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1 Quantifying 450 years of limestone weathering

2 induced by salt crystallization on fortifications in Malta and Gozo

3
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15 16 **Highlights**

- 17
- 18 • SfM photogrammetry and on-site tests were carried out on Maltese fortifications.
 - 19 • A two-rate weathering regime was highlighted within the building limestones.
 - 20 • Cohesiveness and water uptake capacity were identified as controlling factors.
 - 21 • There is no straightforward correlation between durability and surface hardness.
- 22

23 **Abstract**

24

25 Structure from Motion (SfM) photogrammetry, on-site hardness and water absorption tests,
26 and petrographical and porosimetric analyses on targeted samples were carried out on
27 representative areas within six different locations of Maltese fortifications affected by salt
28 weathering. The objective was to quantify the limestone loss over the last half-millennium and
29 to attempt to identify the controlling factors of durability. The results highlight the existence
30 of a two-rate weathering regime within the Miocene Globigerina Limestone which is the main
31 building stone of the Maltese Islands. With a median stone recession of 1.4 mm/century, the
32 subtype locally called *Franka* has resisted atmospheric aggression on average 36 times better
33 than the *Soll* subtype (median stone recession of 50 mm/century). The Oligo-Miocene
34 Coralline Limestone has also resisted well, with a stone recession of on average 1.3
35 mm/century. Two main controls of the varying durability of these limestones have been
36 identified. First, the water uptake capacity of the least durable, already weathered limestone
37 (*Soll*) is two to three times higher than that of the weathered but more resistant *Franka* and
38 Coralline Limestone ($6.3 \text{ g.m}^{-2}.\text{s}^{-1}$ against $2.5 \text{ g.m}^{-2}.\text{s}^{-1}$). Second, there is a marked difference in
39 cohesiveness between these limestones. Whereas the weathered, susceptible *Soll* facies is
40 poorly-cemented or microcracked, the exposed durable *Franka* displays an abundant micritic
41 and microsparitic matrix. The statistical relationship between durability and surface hardness
42 is not straightforward, and other controls such as the clay content of limestones should be
43 explored. Investigating a larger number of sites would allow the refining of the limestone
44 durability scale inferred from the present study.

45

46 **Keywords**

47 Salt weathering

48 Limestone weathering rates

49 Maltese Islands

50 Mediterranean fortifications

51

52 **1. Introduction**

53

54 Limestone has been widely used as building stone over the millennia, and the complexity of
55 decay patterns in this rock material subject both to chemical and mechanical weathering has
56 been thoroughly studied (see an overview in Smith et al., 2010). Regarding quantitative
57 studies, a large number of long-term weathering rate studies are available for carbonate
58 stones used in continental and urban monuments, including tombstones (from Geikie 1880 to
59 Meierding 1993). However little is known about historical weathering rates in coastal areas,
60 except for marble (e.g. Cooke et al., 1995; Inkpen and Jackson, 2000), which are
61 metamorphosed carbonate rocks that behave quite differently from sedimentary limestones
62 which are the focus of this paper. To date, only three studies provide historical weathering
63 rates for coastal limestone monuments (Viles and Goudie, 1992; Augeyre 2006, 2008; Gruson,
64 2013) and they are all restricted to the European Atlantic coast (Table 1). At these sites in S
65 England and SW France, most available recession rates range on average from 1 to 3 mm per
66 century, except for micritic and platy limestones which display much faster recession rates
67 (from 5 to 28 mm per century) than sparitic limestones.

68

69 As far as can be ascertained, no quantitative data has been published to date for coastal
70 historical monuments of the Mediterranean Basin, where extensive outcrops of Oligo-
71 Miocene soft and highly porous limestones, easy to carve, have been quarried for millennia

72 and widely used for building and decoration. It is especially the case in the Maltese Islands
73 which display a rich architectural heritage, including prehistoric temples, Baroque palaces and
74 defensive structures, of which several are inscribed by UNESCO as World Heritage Sites. Most
75 monuments are built in Oligo-Miocene Globigerina Limestone which has been recognized in
76 2019 by the International Union of Geological Sciences (IUGS) as a Global Heritage Stone
77 Resource, following a proposal submitted by the Faculty for the Built Environment and the
78 Department of Geosciences of the University of Malta (Cassar et al., 2017).

79

80 The Globigerina Limestone dates back to the early to mid-Miocene (Aquitanean to Langhian
81 stages, 23–14 Ma) and is 20 to 200 m thick (Pedley, 1976, see also the geological map available
82 at continentalshelf.gov.mt). It has been extensively studied over the last decades (e.g. Cassar,
83 2002, 2004, 2010; Fitzner et al., 1996; Gatt, 2006; Rothert et al., 2007; Vannucci et al., 1994;
84 Zammit and Cassar, 2017). It is a honey-coloured, fine-grained and soft biomicritic limestone,
85 containing > 92% calcite and small amounts of clay minerals, and often displaying bioturbation
86 features (Gatt, 2006). This rapidly absorbing stone has a high porosity, ranging from 24 to 41%
87 (Cassar et al., 2017). In the Maltese salt-laden marine environment (Torfs et al., 1996), many
88 monuments built in Globigerina Limestone have been subject to deterioration and often
89 display conspicuous forms of alveolar weathering (or honeycomb weathering) such as those
90 present on the severely decayed statues of St. Margaret Church at Sannat, on the Island of
91 Gozo (Fig. 1). Alveolar weathering due to salt crystallization is a leitmotiv in the Maltese
92 landscape, and its development has been suggested by Vannucci et al. (1994), Fitzner et al.
93 (1996) and Rothert et al. (2007) to follow a five-stage sequence, from sound stone to totally
94 back-weathered stone, as illustrated in Fig. 2. Gatt (2006) has also proposed a model linking
95 the level of heterogeneity of the Globigerina Limestone to the mode of salt weathering. The

96 severity of weathering damage at some Maltese sites has motivated in the last decades both
97 protective measures such as the installation of polytetrafluoroethylene (PTFE) membranes
98 supported by steel arches anchored by cables over some Megalithic Temples (Cassar et al.,
99 2011, 2018) and extensive restorations of fortifications and historical buildings (Spiteri, 2011).

100

101 Although usually visually homogeneous when freshly cut, the Globigerina Limestone displays
102 two facies, that should be considered as the end members of a variety of subtypes (Diana et
103 al., 2014). These two subtypes can be differentiated on abandoned quarry faces, as recognized
104 for centuries by quarry workers and stonemasons, where a resistant facies traditionally called
105 *Franka* hardens when exposed to the air whereas a less resistant facies traditionally called *Soll*
106 rapidly powders away. They can also be distinguished through salt weathering tests (Fitzner
107 et al., 1996; Rothert et al., 2007; Cassar et al., 2008). Laboratory analyses indicate that the
108 phyllosilicate content of *Soll* is up to four times higher than the one of *Franka* (12% against 3%
109 according to Cassar 1999). Moreover, Cassar (2002) and Rothert et al. (2007) have shown that
110 *Franka* displays larger pores than *Soll* (67% >1 μ m and 33% <1 μ m for *Franka* against 42% >1 μ m
111 and 58% <1 μ m for *Soll*). And recent analyses performed by Zammit and Cassar (2017) have
112 confirmed that the resistant facies (*Franka*) is characterised by a higher macroporosity and a
113 less abundant insoluble residue than *Soll*.

114

115 As an additional building stone, Coralline Limestone is less abundant in outcrop in the Maltese
116 Islands than the Globigerina Limestone (Fig. 3). The Lower Coralline limestone dates back to
117 the Upper Oligocene (Chattian stage, 28-23 Ma) and is up to 140 m thick, whereas the Upper
118 Coralline limestone dates back to the Upper Miocene (Messinian stage, 7-5 Ma) and is up to
119 160 m thick (Pedley, 1976, see also the geological map available at continentalshelf.gov.mt). The

120 Coralline limestone has been empirically recognized for millennia as a resistant building stone.
121 For this reason, it has been used to build the external walls of the Mnajdra and most of
122 Ġgantija prehistoric temples as well as some of the fortifications of of the Gozo Citadel
123 (Cassar, 2002), and the lower courses of ramparts (Spiteri 2008). The porosity of the Coralline
124 Limestone ranges from 2 to 30% (Bonello, 1988).

125
126 Based on this characterization of limestones by previous researchers, the present study was
127 carried out by a multidisciplinary team composed of geomorphologists, archaeologists, GIS
128 scientists and geologists. The objective was to provide quantitative evaluations of the
129 limestone loss having affected monuments of Malta and Gozo over the last half-millennium
130 and to analyze differences between stone types. Study sites were selected among the coastal
131 fortifications erected by the Knights of St John between 1530 and 1798, to protect Malta and
132 Gozo from the expanding Ottoman Empire (Spiteri 2001).

133

134 **2. Study sites and historical context**

135

136 In order to measure limestone recession over the last half-millennium at the surface of
137 Maltese fortifications erected by the Hospitaller Knights of the Order of St John, Structure
138 from Motion (SfM) photogrammetry was carried out in six defensive structures that had
139 undergone limited interventions or none, and still displayed original reference surfaces, i.e.
140 zero datum levels. The test sites were selected based on their construction period, their
141 homogeneous petrography and their accessibility. Extensively restored heritage buildings
142 such as the Gozo Citadel and the Mdina and Vittoriosa fortifications were avoided, but
143 selecting completely untouched defensive walls proved to be difficult due to the importance

144 of restoration works undertaken in the Maltese Islands in the 2000s-2010s (Spiteri, 2011). Of
145 the six investigated ramparts, two are located in the Valletta Ditch, two in Fort St Elmo area
146 and two at Fort Chambray in Gozo (Table 2).

147

148 The first study area is located in the Valletta defensive ditch (Fig. 4A and 5A-B), in the SW part
149 of the Valletta fortified city. This walled city was designed by the Papal engineer Francesco
150 Laparelli, and built in Globigerina Limestone between 1566 and 1570, just after the Great Siege
151 of 1565 (Spiteri, 2001). The site for measuring limestone loss was selected in a non-restored
152 part of the ditch, of particular interest because of its alternating *Franka* and *Soll* layers
153 (determined visually), and of the remarkable preservation of original tooling marks in places.
154 This part of the ditch wall faces the east. To make the comparison between stone materials
155 easier, sections of the investigated photogrammetric imagery in *Franka* have been
156 denominated Site 1 and sections in *Soll* appear as Site 2.

157

158 Site 3 is located in Abercrombie's Curtain. It is part of Fort St Elmo which is located at the NE
159 tip of the Valletta fortified city (Fig. 4 and 5 C). The investigated section of fortifications faces
160 the south-east direction and belongs to the external Carafa bastioned Enceinte designed by
161 Don Carlos de Grunenbergh and built in 1687-89 on the foreshore surrounding the Fort to
162 secure it (Spiteri, 2001). This curtain wall consists of Coralline Limestone. The lime mortar
163 between ashlar blocks is barely visible for it has been eroded from the surface. No repointing
164 of mortar joints had been done at the time of the study.

165

166 Site 4 is located in the NE part of the French Curtain, beneath Fort St Elmo (Fig. 4A and 5D).

167 This curtain wall faces the north-west direction and was built in Globigerina Limestone in the

168 same period as the Carafa bastioned Enceinte (1687-1689), as documented by a plan drawn
169 by the French military engineer Mederico Blondel (Spiteri, 2001, p. 260). The upper part of the
170 wall had been subject to some modifications, possibly during the reign of Grand Master Pinto
171 (1741-1773). In places, the surface of the ashlar blocks displays remnants of old lime render
172 containing coarse sands. The characteristics of this material, which differ from recent lime
173 renders, allow one to conclude that this material predates the mid-1870s, which is the period
174 when cement was definitely in use in Malta (Cassar, 2010). It might have been applied in
175 response to the rapid backweathering of the low quality Globigerina Limestone (*Soll* subtype)
176 used as building stone at this site.

177

178 Sites 5 and 6 were selected at Fort Chambray, in the eastern part of the Island of Gozo (Fig. 4).
179 The construction of this fortress overlooking Mgarr harbour has been retraced by Buhagiar
180 and Cassar (2003) based on historic sources. Fort Chambray was designed in 1716 by the
181 French military engineer Louis François d'Aubigné de Tigné, but due to a lack of funding, its
182 construction was postponed until 1749. At that time, Jacques-François de Chambray,
183 Governor of Gozo, financed the construction and preliminary excavations started based on
184 Tigné's original design modified by Francesco Marandon. Work on the Fort itself began in 1752
185 and was completed by 1760. Stone quality was adjusted to strength requirements in the
186 different parts of the Fortress: on the exposed external wall of the right ravelin (site 5 facing
187 the north-west, Fig. 5E), a high quality Globigerina Limestone (*Franka*) was selected, whereas
188 a lower quality Globigerina Limestone (*Soll*), more prone to honeycomb weathering, was used
189 for the counterguard (site 6 facing the south-west, Fig. 5F). In both places, the surface of a
190 number of stones has retained tooling marks. The original mortar has been partly eroded in

191 the counterguard and is therefore hardly visible at the surface. The external wall has been
192 recently repointed and currently displays light-coloured smooth joints of lime mortar.

193

194

195 **3. Methods**

196

197 Methods combine stone-by-stone analysis of tool marks, photogrammetrical surveys and non-
198 destructive and non-invasive on-site hardness and contact sponge tests, aiming to
199 differentiate the stone materials of the investigated ramparts. Additionally, only a limited
200 number of laboratory analyses could be carried out due to sampling restrictions at heritage
201 sites.

202

203 **3.1. Identification of zero datum levels**

204

205 At each site, the identification of tool marks allowed the inference of both the type of
206 stoneworking tools used for the construction and also to identify secure reference surfaces
207 according to the method used by André and Phalip (2010). These tentative reconstructions of
208 'zero datum levels' allowed the quantitative assessment of the amount of stone decay based
209 on photogrammetric methods.

210

211 **3.2. SfM photogrammetry**

212

213 Structure from Motion (SfM) photogrammetry is an established and widely used method to
214 generate high resolution 3D scans, with applications in geoscience, archeoscience and cultural
215 heritage science (Smith et al., 2015; Historic England, 2017; McCarthy, 2014). This method,
216 which allows the obtaining of a high accuracy on weathered rock surfaces with areas < 10m²
217 (Verma and Bourke, 2019), has already been used for the quantitative assessment of historical
218 weathering rates in limestone monuments such as Mayan temples (Roussel and André, 2013).
219 In the present study, the close-range SfM method was used to produce high resolution 3D
220 models of representative areas of the weathering state (RAWS) of the ramparts, which
221 attributes are described in Table 2.

222

223 Photographs were collected with a Nikon D700 digital camera (12.0 megapixels) with a 35 mm
224 focal length lens to limit distortion effects. At each site, the RAWS was selected based on the
225 representativeness of the erosional processes observed on the fortified wall (above the rising
226 damp front), the necessity to avoid the occurrence of strong contrasts and the presence of
227 objects hindering the taking of photographs. A first series of photographs was taken
228 perpendicular to the ramparts, completed with a series of converging photographs. The
229 shooting distances ranged from 2 m to 6 m, depending on the area of the RAWS. Each point
230 within the RAWS was covered by at least five photographs to avoid the computation of
231 outliers. Scale bars (ruler or measuring tape) were set up around the study areas.

232

233 For each RAWS, data were processed as follows. The 3D reconstruction was performed
234 following the standard workflow of the Agisoft Photoscan Professional software (Westoby et
235 al., 2012; Agisoft 2014) to produce a dense coloured point cloud with a resolution depending
236 on the area of the RAWS, between 5 mm and 10 mm, and a scale bar error less than 3 mm.

237 This cloud was imported into the ArcGIS 10.2 software and converted into a digital elevation
238 model (DEM) in raster format (tiff) using ArcGIS 10.2. The reference surface (zero datum level)
239 was produced by selecting the points located in non-eroded areas of the dense cloud, some
240 of which exhibited original tooling marks. Selected points were then interpolated (with a linear
241 interpolation) to produce the reference surface raster. Reconstructing the reference surface
242 was not a straightforward process in severely weathered zones, where tool marks were hardly
243 visible. In these cases, protruding areas or 'hard points' were used to reconstruct a minimal
244 reference surface. For each RAWS, a model of stone recession since construction was
245 computed as the result obtained from the DEM raster being subtracted from the reference
246 surface raster. Finally, stone recession rates in mm/century (mm.C^{-1}) were computed as the
247 ratio between the recession model and the weathering period (Table 2).

248

249 3.3. Contact sponge tests

250

251 On-site contact sponge tests were carried out to comparatively assess the water uptake
252 capacity of the different investigated limestone materials. This method, developed by Pardini
253 and Tiano (2004) is known to usefully complement the Karsten pipe and capillary rise methods
254 (Vandervoorde et al., 2009). It is a non-destructive, non-invasive and portable method which
255 consists of a 1034 Rodac contact-plate, 5.6 cm in diameter, containing a Calypso sponge which
256 is filled with approximately 7 g of water and weighed on a precision balance. The contact-plate
257 is pressed manually against the stone surface for a given time (30 or 60 seconds), and the
258 sponge is weighed again after this contact with the stone surface. The difference between
259 weights corresponds to the amount of water absorbed by the stone surface under test. Water
260 absorption is expressed in $\text{g.m}^{-2}.\text{s}^{-1}$. At each investigated site, three even-surfaced ashlar

261 blocks representative of the local petrography were selected. On each block, three contact
262 sponge tests were performed, for a total of 54 tests carried out over the 6 investigated sites.

263

264 3.4. Hardness tests

265

266 Surface hardness measurements of limestone material were made on-site using an electronic
267 rebound tester. The Proceq Equotip Piccolo 2 is a portable instrument, less destructive (impact
268 energy less than 11.5 Nmm with the D probe) and as reliable as the Schmidt Hammer (Aoki
269 and Matsukura, 2007; Viles *et al.*, 2011; Desarnaud *et al.*, 2019). Automatic compensation of
270 impact direction allows measurements on vertical surfaces of the ashlar composing the
271 investigated walls. Hardness values are directly readable on an LCD and are expressed in Leeb
272 hardness using the D-probe (HLD) defined as the ratio of the rebound velocity to the impact
273 velocity multiplied by 1000. At the six investigated sites, the hardness values were determined
274 using the single impact (SIM) procedure (Desarnaud *et al.*, 2019): sole measurements were
275 collected at individual points within a sample area to produce robust summary statistics. In
276 this study, at least 20 individual measurements were made on 3 different ashlar for each
277 study site. Overall, a total of 380 measurements were obtained to compare the hardness of
278 the three limestone materials (*Franka*, *Soll* and Coralline limestone).

279

280 3.5. Laboratory analyses

281

282 Only four limestone samples detached from the investigated ramparts could be analyzed,
283 including *Soll* and *Franka* Globigerina Limestones of Fort Chambray and the Valletta Ditch.

284 Sampling was impossible in the Fort St Elmo area: the detached *Soll* material of the French
285 Curtain was too powdery to be sampled and the hard Lower Coralline Limestone of
286 Abercrombie's Curtain did not provide any detached fragments. As two samples for *Franka*
287 and *Soll* had been collected, for comparison two fragments of the Coralline Limestone blocks
288 being used to repair the Gozo Citadel outer walls were also sampled.

289

290 To provide microscopic views of the limestone types and to realize petrographical analyses,
291 plane sections were ground flat using SiC powders, and then polished by hand. Stone samples
292 were cut to fit a 45x30 mm glass slide and impregnated with an epoxy resin under vacuum
293 before making 30 µm thin sections. These were examined using an optical polarizing
294 microscope (Olympus BX61) equipped with a camera (Qicam Fast 1394 color) linked to the
295 software Saisam from Microvision instruments.

296

297 To assess the total porosity (P_c) and the pore access distribution of the stones, mercury
298 intrusion porosimetry (MIP) was performed on samples of size 1 cm³ with a Micromeretics
299 AutoPore IV 9500. According to the method, the pore access radius measured by the
300 instrument ranges from 200 µm (0.003 MPa) to 0.003 µm (207 MPa). Thus, pores of larger
301 access radius such as macropores of 0.2 mm diameter and pores of smaller access radius of
302 0.003 µm were not taken into account. Spreading of the cumulative curve and thus
303 heterogeneity of the material, can be defined by the scatter coefficient (C_d) calculated from a
304 ratio of pores access radii (Wardlaw et al., 1988; Remy, 1993):

305
$$C_d = \frac{r_{20} - r_{80}}{r_{50}}$$

306 where r_{80} , r_{50} and r_{20} are the pore access radii allowing respectively the filling of 80, 50 and
307 20% of the porous network. If $C_d < 1$, the pore distribution is concentrated around one pore
308 radius, and a mean pore radius (R_m) for which the intrusive volume is maximal can be
309 extracted from the incremental curve. If $C_d > 1$, the pore distribution is spread. This means that
310 the porous network is partitioned into several domains of different pore sizes (Remy, 1993)
311 and no mean pore access radius can be determined by the incremental curve. The proportion
312 of pore access larger than 1 μm and smaller than 1 μm was calculated to compare the results
313 to previous studies (Cassar et al., 2002; Cassar et al., 2017; Zammit and Cassar, 2017).

314

315 3.6. Statistical analyses

316

317 As the distributions of stone recession rates, hardness and water absorption values were not
318 normal, the non-parametric Kruskal-Wallis test and a post-hoc pairwise analysis (Dwass-Steel-
319 Crichtlow-Fligner test) were used to assess the statistical significance of stone recession rates
320 and of hardness and water absorption differences between the investigated materials.
321 Moreover, following the recommendations of Mottershead (2000) and Wilhelm *et al.* (2016),
322 median, median absolute deviation (MAD), the 5th and 95th percentiles were computed for
323 stone recession rates, hardness and water absorption distributions as they are more robust
324 summary statistics for non-normally distributed data (Filzmoser and Todorov, 2013).
325 Additionally, 95% confidence intervals of summary statistics were estimated using a bootstrap
326 technique (resampling with replacement, bootstrap samples = 1000).

327

328 4. Results

329

330 4.1. Identification of zero datum levels

331

332 Tool marks were sought to help to reconstruct the original surfaces and tentatively estimate
333 the limestone loss since construction, based on photogrammetry. At Fort Chambray, both
334 vertical and oblique marks left by toothed stone axes are preserved in the Globigerina
335 Limestone on a number of ashlar blocks of the counterguard (Fig . 6A) and the right ravelin
336 (Fig. 6C). In the Valletta Ditch, marks left by pickaxes are found very well preserved in many
337 places on the high quality Globigerina Limestone (*Franka*) but not on the low quality *Soll* that
338 outcrops as backweathered lenses within the *Franka* (Fig. 6B). The greatest difficulties were
339 met in the St Elmo area. In Abercrombie's Curtain, the Coralline Limestone stone surface has
340 retained very few tool marks, due to the abundance of Coralline algae which make the stone
341 surface rough and irregular compared to the smooth surface of Globigerina Limestone. And in
342 most of the French Curtain, the *Soll* material has been extensively subjected to
343 backweathering, leaving very few intact stones which could have allowed the reconstruction
344 of a reference surface. Although intra-burrow cemented material is often protruding (Fig. 6D),
345 it has been itself subject to weathering and does not indicate the original top surface of the
346 stonework. The zero datum level was therefore tentatively sought in the stones of the upper
347 part of the French Curtain.

348

349 4.2. Weathering rates inferred from SfM photogrammetric analysis

350

351 Computing of 3D models of stone recession such as the one of Valletta Ditch presented in Fig.
352 7 has yielded median values of total stone recession since construction that are ranging from

353 4.1 mm to 179.8 mm (Table 3). Distributions of stone recession values exhibit two contrasting
354 shapes (Fig. 8). The harder limestone types (Coralline Limestone and *Franka* facies of
355 Globigerina Limestone) of sites 1, 3 and 5 show concentrated low values and a very low
356 positive skewness of stone recession distributions ($MAD < 4$). On the contrary, the softer *Soll*
357 facies of Globigerina Limestone of sites 2, 4 and 6 exhibit highly dispersed values (MAD ranging
358 from 38.8 to 81.4) with a strong positive skewness.

359

360 Based on the duration of exposure of the investigated fortifications to the salt-laden corrosive
361 atmosphere, the SfM data yielded median stone recession rates ranging from 1.2 mm to 60.7
362 mm/century (Fig. 9, top). The most resistant limestones, with recession rates ranging from 1.2
363 to 1.6 mm/century, were the high quality Globigerina Limestone (*Franka*) of the Valletta Ditch
364 and Fort Chambray and the Coralline Limestone of Abercrombie's Curtain at St Elmo. By
365 contrast, the low quality Globigerina Limestone (*Soll*) has been subject to rapid weathering, of
366 40.5 mm/century in the Valletta Ditch and 60.7 mm/century in the Fort Chambray
367 Counterguard. The highest recession rates as expressed by the 95th percentile confirm the high
368 contrast between the resistant and the soft facies, with values of 3-10 mm/century for
369 Coralline and *Franka* facies against 109-140 mm/century for *Soll* facies. As to the median
370 recession rate of 21.5 mm/century obtained for the *Soll* of the French Curtain, this could be a
371 questionable value that will be dealt with further in the discussion.

372

373 The Kruskal-Wallis test confirmed that the stone recession rates are significantly different
374 ($\alpha=0.05$; $K= 203929256$; $P<0.0001$). The post-hoc pairwise analysis (Dwass-Steel-
375 Crichtlow-Fligner test) identified five different groups of stone recession rates among the six
376 investigated sites. The first group gathers the undifferentiated lowest recessions rates of the

377 Coralline Limestone of site 3 (Fort St Elmo) and *Franka* Globigerina Limestone of site 1 (Valletta
378 Ditch). The four last groups of stone recession rates contain one site each and are upwardly
379 sorted as follows: The Globigerina *Franka* of site 5 (Fort Chambray), the Globigerina *Soll* of site
380 4 (French curtain), the Globigerina *Soll* of site 2 (Valetta Ditch), the Globigerina *Soll* of site 6
381 (Fort Chambray).

382

383 4.3. Stone characterization based on non-destructive on-site tests

384

385 The results of the contact sponge and surface hardness tests are summarized in Table 4 and
386 Fig. 9. Contact sponge data indicate that the water uptake capacity of *Soll* was on average two
387 to three times higher than that of *Franka* and Coralline Limestone ($6.3 \text{ g.m}^{-2}.\text{s}^{-1}$ against 2.5
388 $\text{g.m}^{-2}.\text{s}^{-1}$). Interestingly, the water uptake capacities of *Franka* and Coralline Limestone are of
389 the same order of magnitude at the investigated sites. The contrast between the two facies
390 of Globigerina Limestones (*Franka* and *Soll*) is particularly striking for the highest values (2.7
391 against $14.6 \text{ g.m}^{-2}.\text{s}^{-1}$ for the centile 95th at the five investigated sites). In the more resistant
392 stone types (Coralline Limestone and *Franka*), data collected on three different stones for
393 every site were quite similar, in sharp contrast with the results obtained for the friable *Soll*
394 material. In particular, the three ashlar blocks tested for the *Soll* material of the French Curtain
395 showed a marked variability in the values of water uptake capacity ($\text{MAD} > 1.0$) as expressed
396 on boxplots (Fig. 9, middle).

397

398 The Kruskal-Wallis test confirmed that the water absorption of the tested materials was
399 significantly different ($\alpha=0.05$; $K=40.449$; $P<0.0001$; the p-value was calculated using

400 10,000 Monte Carlo simulations). The post-hoc pairwise analysis (Dwass-Steel-Crichtlow-
401 Fligner test) identified three different groups of water absorption among the six investigated
402 sites. The first group gathers the undifferentiated lowest water absorption values of the
403 *Franka* Globigerina of site 1 (Valletta Ditch) and the Coralline Limestone of site 3 (Fort St Elmo).
404 The second group contains only the *Franka* Globigerina Limestone of site 5 (Fort Chambray)
405 characterized by intermediate water uptake values. The last group gathers the high values of
406 water absorption of the *Soll* Globigerina Limestone of site 2 (Valetta Ditch), site 4 (French
407 curtain) and site 6 (Fort Chambray).

408

409 Regarding the surface hardness recorded by the Equotip portable tester, the results clearly
410 indicated a gradient in the mechanical resistance of the three tested stone materials (Table 4
411 and Fig. 9, bottom). The Coralline Limestone of St Elmo was by far the hardest material (434.5
412 HLD), followed by the *Franka* (365 and 276 HLD for sites 5 and 1). Last, the *Soll* was the least
413 mechanically resistant material, with median values ranging from 172.5 to 269.0 HLD. Results
414 of the Kruskal-Wallis test confirmed that the surface hardness of the tested materials was
415 significantly different ($\alpha=0.05$; $K=278.34$; $P<0.0001$). Moreover, the post-hoc pairwise
416 analysis (Dwass-Steel-Crichtlow-Fligner test) identified five different groups of material
417 hardness in the six investigated sites, from the softest *Soll* of the Valetta Ditch (site 2) to the
418 hardest Coralline Limestone of Abercrombie's Curtain at Fort St Elmo (site 3). Whereas the
419 surface hardness of *Franka* and *Soll* was significantly different at Fort Chambray and in the
420 Valletta Ditch, the post-hoc analysis concluded an absence of hardness difference between
421 the *Soll* of the French Curtain (site 4) and the *Franka* of the Valletta Ditch (site 1).

422

423 4.4. Stone characterization based on laboratory analyses

424

425 Thin sections allowed the differentiation of the three limestone types. The *Franka* facies of
426 the Valletta Ditch is a fine-grained limestone displaying very small and well sorted bioclasts
427 (<250 μm), mainly foraminifers such as *Globigerina*, and additional fragments of echinoderms
428 (Fig. 10A). These small bioclasts are embedded within an abundant micritic and microsparitic
429 matrix which reduces the macroporosity; the Franka appears therefore as a mainly
430 microporous and rather cohesive stone. By contrast, the *Soll* of the Valletta Ditch can be
431 described as a non-cohesive bioclastic grainstone containing large benthic foraminifers and
432 pelletoids (Fig. 10B). The macroporosity of this facies of *Globigerina* Limestone is high and well
433 connected. This stone is poorly cemented by a sparse biomicritic material, and can be
434 classified either as a biopelmicrite (Folk classification) or as a biopellitic wackestone (Dunham
435 classification). The *Soll* sample of Fort Chambray, which is entirely microcracked, displays the
436 same large benthic foraminifers as those of the Valletta Ditch. However, at Chambray, the
437 bioclasts are embedded within a more abundant biomicritic matrix filling most of the
438 macropores (Fig. 10C). Last, the thin sections of the Coralline Limestone sampled at Gozo
439 Citadel (Fig. 10D) show large, heterogeneous and often broken bioclasts including
440 echinoderms, foraminifers, coralline red algae and fragments of oyster shells. Fragmented
441 echinoderms, including sea urchins, display at places rather large syntaxial sparitic cements.
442 More importantly, the bioclasts of the Coralline Limestone are embedded within an
443 heterogeneous biomicritic matrix which does not occlude all the intergranular macropores.

444

445 The results of the mercury intrusion porosimetry obtained for the three limestones types are
446 summarized in Table 5 and Fig. 11. Values of total porosity (P_c) range from 20.5 to 37.5%. The
447 two samples of Coralline Limestone, which were collected at the same site, provided

448 comparable values (20-22%). By contrast, the samples of Globigerina Limestone showed a
449 marked variability between sites, with values ranging from 27 to 37%. This variability was
450 observed both in *Franka* and *Soll*, with contrasted values between Fort Chambray and the
451 Valletta Ditch. Interestingly, at this last site, the mean pore radius (R_m), for which the intrusive
452 volume is maximal, allowed differentiation between the two lithofacies of Globigerina
453 limestone, with a R_m value 27 times higher in *Soll* than in *Franka*. Moreover, the analyses
454 indicated that both the Coralline Limestone and the *Soll* Globigerina Limestone were mainly
455 macroporous (64 to 79% pores $>1\mu\text{m}$), whereas *Franka* displayed up to 60% pores $<1\mu\text{m}$, with
456 a marked variability between sites.

457

458 **5. Discussion**

459

460 Data computing of high-resolution 3D models of weathered fortifications obtained by SfM
461 photogrammetry has yielded median stone recession rates ranging from 1.2 to 60.7
462 mm/century, which should be considered as rough orders of magnitude. These quantitative
463 data allow fruitful comparisons between stone materials of the Maltese Islands, except in one
464 site, the French Curtain near Fort St Elmo, for which the quantitative results prove to be
465 unreliable. This is due to the uncertainties related to the reference surface reconstructed to
466 quantify the limestone recession. At this site, the generalized backweathering of the *Soll* ashlar
467 blocks has erased most tool marks. This has significantly reduced the number of reliable 'hard
468 points' which would have allowed the more certain reconstruction of the zero datum level.
469 Moreover, it seems that the backweathering of this rampart had started rapidly after
470 construction, requiring the application of lime render still visible at places. This application,
471 which predates the use of cement starting from the 1870s in Malta, has therefore reduced the

472 exposure time of the stone ashlar. As both the geometric reconstruction and the
473 chronological control of the reference surface are uncertain, it seems appropriate not to take
474 into consideration the recession value obtained for the French Curtain in the following
475 discussion of quantitative results.

476

477 Based on the five remaining sites, the limestone durability scale can be expressed as follows :
478 Coralline \geq *Franka* \ggg *Soll*. Both the Coralline Limestone and the high quality Globigerina
479 Limestone (*Franka*) have yielded very low recession rates, between 1 and 2 mm/century.
480 These results confirm the great durability of these building limestones, which is on the same
481 order of magnitude as the one of the sparitic limestones used in the Vauban fortifications of
482 the French Atlantic coast (Gruson, 2013). By contrast, the rapid recession rates obtained for
483 *Soll* (40-60 mm/century) confirm the low durability of the *Soll* facies, as observed previously
484 on abandoned quarry faces and through salt weathering tests (Cassar 2002, 2010; Fitzner et
485 al., 1996; Rothert et al., 2007; Cassar et al., 2008; Zammit and Cassar, 2017). This soft subtype
486 of Globigerina Limestone appears even more prone to decay than the micritic and platy
487 limestones of the French Atlantic coast for which the maximum recession rates hardly reach
488 30 mm/century (Gruson, 2013).

489

490 As expressed in Fig. 12, the results of the on-site behaviour of the investigated limestones
491 (water absorption and hardness), as well as their microscopic structure, shed some light on
492 the controlling factors of their contrasted durabilities. *Soll*, which has yielded the fastest
493 weathering rates is the least mechanically resistant material (median surface hardness below
494 230 HLD) and has the highest on-site water uptake capacity (median over 4.9 g.m⁻².s⁻¹).
495 Moreover, microscopic observations indicate that it is a non-cohesive, poorly cemented or

496 microcracked biomicritic Globigerina Limestone. Conversely, *Franka*, which is the most
497 durable facies of Globigerina Limestone, presents a higher mechanical resistance (median
498 surface hardness ranging from 276 to 365 HLD) and a lower on-site water uptake capacity
499 (median values ranging from 1.8 to 3.6 g.m⁻².s⁻¹). The observation of thin sections shows that
500 it is a fine-grained and cohesive limestone of which small and well-sorted bioclasts are bound
501 together with an abundant micritic and microsparitic matrix. Last, the investigated facies of
502 Coralline Limestone, which is at least as durable as *Franka*, has a low on-site water uptake
503 capacity (1.8 g.m⁻².s⁻¹) and is by far the most mechanically resistant material (median surface
504 hardness of 434.5 HLD).

505

506 The results of the porosimetric analyses are more ambiguous. On the one hand, the values of
507 total porosity (20-22% for Coralline limestone and 27-37% for Globigerina limestones) fall
508 within the ranges of 2-30% and 24-41% provided by previous authors (Bonello, 1988; Cassar,
509 2002). On the other hand, the tendency of our samples of *Soll* to be more macroporous than
510 those of *Franka* does not fit with previous results showing that *Franka* displays predominantly
511 larger pores than *Soll* (Cassar, 2002; Rothert et al., 2007; Zammit and Cassar, 2017). However,
512 our results do not question these conclusions that are based on a much larger number of
513 samples from quarry faces, which has allowed the previous authors to minimize the effects of
514 the variability of porosimetric characteristics between sites and between samples. This
515 variability is known to be very high in the Globigerina Limestone which includes a variety of
516 subtypes (Diana et al., 2014). The small difference of hardness between the *Franka* of the
517 Valletta Ditch and the *Soll* of the French Curtain is another illustration of the complexity of the
518 Maltese Globigerina limestone lithofacies.

519

520 Concerning the much higher porosities of *Franka* and *Soll* of the Valletta Ditch than those
521 measured on the samples from Fort Chambray, these might be explained by the longer
522 exposure time in the Ditch (444 years against 254 years) and by the easier diffusion of water
523 within the continuous limestone layers of the Ditch than in the ashlar masonry of Fort
524 Chambray. Last, the unusually high variability of the water uptake capacity of the *Soll* material
525 of the French Curtain, with values ranging from 2.4 to 16.1 g.m⁻².s⁻¹ might be explained by
526 differing surface conditions occurring in different ashlar blocks (cf. the model of limestone
527 weathering by Rothert et al. (2007), which includes episodes of surface hardening due to
528 calcite migration). In the investigated sites, the highest water uptake capacity was found on
529 blocks still displaying flaking features, whereas the stone material exposed after detachment
530 of the flakes absorbed less water.

531

532

533 **6. Conclusions**

534

535 In the investigated Maltese fortifications, the present study provides novel quantitative data
536 which highlights the existence of a two-rate weathering regime within the Globigerina
537 Limestone types, the main building stone of the Maltese Islands. With a median stone
538 recession of 1.4 mm/century against 50.6 mm/century, the cohesive subtype called *Franka*
539 has resisted 36 times better to salt-laden atmospheric aggression than the non-cohesive *Soll*
540 subtype. The Lower Coralline Limestone has also resisted quite well, with a stone recession of
541 1.3 mm/century, on the same order of magnitude as *Franka*. These quantitative results are in
542 line with the two-rate weathering regime found for eight limestone types within fortifications
543 of the French Atlantic coast. With 2.4 mm/century against 17.9 mm/century, the sparitic

544 limestones are on average 7 times more durable than the micritic and platy limestones
545 (Gruson, 2013). The contrast between durable and fragile limestones is therefore five times
546 less pronounced on the Atlantic coast than in the Maltese Islands. It is probably due to the
547 high susceptibility to powdering of the Maltese *Soll* facies of Globigerina Limestone which has
548 no equivalent on the Atlantic coast.

549

550 Regarding the controlling factors of the two-rate weathering regime, the on-site contact
551 sponge tests reveal that the median water uptake capacity of the least durable limestone (*Soll*)
552 is on average two to three times higher than that of *Franka* and Coralline Limestone (5.4 to
553 $5.9 \text{ g.m}^{-2}.\text{s}^{-1}$ against 1.8 to $3.6 \text{ g.m}^{-2}.\text{s}^{-1}$). The correlation of limestone durability with surface
554 hardness is not as straightforward as with water absorption. There is a decreasing gradient in
555 the median values of mechanical resistance of the three tested materials, with 434.5 HLD for
556 the Coralline Limestone, 316 HLD for the *Franka* and 228 HLD for the *Soll*. If this last facies is
557 both the least durable and the least mechanically resistant, the two other limestones, which
558 have similar durabilities, have significantly different hardness. This result could be interpreted
559 as a compensation of a lower hardness by a better capacity to allow water circulation and
560 therefore moisture wicking, but it is quite clear that other controlling factors do exist.
561 Microscopic examinations have revealed differences in cohesiveness between the durable
562 *Franka* and the friable *Soll*: whereas the bioclasts of the first facies were bound together by
563 an abundant micritic and microsparitic matrix, the second facies was poorly-cemented or
564 microcracked. But additional controls should be explored, such as the abundance and nature
565 of the insoluble residue, which might be an important controlling factor of varying durability
566 as suggested by Cassar (1999) and Zammit and Cassar (2017).

567

568 Further research should be based on a larger number of sites and of representative areas of
569 the weathering state (RAWS) of ramparts and comparisons with fresh quarry samples.
570 Moreover, the implementation of the on-site tests should be based on a refined methodology:
571 the surface conditions of the tested ashlar blocks should be taken into account for they impact
572 their water uptake capacity. Last, additional laboratory analyses should be carried out, with
573 special reference to the identification of the nature of the insoluble residue including the clay
574 content. Such an improved methodology applied to additional sites should allow to refine the
575 quantitative estimates and the limestone durability scale inferred from the present study.

576

577

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579

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587

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849

Table 1

| Location | Monument Type | Limestone Type | Building Date | Weathering Period (yr) | Recession Rates (mm/century) | | | Source (method) |
|-------------------------|-------------------------------|----------------|---------------|------------------------|------------------------------|-----------------|--------------|---|
| | | | | | min | mean | max | |
| Weymouth, S UK | Carlton Hotel (columns) | oosparitic | 1860 | 135 | | 2.0* 4.0** | | Viles & Goudie 1992 (carpenter's profile gauge) |
| Ré Island, W France | Tombstones Ars-en-Ré (21) | sparitic | 1808-1932 | 73-197 | 0.00 | 1.64 | 32.8 | Augeyre 2006, 2008 (plexiglass grid and metal ruler) |
| | Tombstones La Couarde (11) | sparitic | 1878-1925 | 80-127 | 0.00 | 1.78 | 31.5 | |
| | Tombstones Le Bois-Plage (28) | sparitic | 1867-1927 | 78-138 | 0.00 | 3.64 | 113.9 | |
| | Tombstones St. Martin (25) | sparitic | 1840-1933 | 72-165 | 0.00 | 1.77 | 21.7 | |
| | Fortifications | micritic | 1682 | 331 | 1.78 | 5.60 | 11.70 | |
| | Fortifications | sparitic | 1682 | 331 | 0.43 | 1.92 | 7.54 | |
| Oléron Island, W France | Church wall | sparitic | 1862 | 151 | 0.36 | 3.81 | 18.86 | Gruson 2013 (multi-image photogrammetry) |
| | Fortifications | sparitic | 1675 | 338 | 0.91 | 3.42 | 10.07 | |
| | Fortifications | platy | 1675 | 338 | 2.50 | 7.08 | 20.94 | |
| La Rochelle, W France | Church | sparitic | 1703 | 310 | 0.41 | 3.16 | 14.97 | |
| | Fortifications | sparitic | 1568 | 445 | 0.33 | 2.40 | 5.75 | |
| Brouage, W France | District Court | sparitic | 1784 | 229 | 0.17 0.79 | 1.63* 4.90** | 4.70 9.78 | |
| | Church wall | sparitic | 1608 | 405 | 0.62 | 1.59 | 3.33 | |
| Esnandes, W France | Bastions | sparitic | 1635 | 378 | 0.05 | 2.53 | 8.57 | |
| | Enclosure | sparitic | 1853 | 160 | 0.95 | 3.29 | 10.22 | |
| | Enclosure | platy | 1853 | 160 | 8.00 | 28.85 | 54.67 | |
| Esnandes, W France | Church (W portal) | sparitic | 1150 | 863 | 0.00 | 1.59 | 4.68 | |
| | Church (W portal restored) | sparitic | 1885 | 128 | 0.00 | 1.53 | 4.55 | |
| | Church (restored walls) | sparitic | 1883 | 130 | 1.48 | 2.81 | 7.80 | |

*sheltered from sea spray **exposed to sea spray

TABLE 2

| SITE ID | LOCATION | ARCHITECTURAL ELEMENT | BUILDING PERIOD | LIMESTONE TYPE | ASPECT | DISTANCE TO SEA (m) | SURFACE AREA (m ²) |
|---------|-------------------------|-----------------------|-----------------|----------------------------|--------|---------------------|--------------------------------|
| 1 | SW Valletta walled city | Ditch counterguard | 1566-1570 | Globigerina/ <i>Franka</i> | E | 255 | 33.32 |
| 2 | SW Valletta walled city | Ditch counterguard | 1566-1570 | Globigerina/ <i>Soll</i> | E | 255 | 29.50 |
| 3 | E Fort St Elmo | Abercrombie's curtain | 1687-1689 | Coralline | SE | 12 | 2.71 |
| 4 | SW Fort St Elmo | French curtain | 1687-1689 | Globigerina/ <i>Soll</i> | NW | 25 | 15.99 |
| 5 | N Fort Chambray, Gozo | Right ravelin | 1749-1760 | Globigerina/ <i>Franka</i> | NW | 360 | 2.35 |
| 6 | N Fort Chambray, Gozo | Counterguard | 1749-1760 | Globigerina/medium quality | SW | 420 | 4.49 |

| | Total stone recession since construction (mm) | | | | Weathering Period (yr) | Stone recession rates (mm/century) | | | |
|--|--|----------------------------|-------------------------|----------------------------|-----------------------------------|---|-------------------------|-------------------------|----------------------------|
| | 5th | Median | MAD | 95th | | 5th | Median | MAD | 95th |
| Site 1 - Valletta Ditch-Globigerina/Franka | 0.3 (0.31 ; 0.36) | 5.1 (4.98 ; 5.25) | 4.0 (3.89 ; 4.12) | 43.9 (42.8 ; 45.01) | 444 | 0.1 (0.07 ; 0.08) | 1.2 (1.12 ; 1.18) | 0.9 (0.87 ; 0.92) | 9.9 (9.64 ; 10.13) |
| Site 2 - Valletta Ditch-Globigerina/Soll | 59.2 (58.38 ; 60.04) | 179.8 (177.83 ; 181.76) | 81.4 (79.6 ; 83.1) | 484.6 (479.33 ; 489.81) | 444 | 13.3 (13.14 ; 13.52) | 40.5 (40.05 ; 40.93) | 18.3 (17.93 ; 18.71) | 109.1 (107.95 ; 110.31) |
| Site 3 - Fort St Elmo-Coralline | 0.3 (0.31 ; 0.36) | 4.2 (4.14 ; 4.34) | 3.0 (2.88 ; 3.04) | 20.4 (19.86 ; 20.87) | 325 | 0.1 (0.09 ; 0.11) | 1.3 (1.27 ; 1.33) | 0.9 (0.88 ; 0.93) | 6.3 (6.11 ; 6.42) |
| Site 4 - French Curtain-Globigerina/Soll | 5.2 (4.94 ; 5.42) | 69.9 (69.21 ; 70.53) | 38.8 (38.36 ; 39.27) | 177.2 (175.97 ; 178.45) | 325 | 1.6 (1.52 ; 1.67) | 21.5 (21.29 ; 21.70) | 11.9 (11.80 ; 12.08) | 54.5 (54.14 ; 54.90) |
| Site 5 - Fort Chambray-Globigerina/Franka | 1.5 (1.43 ; 1.51) | 4.1 (4.08 ; 4.14) | 1.2 (1.15 ; 1.18) | 7.7 (7.62 ; 7.85) | 254 | 0.6 (0.56 ; 0.59) | 1.6 (1.6 ; 1.63) | 0.5 (0.45 ; 0.46) | 3.0 (3 ; 3.09) |
| Site 6 - Fort Chambray-Globigerina/Soll | 26.5 (25.54 ; 27.48) | 154.1 (152.68 ; 155.54) | 65.5 (64.81 ; 66.08) | 357.0 (353.64 ; 360.3) | 254 | 10.4 (10.05 ; 10.82) | 60.7 (60.11 ; 61.23) | 25.8 (25.51 ; 26.01) | 140.5 (139.23 ; 141.85) |

Table 3

| | Water absorption (g.m-2.s-1) | | | | Hardness (Leeb hardness units) | | | |
|---|--------------------------------------|----------------------|-----------------------|------------------------|---------------------------------------|----------------------------|-------------------------|----------------------------|
| | 5th | Median | MAD | 95th | 5th | Median | MAD | 95th |
| Site 1 - Valletta Ditch- Globigerina/Franka | 1.1 (0.83 ; 1.41) | 1.8 (1.26 ; 2.38) | 0.4 (0.04 ; 0.79) | 2.7 (1.88 ; 3.61) | 186.0 (168.42 ; 203.57) | 276.0 (252.75 ; 299.24) | 53.5 (39.82 ; 67.17) | 434.8 (400.31 ; 469.18) |
| Site 2 - Valletta Ditch- Globigerina/Soll | 3.6 (2.33 ; 4.81) | 5.4 (4.27 ; 6.52) | 1.0 (0.29 ; 1.66) | 7.1 (6.23 ; 7.89) | 122.0 (113.32 ; 130.67) | 172.5 (158.35 ; 186.64) | 25.0 (17.53 ; 32.46) | 245.1 (229.09 ; 261.1) |
| Site 3 - Fort St Elmo-Coralline | 1.0 (0.85 ; 1.1) | 1.8 (0.5 ; 3) | 0.8 (0.21 ; 1.32) | 3.0 (2.81 ; 3.2) | 336.0 (314.95 ; 356.94) | 434.5 (410.81 ; 458.18) | 46.0 (29.66 ; 62.33) | 578.4 (543.23 ; 613.56) |
| Site 4 - French Curtain- Globigerina/Soll | 2.6 (2.13 ; 3.01) | 4.9 (0 ; 10.58) | 2.3 (-1.62 ; 6.24) | 14.6 (9.01 ; 20.21) | 214.8 (199.81 ; 229.78) | 269.0 (260.75 ; 277.24) | 14.5 (6.71 ; 22.28) | 307.6 (279.83 ; 335.36) |
| Site 5 - Fort Chambray- Globigerina/Franka | 3.0 (2.56 ; 3.38) | 3.6 (2.94 ; 4.35) | 0.4 (0.01 ; 0.82) | 4.4 (3.96 ; 4.89) | 246.9 (213.08 ; 280.61) | 365.0 (345.36 ; 384.63) | 46.5 (33.95 ; 59.04) | 446.6 (420.13 ; 473.06) |
| Site 6 - Fort Chambray- Globigerina/Soll | 4.4 (3.43 ; 5.38) | 5.9 (3.1 ; 8.67) | 1.5 (0.5 ; 2.58) | 8.8 (8.01 ; 9.66) | 147.8 (117.22 ; 178.27) | 230.0 (218.13 ; 241.86) | 30.0 (19.15 ; 40.84) | 302.2 (280.53 ; 323.76) |

Table 4

Table 5

| Stone type | Globigerina / <i>Franka</i> | | Globigerina / <i>Soll</i> | | Coralline | |
|-----------------------|-----------------------------|----------------|---------------------------|----------------|--------------|--------------|
| Sample | MT15 | MT28 | MT13 | MT27 | MT18 | MT21a |
| Site location | Fort Chambray | Valletta Ditch | Fort Chambray | Valletta Ditch | Gozo Citadel | Gozo Citadel |
| Pc (%) | 26.9 | 32.8 | 29.2 | 37.5 | 22.1 | 20.5 |
| Rm (μm) | / | 1.4 | / | 38.5 | / | / |
| Cd | 8.7 | 1.5 | 4.2 | 1.9 | 3.0 | 2.0 |
| Pores<1 μm | 46% | 60% | 36% | 21% | 25% | 25% |
| Pores>1 μm | 54% | 40% | 64% | 79% | 75% | 75% |



Figure 2

[Click here to access/download;Figure \(Color\);FIG_2.jpg](#)

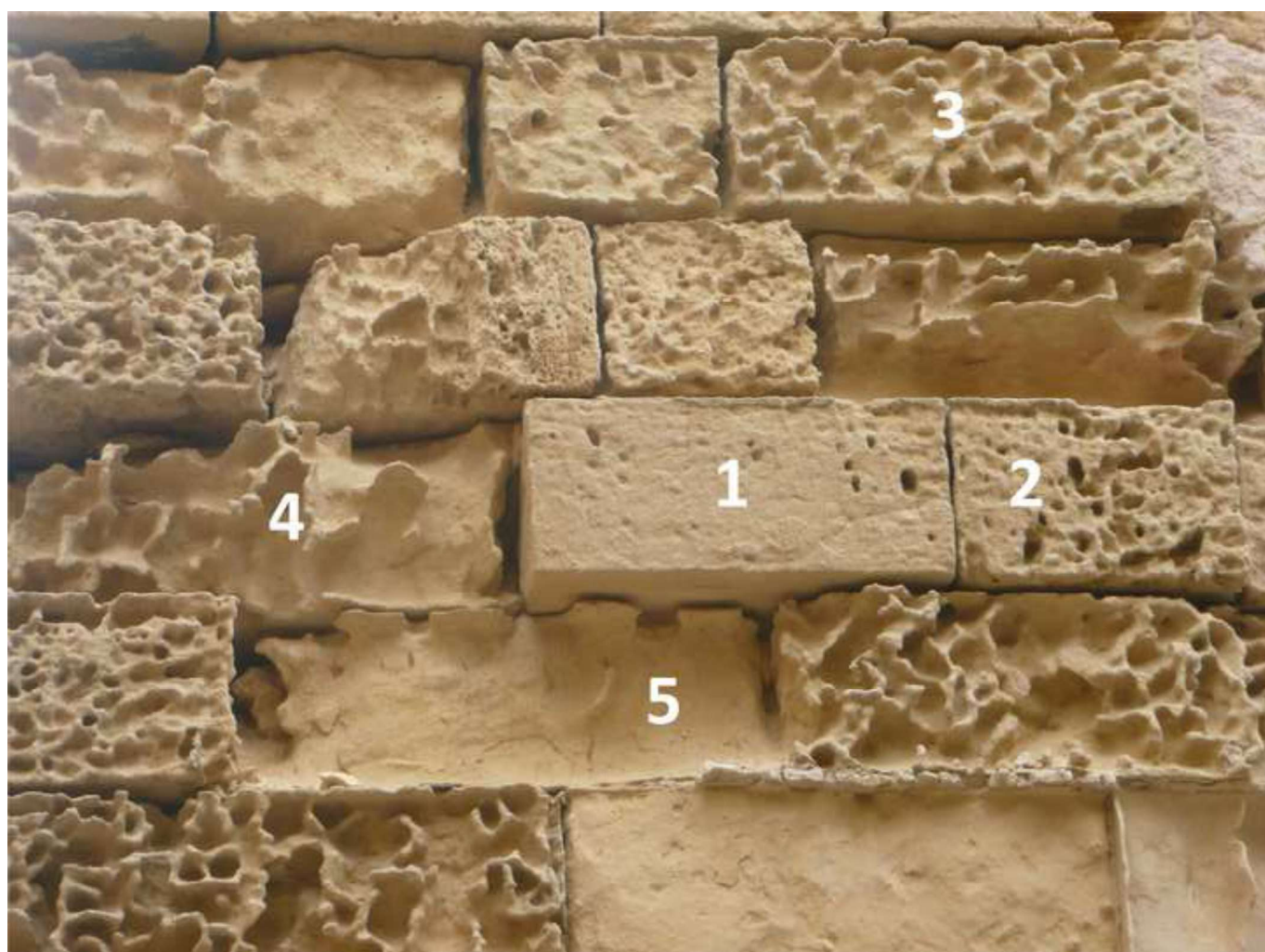


Figure 3

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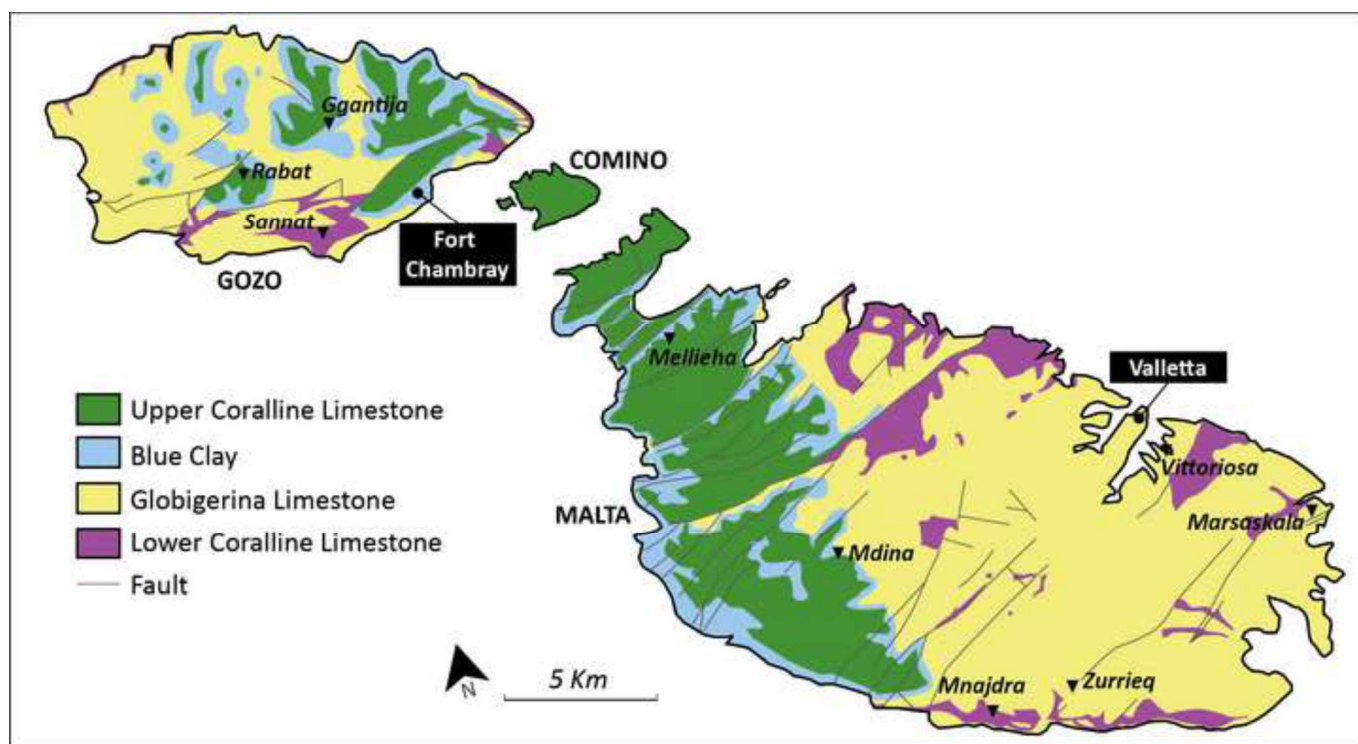
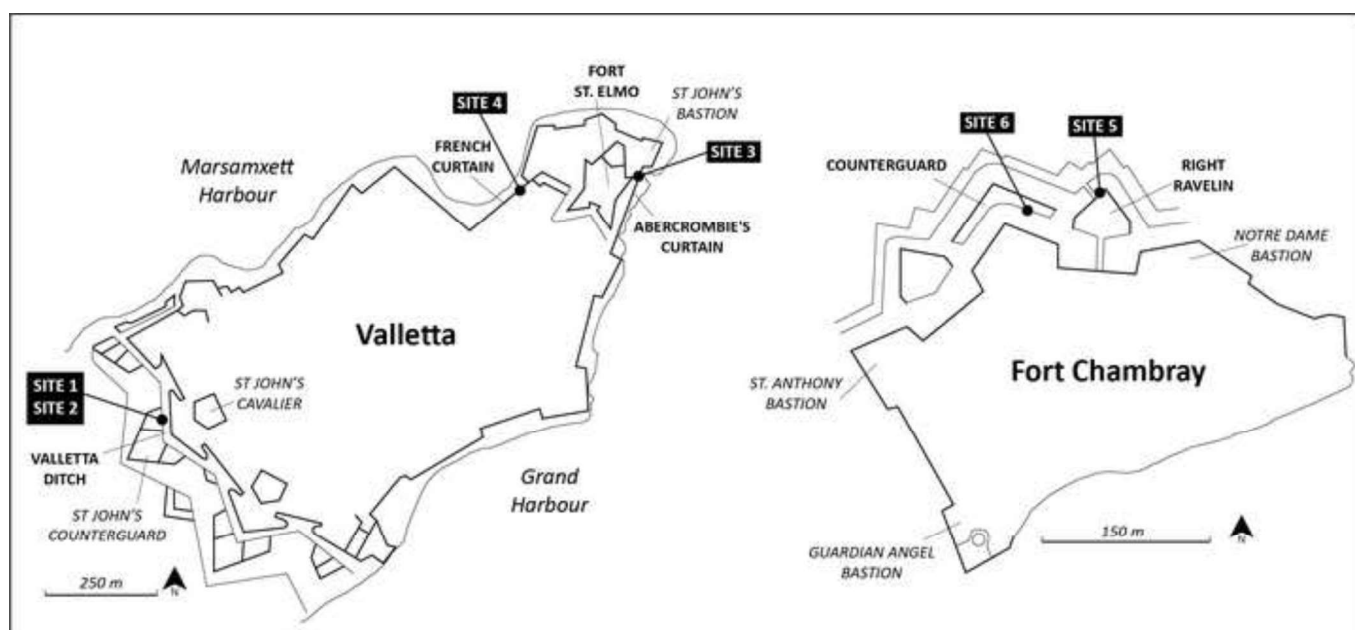


Figure 4

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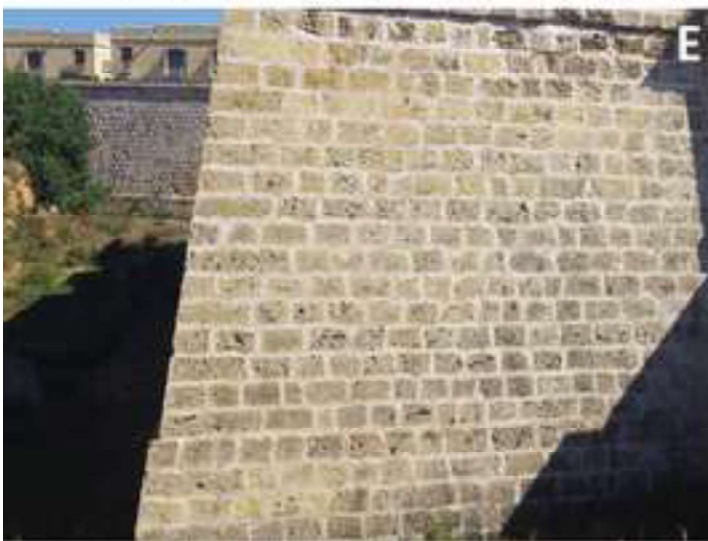
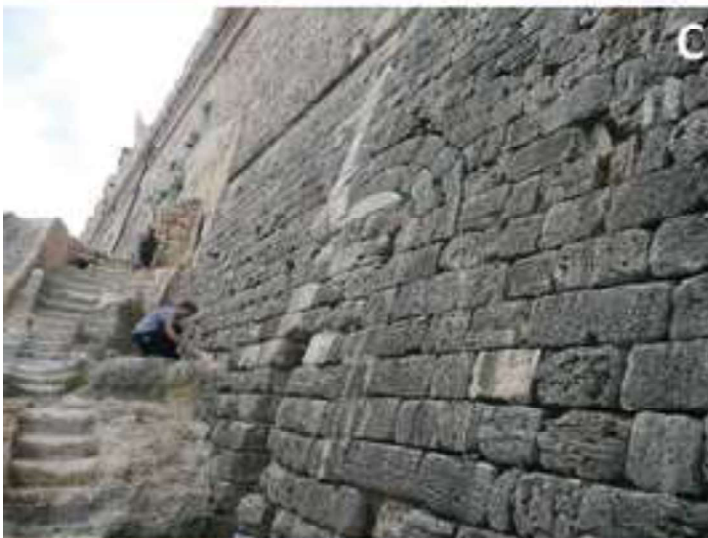


Figure 6

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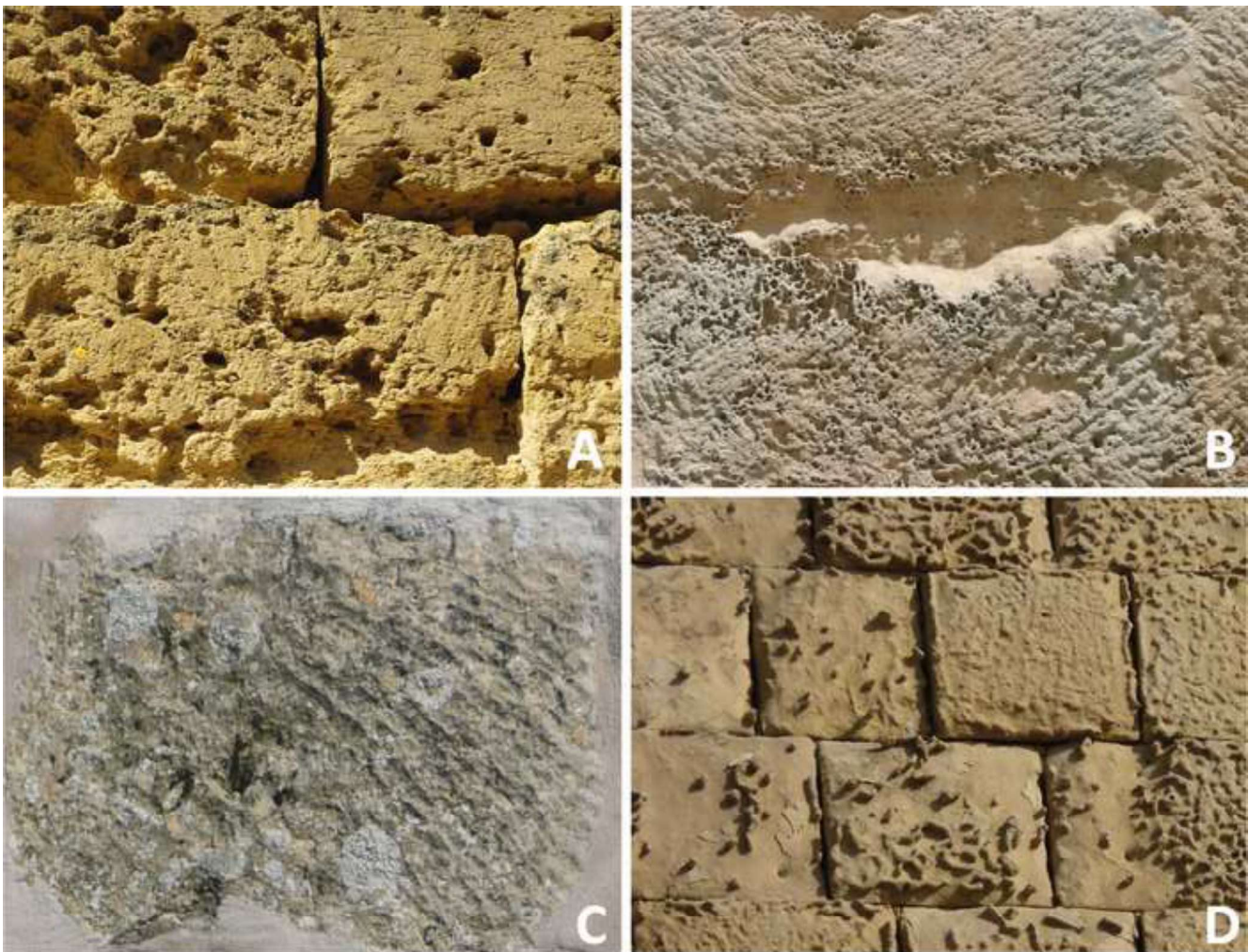


Figure 7

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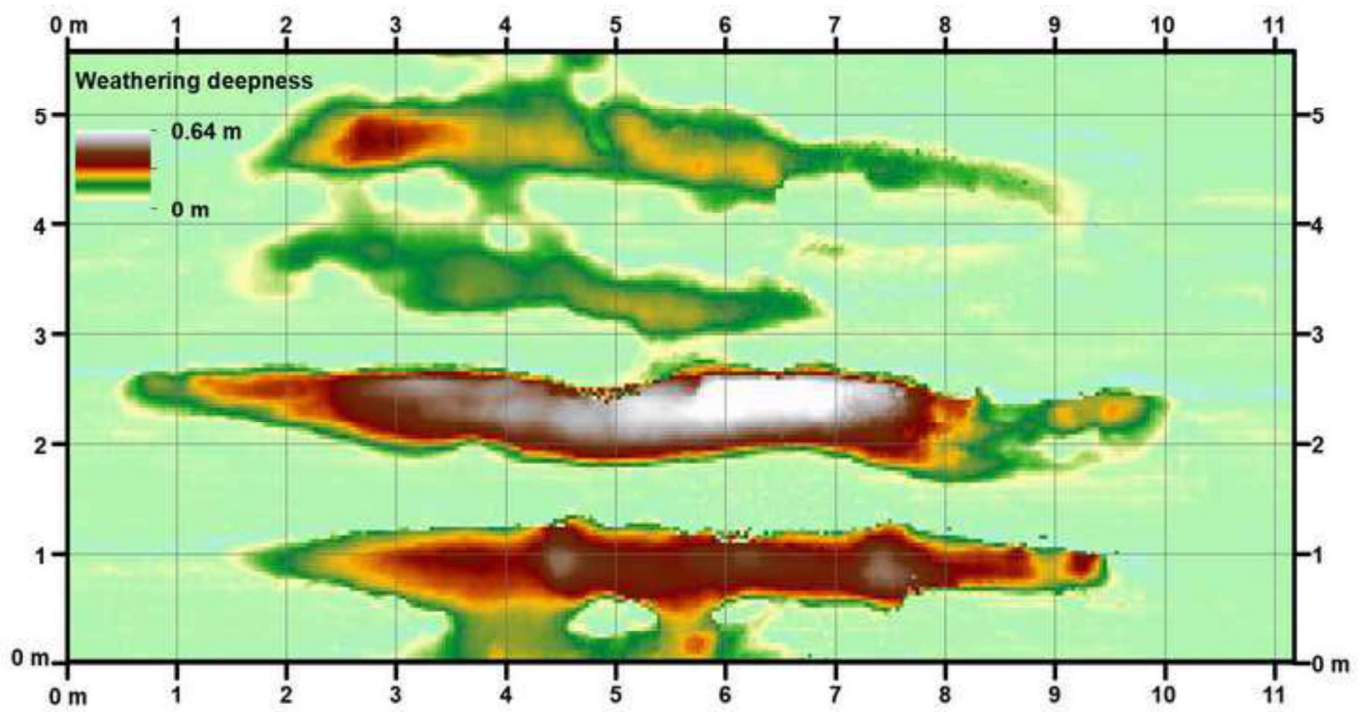
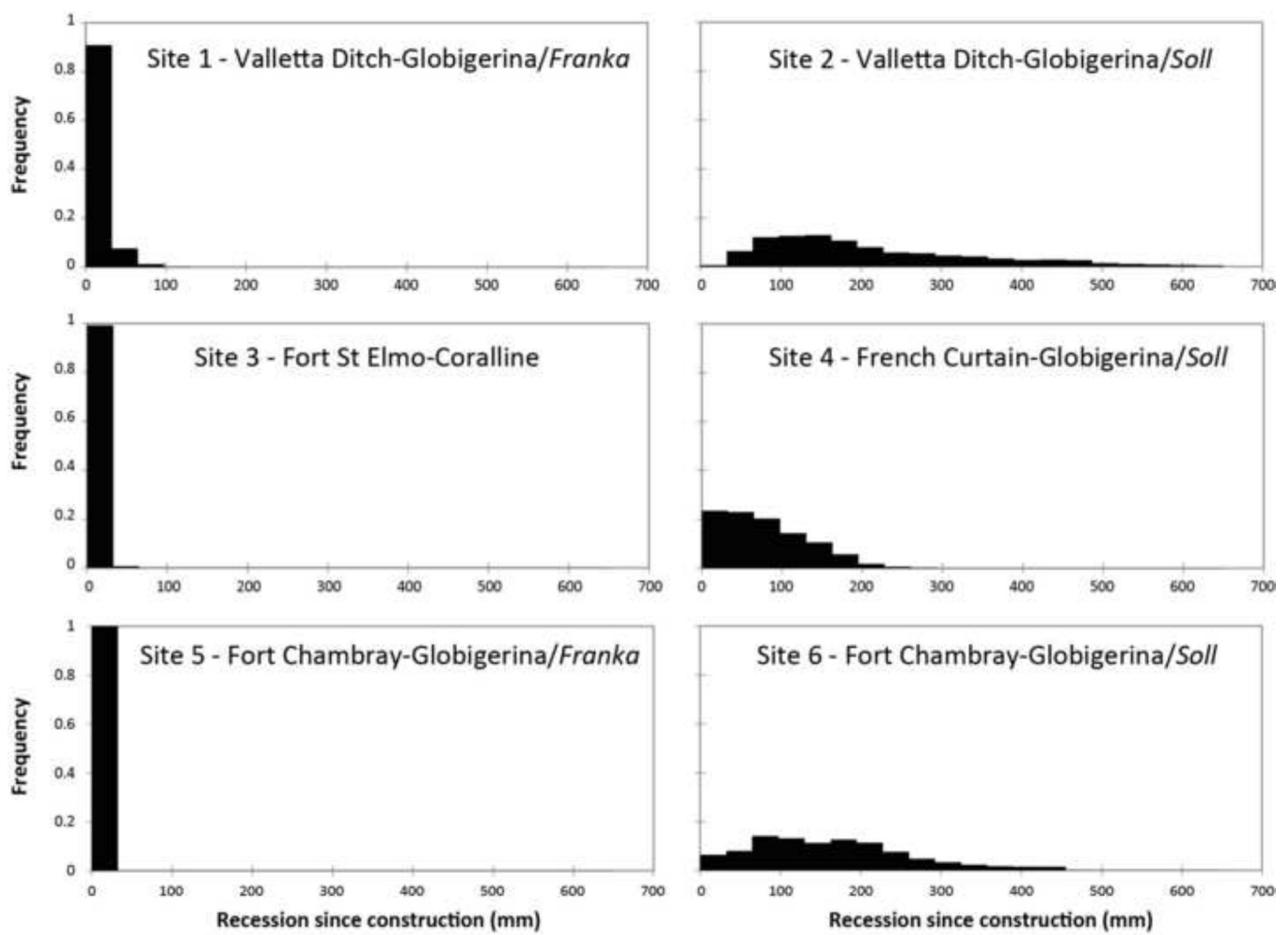


Figure 8

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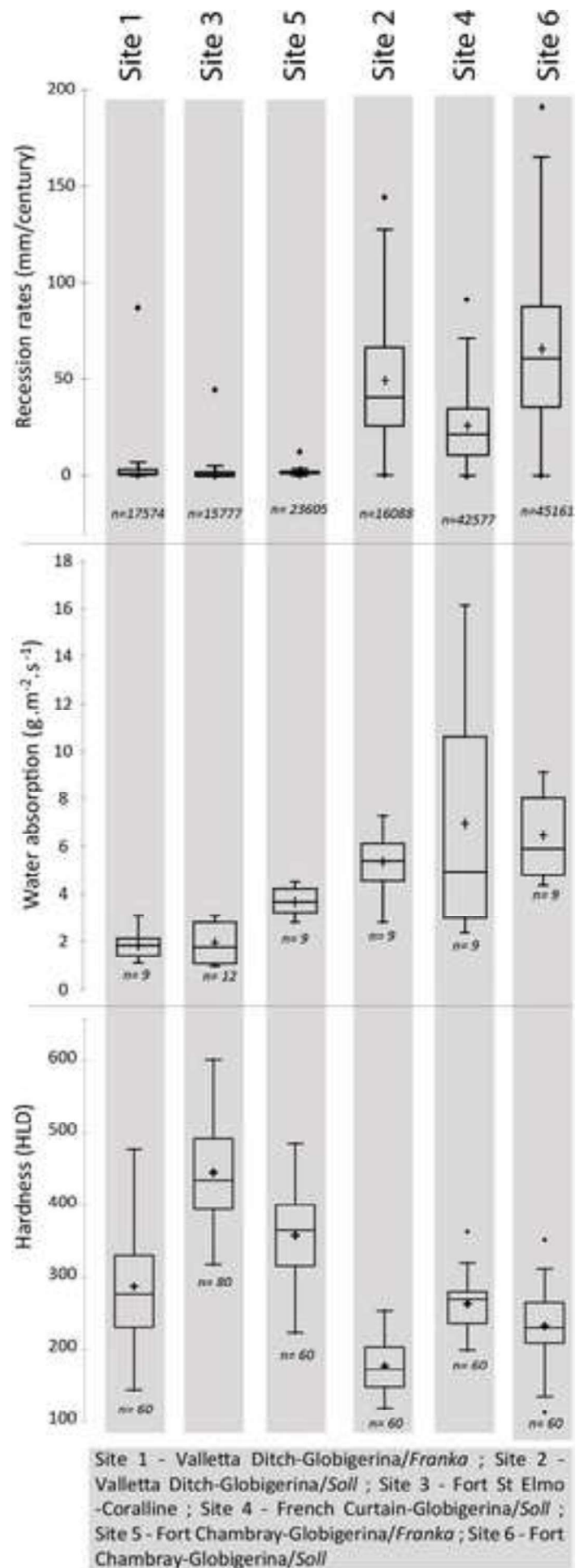
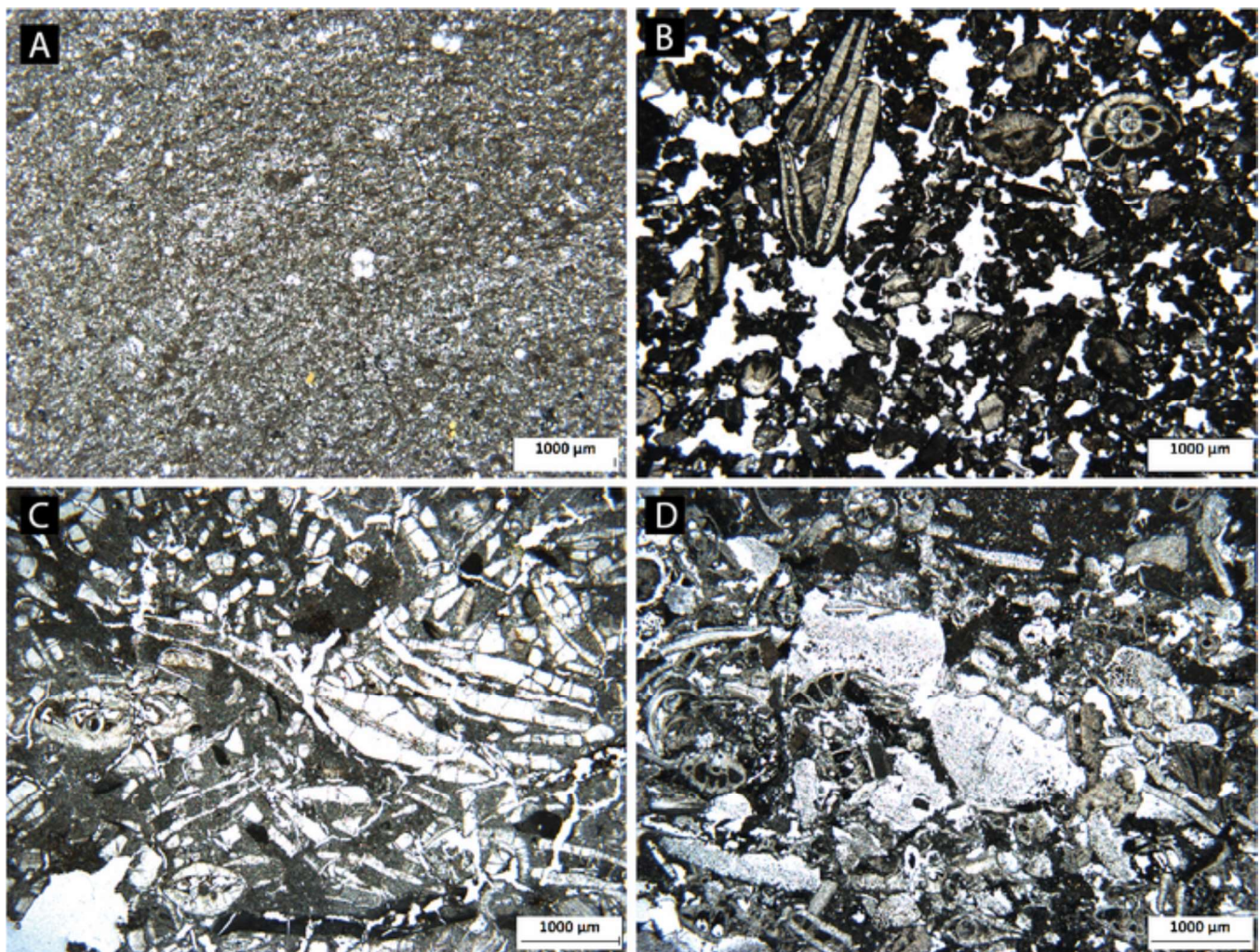


Figure 10

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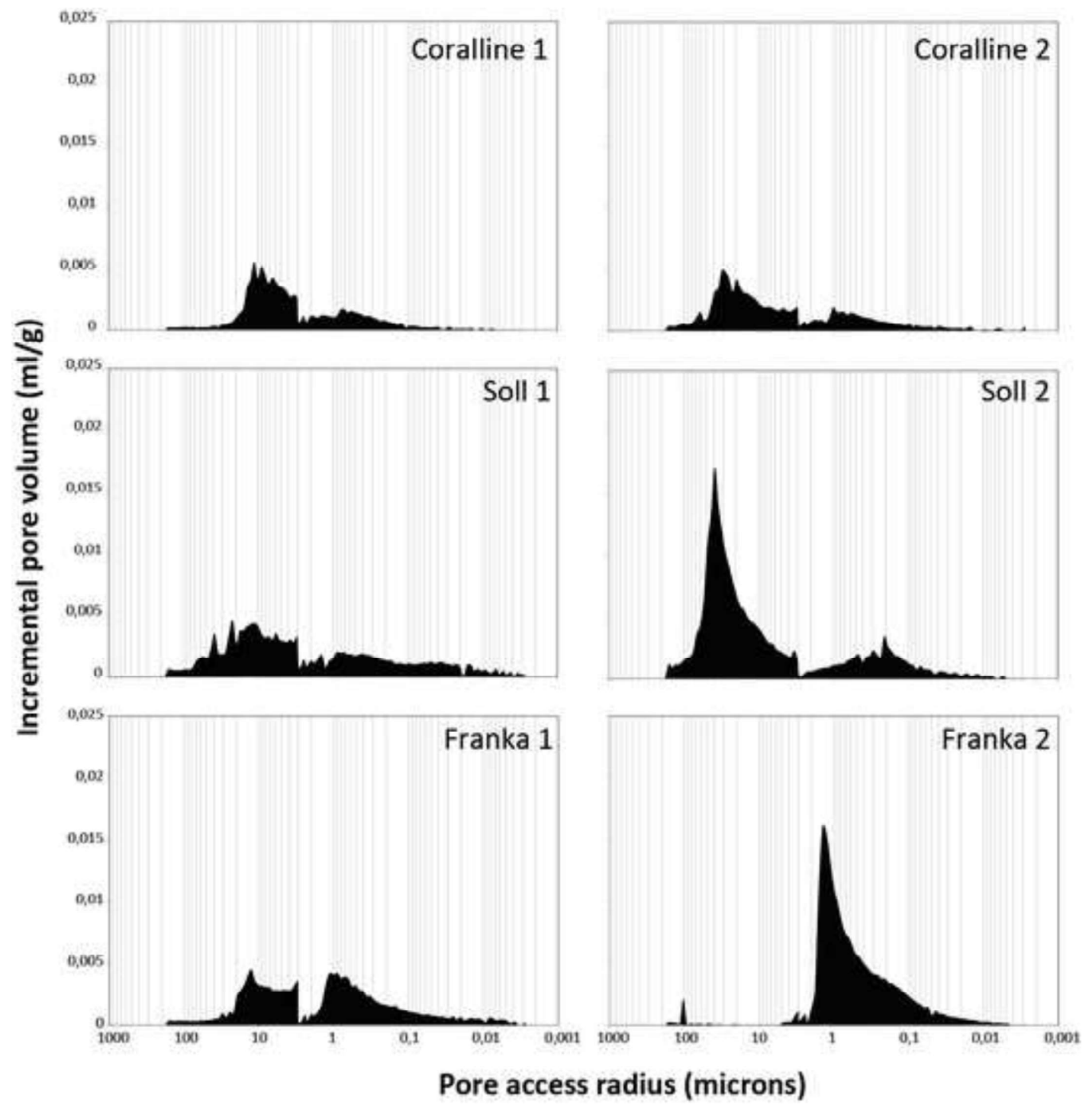


Figure 12

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