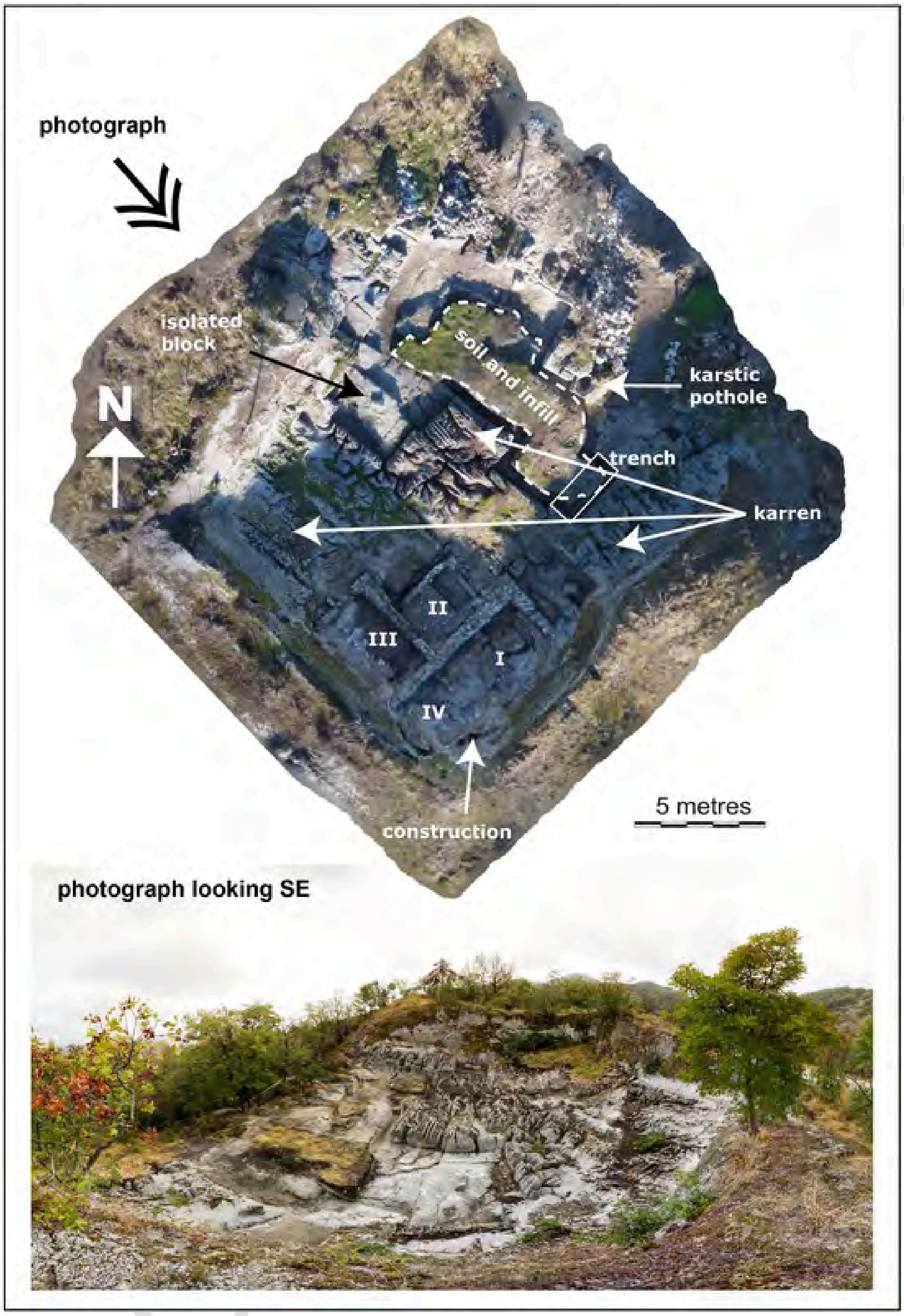

Fig. 5. Orthophoto of the quarry with the main elements highlighted. The photograph below shows a SE looking view on the quarry.

From bottom to top the stratification is composed of four stratigraphic units: US103 composed of a loamy layer of a couple of cm directly laying upon the bare gypsum rock; US102 composed of a 15–30 cm thick layer of gypsum fragments (extraction rubble); US101 an up to half-a-metre thick loamy layer and; US100 another half-a-metre layer of gypsum fragments. This entire package is covered by an almost half-a-metre thick soil cover (Fig. 9).

At the base of US103, in contact with the gypsum rock, there are evident traces of fire, and fragments of charcoal, which were sampled for dating. Both loamy units US101 and 103 contained fragments of transported protohistoric ceramics, some of which might pertain to the Late Bronze age. US103 delivered 10 pieces of charcoal and a fired clay fragment, whereas in US101 only one charcoal and one bone fragment were found. This bone fragment showed cutting marks. The charcoal fragments were found concentrated in one place, as if belonging to a single fire, and showed no evidence of transport.

One of the charcoal fragments of the lower US103 unit was dated at Beta Analytics (Miami, USA) and gave a date of 2190 +/- 30 yr BP (sample Beta – 495854) which calibrates to 361–178 cal BP (IV-II century BC) (Fig. 9).

4.5. The building

The built structure in the Southern corner of the quarry occupies an area of approximately 50 m^2, along the Eastern and Western walls (Guarnieri & D'Amato, 2019). The stone walls reach their maximum height along the SW quarry wall (1.4 m). It is composed

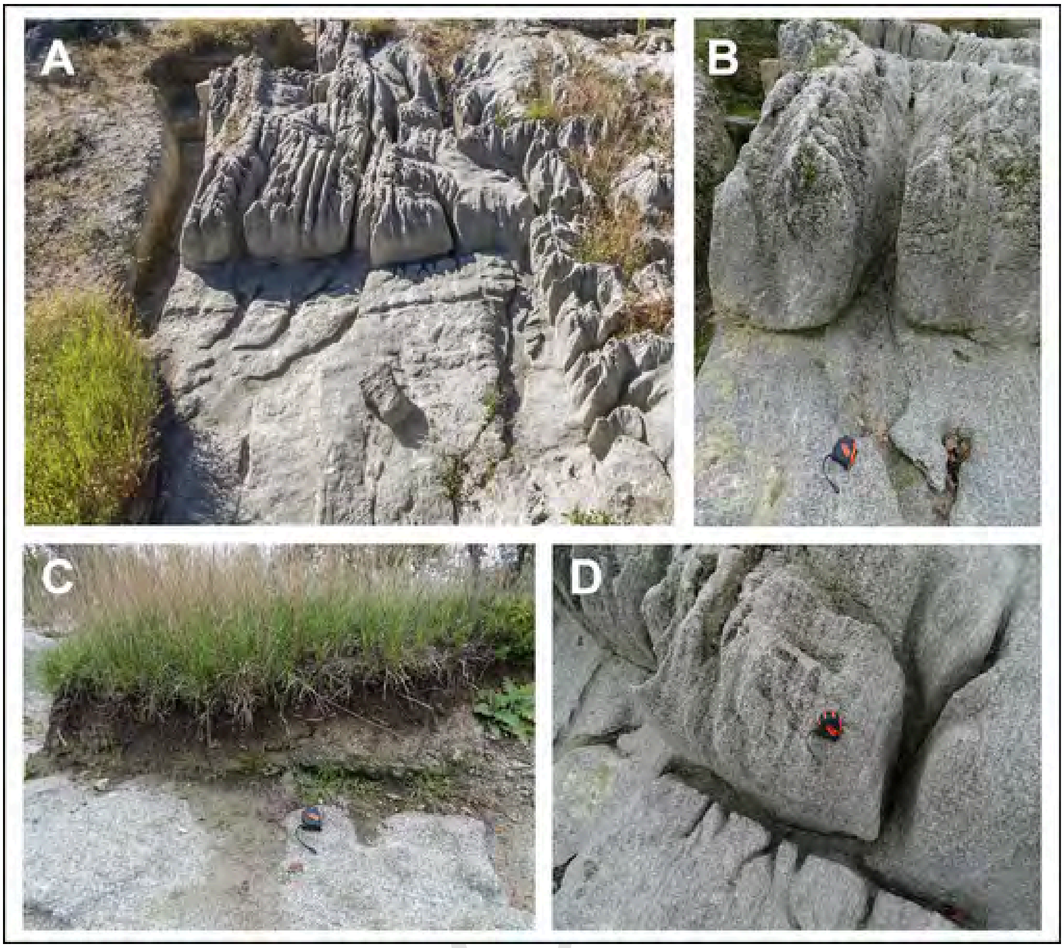

Fig. 6. Natural and artificial features on the quarry floor: A. General overview of the lower three quarry benches in the northern part of the quarry with the isolated block, extraction grooves, and flat bottomed dissolution rills on these flat lower floors, and the intensely dissolved karren field above and to the right; B. Detail of a flat floored dissolution rill in the third bench, starting from the concentrated runoff coming for the above lying karren field; C. Contact between the quarry floor in gypsum and the topsoil, here half a metre thick; D. Topview on the third bench with the well-developed karren on the upper (fourth bench) connected to the extraction groove below, substantially enlarged by dissolution and with some additional rills.

of 4 adjacent rooms (room I-IV) (Fig. 5) elongated along the main stone wall, which develops over 7 m in an ENE-WSW direction. The stratigraphic order of construction shows the building to have been constructed in at least two phases, a first in which the rooms I and IV were constructed, followed by a second and coarser construction of room III and II. The first part of the building was probably used as a living quarter, being more robust, larger, and showing the traces of mortar and reed covering the walls. Some ceramics of pottery usually used for cooking confirm this hypothesis. The floor of these rooms was probably made of wooden boards, or maybe of gypsum tiles (20x20x2.5 cm), some fragments of which were found in the stratigraphy. The annexed rooms are composed of poorly elaborated gypsum blocks kept together with loam and clay, and were probably used as storage rooms or as shelter for animals. Room III delivered a relatively undisturbed stratigraphy, with a layer of ash (probably what remains of a wooden floor) covering a loamy substratum containing a large quantity of archaeological material, contemporary to the construction of the building (XVI-XVII century). Room II was constructed after Room III but the materials recovered here fall in the same period.

4.6. Estimation of volumes

Thanks to the laser scan acquisition and the aerial photographs, a 3D model of the quarry has been constructed allowing for a quantitative estimation of the volumes gypsum quarried (Fig. 10). These estimates rely on some assumptions: the original topography of the area in which the quarry lies is unknown. We used the borders of the quarry today and reconstructed two different possible topographies (a plane, Fig. 10A-B and a convex surface, Fig. 10C-D), thus obtaining two different estimates of the total possible amount of gypsum blocks extracted from the quarry.

The topography of the quarry prior to the archaeological excavation also relies on a reconstruction based on the present position of the upper borders of the quarry. These borders, and especially the higher (southern) ones, might have undergone more substantial lowering by surface denudation (dissolution) than the quarry floor, which was covered by soil and more protected from dissolution. This most probably leads to an underestimation of gypsum removed from the site. The estimates of total quarried gypsum range from 1300 m^3 considering a flat upper surface, to 2000 m^3 supposing the surface topography was more convex. It is safe to think the real amount of quarried gypsum blocks should fall in between these two values.

5. Discussion

Gypsum in Emilia Romagna region has been quarried for centuries, in the Roman period, during the Medieval, and until the 70 s. Now most quarries are closed and the gypsum areas protected by national and regional laws (almost all evaporite areas in this regional are regional parks or natural reserves). The most intense exploitation

Fig. 7. Signs of excavation in the quarry: A. The straight groove on the floor of the third bench; B. Pick marks on the vertical wall of the quarry between the second and third bench (arrow highlights the area with the most evident grooves (dashed lines)); C. More or less defined block to be extracted (note the upper severely dissolved part), with the signs at its base where the wedges were inserted; D. Artificially enlarged and plastered cone-shaped pit and, to its right, a gypsum block partially prepared for extraction; E. Partially isolated gypsum block on the corner. Meter for scale.

period is the period covering the XI-XIV centuries, when many Medieval towns used gypsum blocks for the construction of walls and the foundation of the major buildings. Many of these Medieval quarries exploited gypsum in the same places where Romans used to carve the rock, and therefore traces of the older Roman quarries are very hard to find, since they have been destroyed and overprinted by later quarrying works.

The Ca' Castellina quarry was thought to be one of those Medieval extraction sites, possibly related to the building of the nearby VIII century Castle on Mt. Mauro (Guarnieri, 2019). But the nearby presence of several *lapis specularis* quarries, discovered in the last decades (e.g. Lucerna Cave, I-V AD) casted some doubts on this chronological collocation. The archaeological excavations initially confirmed the Medieval-historical age of the quarry, with the remains of the small house (XVI-XVII century). However, the presence of archaeological, albeit transported, material of protohistoric age (probably Late Bronze age) in the first loamy layer overlying the quarry floor again pointed to the possibility that the quarry was much older. The size of the blocks that were extracted, based on a significant number of measurements, is only in part compatible with Roman measures (pes = foot = 29.6 cm; ¾ pes = 22.2 cm; cubitum = cubit = 44.4 cm). A series of measurements on blocks in three areas of the quarry are much larger (62^{+6}_{-7} cm) and might reflect a later excavation period, possibly related to the building of the Medieval house. This is confirmed by the fact that all these measurements relate to blocks located in the highest lying areas (and thus possibly most recent ones) of the quarry. All other measured blocks have measures that are slightly higher than the cubitum (average length of 47 cm) and slightly lower than the pes or higher than ¾ of a pes (average width of 22 cm). Measures made on walls A, B, and C are more corresponding (30, 22, and 44 cm respectively), with the exception of the five measures made on wall D (close to the large

Table 1
Measures (in metres) of length *L*, width *W*, and height *H* of gypsum blocks in four areas of the quarry (see Fig. 8).

Block 1			Block 2			Block 3			Block 4			
W	***L***	***H***	***W***	***L***	***H***	***W***	***L***	***H***	***W***	***L***	***H***	
0.62	1.80	0.24	0.20	0.42	/	0.22	0.53	0.08	0.27	0.53	/	
0.61	1.71	0.25	0.18	0.47	/	0.18	0.51	0.09	0.32	0.55	/	
0.59	1.69	0.22	0.23	0.46	/	0.21	0.52	0.07	0.23	0.54	/	
0.55	1.74	0.26	0.22	0.48	/	0.25	0.46	0.08	0.25	0.48	/	
0.63	1.72	0.25	0.23	0.43	/	0.23	0.42	0.11	0.33	0.44	/	
0.61	1.68	/										
0.66	1.68	/										
0.68	1.65	/										
0.60	1.63	/										
0.62	1.64	/										
0.62	***1.69***	***0.24***	***0.20***	***0.45***		***0.22***	***0.49***	***0.09***	***0.28***	***0.51***		
Block 5			Block 6			Block 7			A	B	C	D
W	***L***	***H***	***W***	***L***	***H***	***W***	***L***	***H***	***H***			
0.70	1.56	/	0.23	0.40	0.24	0.80	1.44	0.37	0.33	0.17	0.42	0.58
0.76	1.56	/	0.22	0.41	0.23	0.78	1.41	0.40	0.32	0.19	0.45	0.61
0.78	1.61	/	0.23	0.43	0.25	0.77	1.46	0.40	0.27	0.23	0.43	0.62
0.79	1.57	/	0.23	0.46	0.25	0.78	1.51	0.39	0.29	0.21	0.52	0.55
0.80	1.59	/	0.19	0.48	0.22	0.76	1.42	0.42	0.31	0.25	0.45	0.53
0.75	1.55	/	0.20	/	0.21	0.75			0.31	0.26	0.41	
0.73	1.56	/	0.22	/	0.19	0.74			0.32	0.22	0.41	
0.69	1.54	/	0.17	/	0.25	0.72			0.27	0.23	0.44	
			0.18	/	0.21	0.71			0.26	0.21	0.42	
			0.19	/	0.24	0.76			0.27	0.18	0.45	
0.75	***1.57***		***0.21***	***0.44***	***0.23***	***0.76***	***1.45***	***0.40***	***0.30***	***0.22***	***0.44***	***0.58***

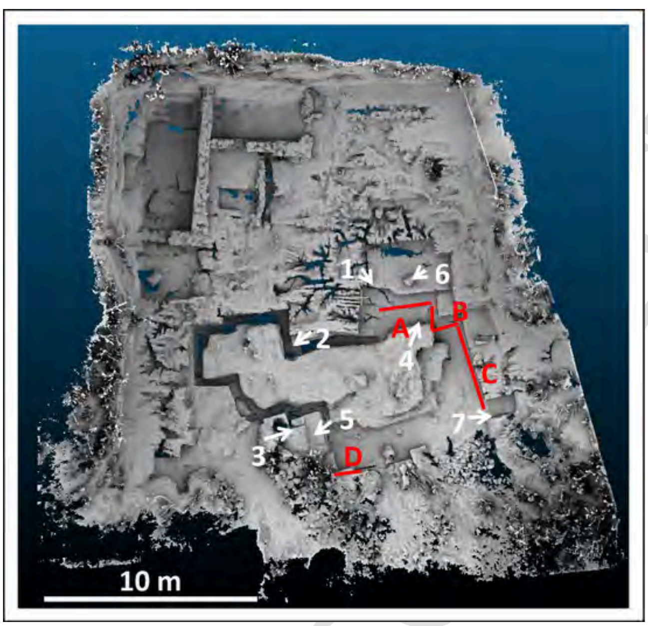

Fig. 8. The areas in which blocks were measured.

Block 5), which are much higher (mean measure of 58 cm). The size of the blocks, although compatible with Roman measures, are thus not a clear proof of the Roman age of the quarry.

When quarries are associated to important roman infrastructures (such as the *Via Appia* South of Rome) different measurements of blocks and overall shape of the quarries can allow to distinguish Roman from Bourbon age (XIX century) extraction periods (Di Luzio and Carfora, 2018). In the North-African Arab world, quarries were often used in different periods spanning from the Roman age to well into the XIX century, and extraction techniques did not differ substantially. Pick and tool marks can thus not be used to date these quarries, and nor does the measure of the extracted blocks allow to give a firm chronological clue. In these cases, the presence of Roman buildings nearby, and measurements of blocks used in these constructions and those carried out in the ancient extraction sites can indicate a Roman age to some quarries (Gaied et al., 2010). Extraction techniques used during Roman times are well-known from numerous studies in quarries of different lithologies (limestone, calcarenite, marble, basalt, etc.) in the Mediterranean area (Bessac, 1988). Similar techniques have surely been used in the Ca' Castellina gypsum quarry, where the soft rock could easily be carved by classical Roman tools such as picks, double-pick hammers, pick-axes, iron wedges and sledge-hammers (Rockwell, 1990; Coli et al., 2011).

Fortunately, the radiocarbon dating of a charcoal fragment taken in the layer immediately covering the quarry floor did not leave any doubt: 2190 ± 30 yr BP (IV-II century BC). This is the period in which the Roman empire settled in this area, with the construction of cities such as *Forum Cornelii* (today's Imola, II century BC) (Susini, 1957) and *Faventia* (today's Faenza, III century BC) (Guarnieri, 2000). Ca' Castellina is, therefore, a Roman gypsum quarry for construction material of this period in the region, and among the few that arrived almost intact to us in the Mediterranean area.

Archaeological and stratigraphic evidence suggests this quarry to have been active for a short period of time, and then abandoned rather quickly (Fig. 11). The whole quarry site was covered with debris and soil almost immediately after abandonment, thus preserving the rock floor and the numerous pick marks and grooves made to extract the gypsum blocks. Gypsum, in fact, is a very soluble rock, with a solubility of 2.4 g L^{-1} (Sanna et al., 2010), and it is also a mineral with very low hardness (2 on the Mohs scale), and thus eroded very easily. Lowering rates of a horizontal gypsum surface in the Mediterranean area, normalized to an annual rainfall of 1000 mm (which is

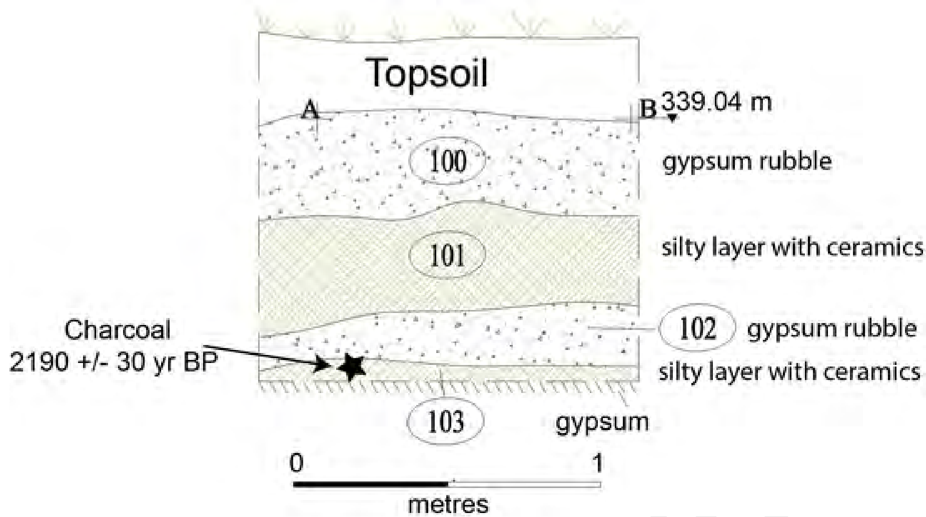

Fig. 9. Stratigraphy of the exploration trench dug in the central part of the quarry. The dated charcoal fragment was one of 10 pieces recovered from this surface, in contact with the underlying gypsum, in an area with widespread traces of fire.

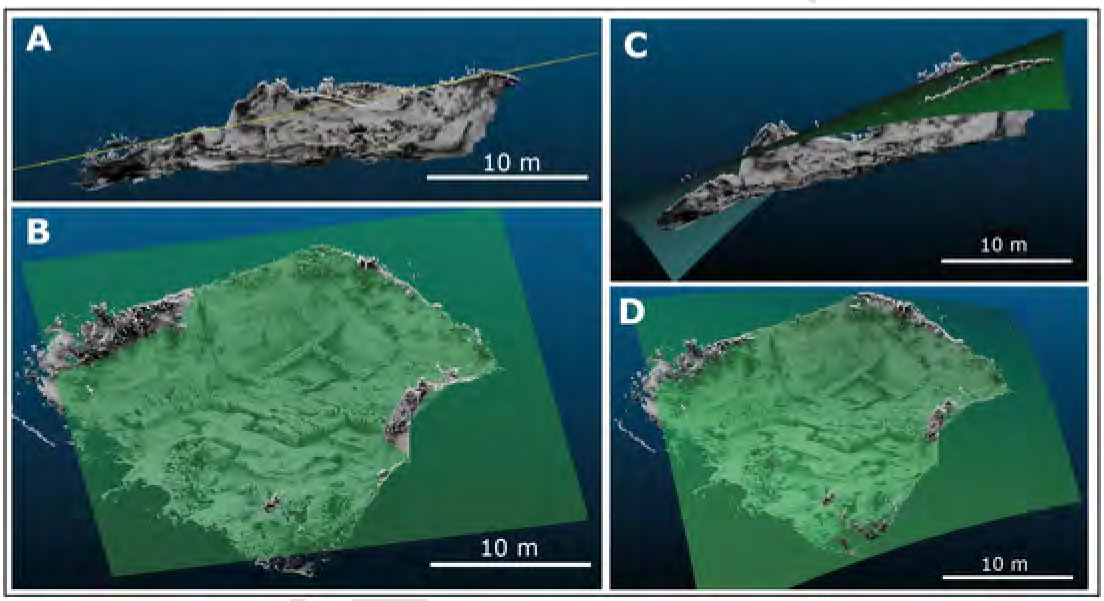

Fig. 10. Estimation of volume of the quarried gypsum blocks. A. Profile view and B. Upper overview of the plain reference surface, and C. Profile and D. Upper view of the convex surface used to estimate the quarried volume of gypsum.

the mean annual rainfall of the study area) are around 0.70 ± 0.17 mm yr^{-1} (Cucchi et al., 1998). Near Bologna (Cava a Filo, Forti, 2005) this value ranged between 0.69 and 0.91 mm yr^{-1} on the macrocrystalline variety of the Messinian gypsum (selenite). Considering the fact that the microcrystalline variety of Messinian gypsum, such as the one of Ca' Castellina quarry, is slightly more soluble, we can hypothesize a mean denudation rate of 1 mm yr^{-1} for our study site.

At this rate of dissolution (denudation) the bare horizontal rock surface would have lowered for 2 m over the last two millennia. Instead, because of the protective cover of soil, this dissolution and erosion was almost completely inhibited. Dissolution on the original Roman quarry floor was focused in a few places, where concentrated water infiltrated from above, with the creation of the couple of cm deep runnels. These channels, located below important karren fields, testify to the activation of intense runoff, with consequent piping phenomena at the contact between soil/debris and gypsum rock. This has occurred at an overall downcutting rate of less than 0.025 mm yr^{-1}.

The karren fields in the central part of the quarry do demonstrate that dissolution by surface waters has occurred at some stage. The deepest karren features reach 1 m depth, which would lead to a formation period of 1000 years, using the mean denudation rate mentioned above. However, concentrated runoff on gypsum surfaces cause denudation rates ten times greater than normal (10 mm yr^{-1}) (Forti, 2005) and it is thus plausible to give them a timeframe of a century to form. Their location surrounding the building suggests them being genetically related. The highest quarry bench, with block size of over 60 cm (far from the normal Roman measures), is also probably of the same Medieval age. We believe that the quarrying of the larger blocks, and the karren fields formed during the occupation of this building, thus during the XVI-XVII century (Fig. 11).

The smooth 2-metre wide gypsum patch NW of Room III along the borders of the quarry, in which there is no trace of karren formation, might be explained by their regular use (access to the house),

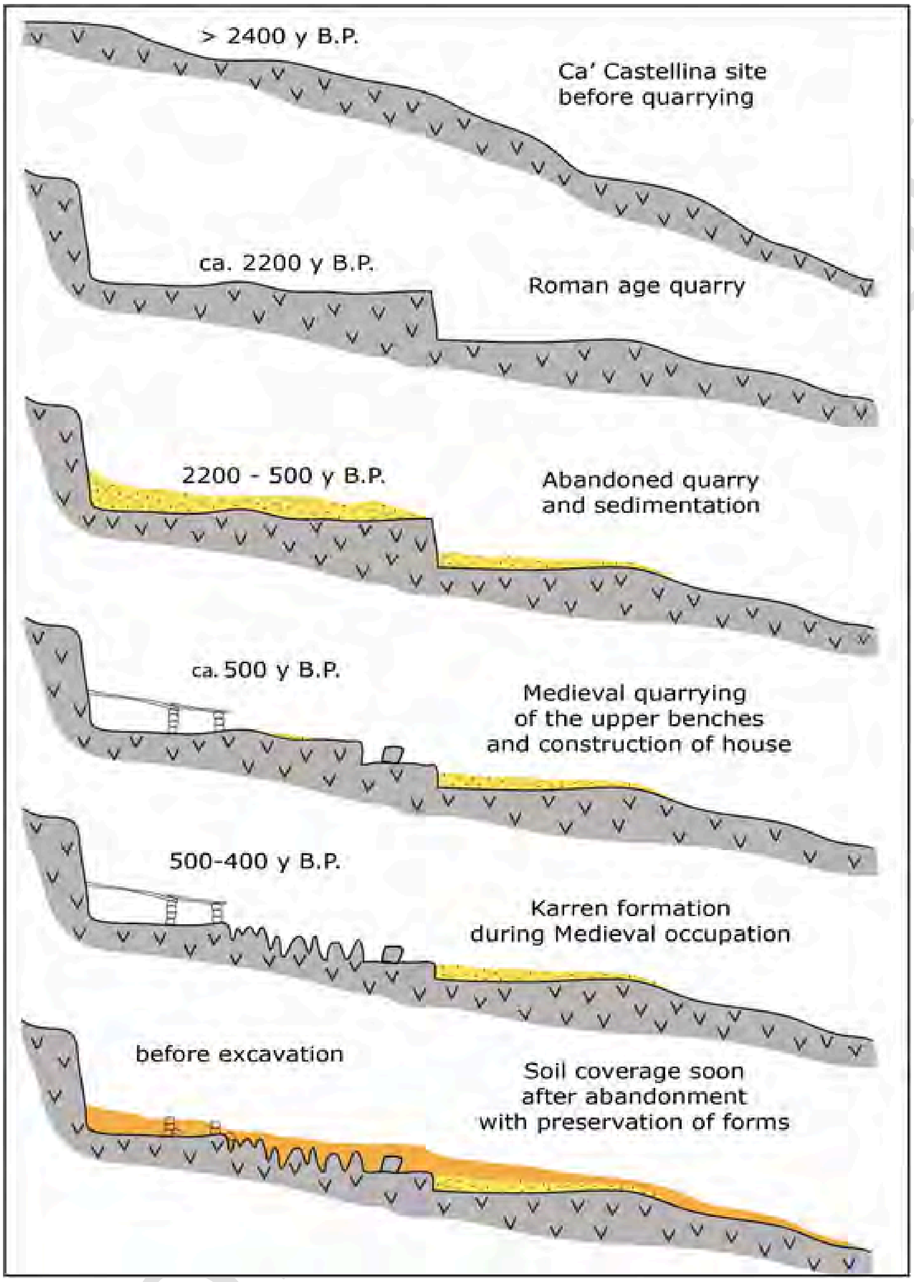

Fig. 11. Evolution of the Ca' Castellina gypsum quarry. Gypsum is shown in grey (with v symbols), the dotted lighter tones are covering sediments (two generations). See text for a detailed description of the different phases.

making erosion (by walking) prevail over dissolution. The rather fresh appearance of all these features (the karren field and the smooth surfaces) suggest their complete coverage with a thin layer of soil, inhibiting their further rapid erosion-dissolution, soon after the abandonment of the house.

A final consideration is related to the use of the quarried gypsum blocks in Roman times. Our estimations suggest a total volume comprised between 1300 and 2000 m^3 of gypsum to be quarried from this site alone (corresponding to approximately 59,000–91,000 blocks of gypsum like the ones found almost intact in the quarry). This would allow for the construction of a wall 2.9–4.5 km long and 2 m high, for a width of 22.2 cm. Such a wall, free of soil and subdued to surface weathering, would have been entirely dissolved away in 2,000 years. If these blocks would have been used for the construction of local structures, nothing would be left, or their remains would have been covered entirely by soil. Their use for construction of building related to the extraction sites of *lapis specularis* is highly unlikely, given their age difference (at least three centuries apart). In summary, there is no evidence whatsoever, in the neighborhood, of important buildings or structures of Roman age. Another possibility would be the use of these blocks for the construction of important monuments in the Roman cities of *Forum Cornelii* and *Faentia*. This would have been possible bringing the quarried blocks down to the Sintria and Senio Valleys, to be then transported by small vessels for 15 km northward, to the *Via Aemilia*, and from here to the two cities. However, no traces of gypsum blocks were yet found in these cities, and it remains unclear why the Romans would have chosen Ca' Castellina as a quarrying site, other possible gypsum sites being more accessible and closer to the cities.

6. Conclusions

Our investigations have confirmed the Ca' Castellina quarry to be of Roman age, based on a series of evidences including a radiocarbon date of charcoal in contact with the quarry floor, the recovery of archaeological material from Late Bronze to historical age, and the size of the quarried blocks (using Roman units such as *pes*, ¾ *pes* and *cubitum*). The quarry site has been protected by soil cover for most of the time after abandonment, with a short (probably two-century) interruption in the XVI-XVII century, when a building was constructed and inhabited for a rather short time, thus causing some further modification and quarrying of the most exposed areas in the quarry. During the entire two millennia since its abandonment most of the quarry floor, benches and faces were protected from natural dissolution and erosion, except for some extremely localised spots. The original traces of the Roman quarry-men, such as grooves and carvings made by pick-axes, and holes in which wedges were inserted, are still well-visible in several areas of the quarry. This makes the area unique and worthy to be preserved and protected.

The laser scanning survey, together with the drone-supported 3D photogrammetry, besides having given the chance to study in detail the archaeological site, also have fixed the *status quo* of this quarry at the time of excavation. Unfortunately, it will be extremely difficult to make this Roman extraction site a place to visit by tourists, which would require the construction of a protective cover and adequate measures of protection of the quarry rocky substrate. It is therefore advisable to cover the site with impermeable material, and construct an efficient drainage system, in order to inhibit the contact of running surface waters with the naked gypsum rock.

This Roman quarry can be made open for visits in a digital manner, with a realistic 3D reconstruction of the site, and virtual reality visits, without compromising the integrity of this unique site. Regarding the destination of the quarried gypsum blocks, on the other hand, further research will be necessary, and only a few hypotheses can be forwarded.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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