Title of Original Article

Estimating the age and mechanism of boulder transport related with extreme waves using lichenometry

Supplementary Material

The Coxos Boulder deposit

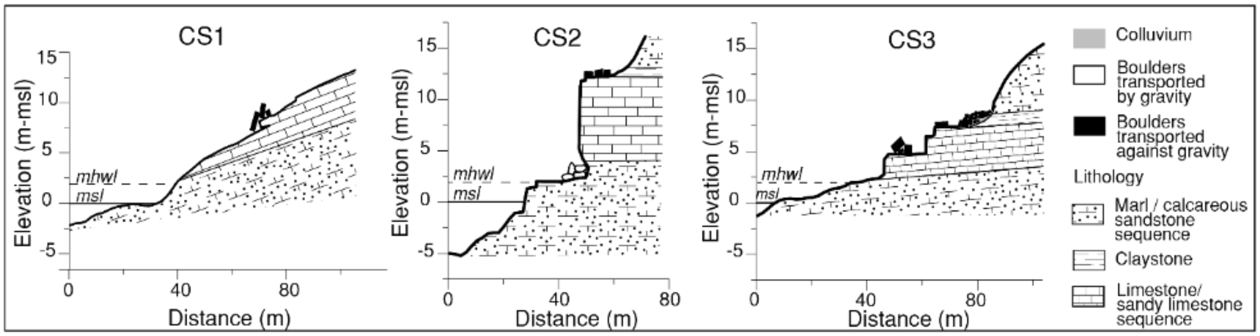

Figure S1: Cross-sections of the study area (see Figure 1a for location)

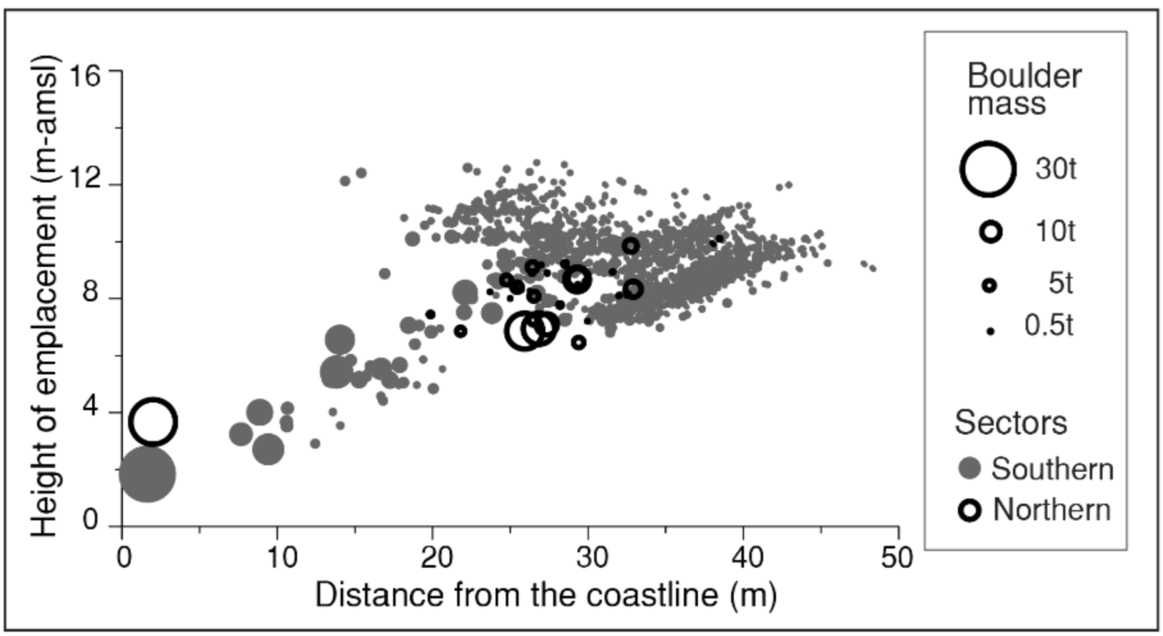

Figure S2: Boulder height of emplacement plotted against distance from the coastline. The size of the circles is based on boulder mass

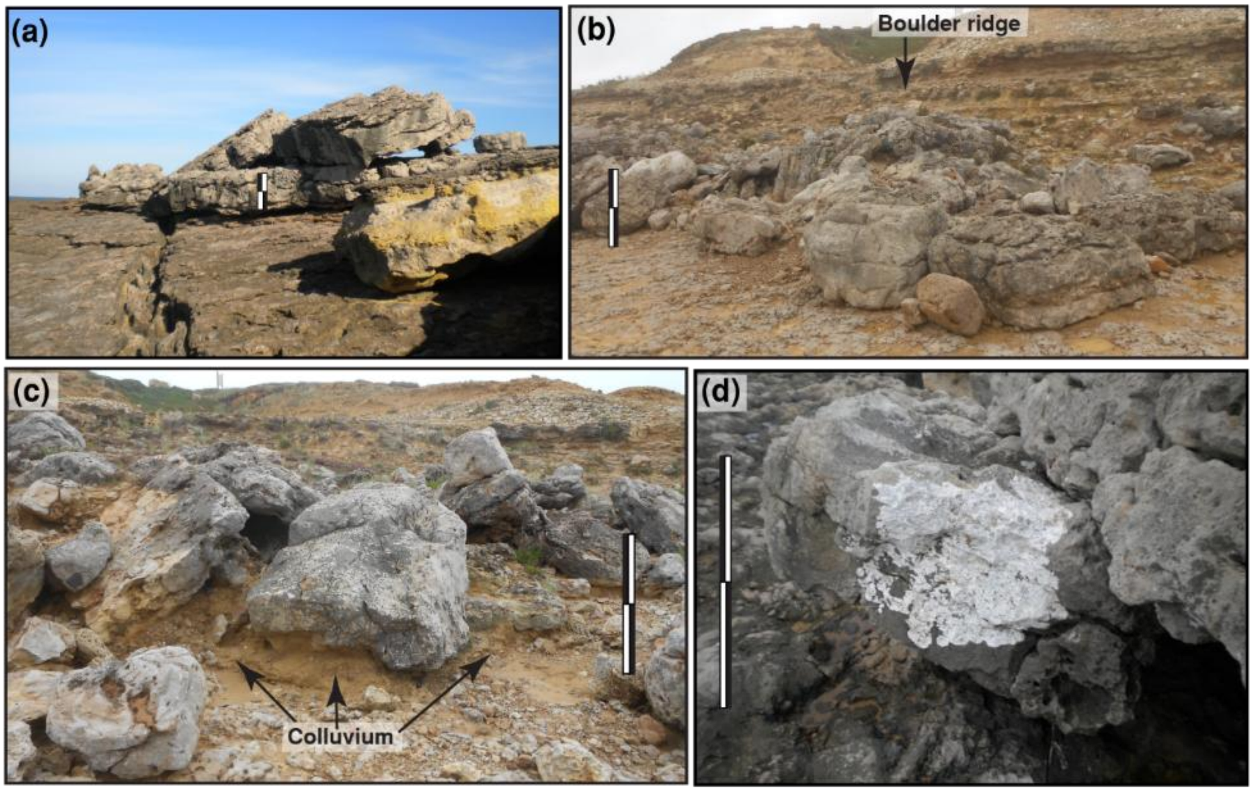

Figure S3: (a) 10-20ton boulders leaning against a bench edge; (b) Boulder ridge; (c) colluvium deposit developing around and partly covering boulders; (d) boulder colonized by the lichen species *Opegrapha durieui*. Scale corresponds to ~1m.

Grain size analysis and morphoscopy of the marine sand patch and sediment sources

Table S1: Grain size data, graphic parameters, and classification of sediment samples collected. From Oliveira (2017)

Sample	Graphic Mean (MZ) (ϕ)	Inclusive Graphic Standard Deviation (σ_I) (ϕ)	Inclusive Graphic Skewness (SKI)	Kurtosis (KG)	<63μm (%)	Heavy mineral of the 0-2ϕ fraction (%)
Beach	0.47	0.38	0.12	1.04	0.2	12.1
	Coarse sand	Well sorted	Positive-skewed	Mesokurtic		
Storm	0.72	0.76	0.09	1.22	0.9	13.2
	Coarse sand	Moderately sorted	Nearly Symmetrical	Leptokurtic		
Colluvium	1.87	2.47	-0.60	0.72	39.6	2.2
	Medium sand	Very poorly sorted	Very negative-skewed	Platykurtic		
Sand patch	2.32	1.09	0.14	1.05	11.2	0.6
	Fine sand	Poorly sorted	Positive-skewed	Mesokurtic		

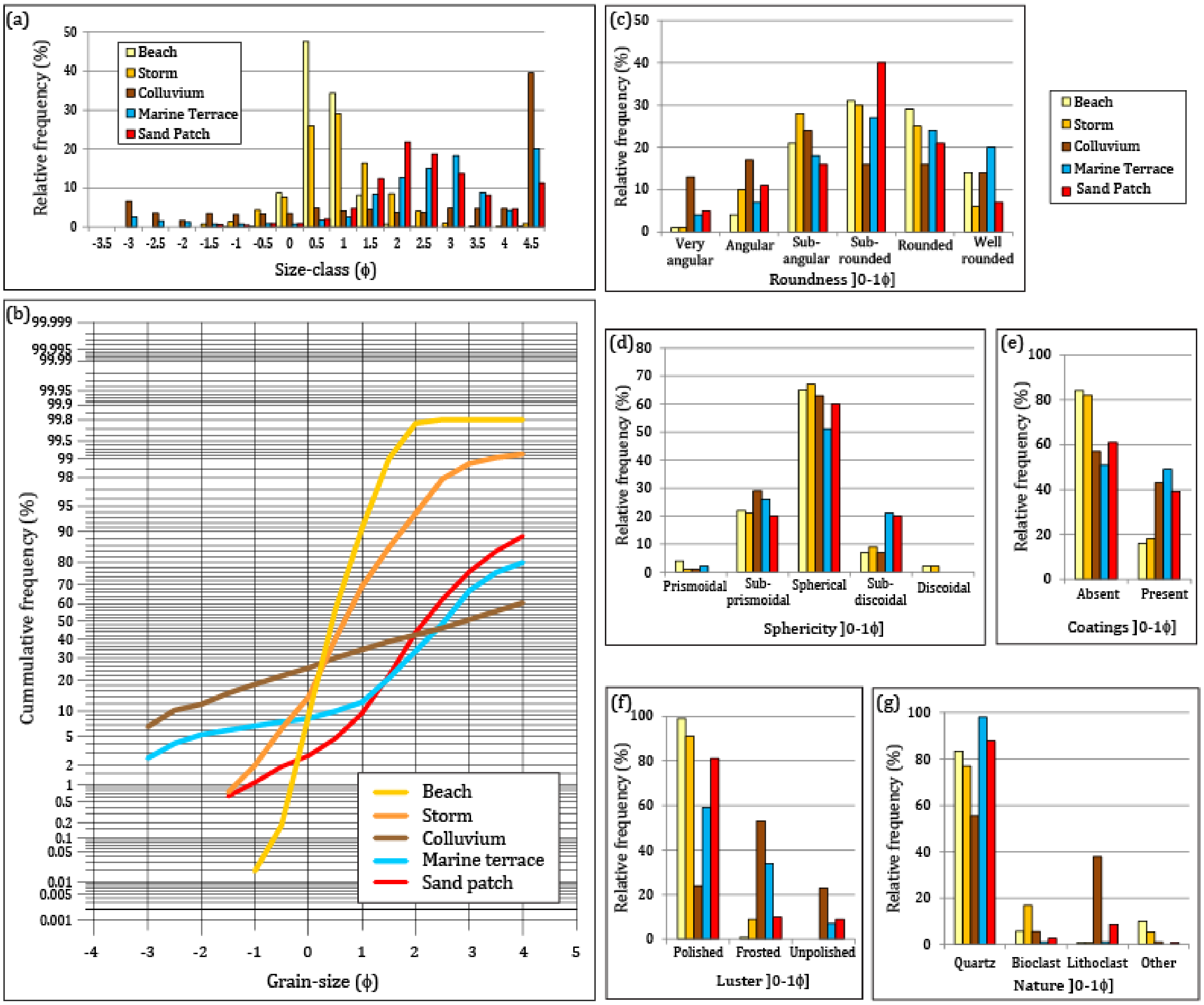

Figure S4: Grain-size and morphoscopy of the marine patch and source sediments in the study area: (a) grain size relative frequency histogram; (b) grain-size cumulative distribution curves. Particle morphology and surface features obtained with morphoscopic analysis of the 0-1ϕ fractions: (c) roundness; (d) sphericity; (e) coatings; (f) luster; (g) composition. From Oliveira (2017)

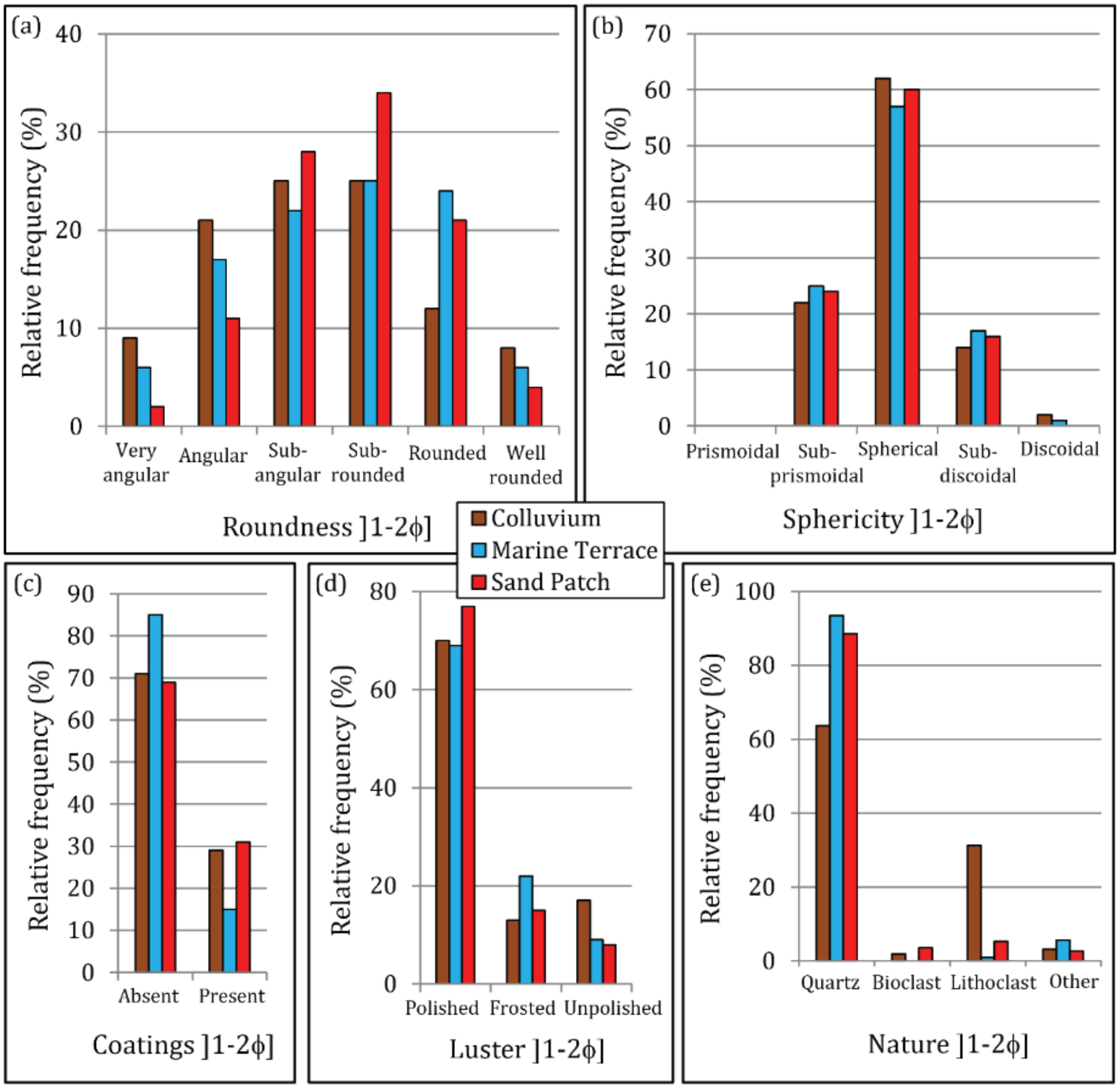

Figure S5: Particle morphology and surface features obtained with morphoscopic analysis of the 1-2ϕ fractions: (a) roundness; (b) sphericity; (c) coatings; (d) luster; (e) composition. From Oliveira (2017)

Control points used in indirect and direct lichen growth methodologies

Lichen size and cover were measured in control surfaces with known age of exposure (Figure S6). Direct measurements of lichen growth data in control surfaces are also provided in an excel spreadsheet as supplementary materials.

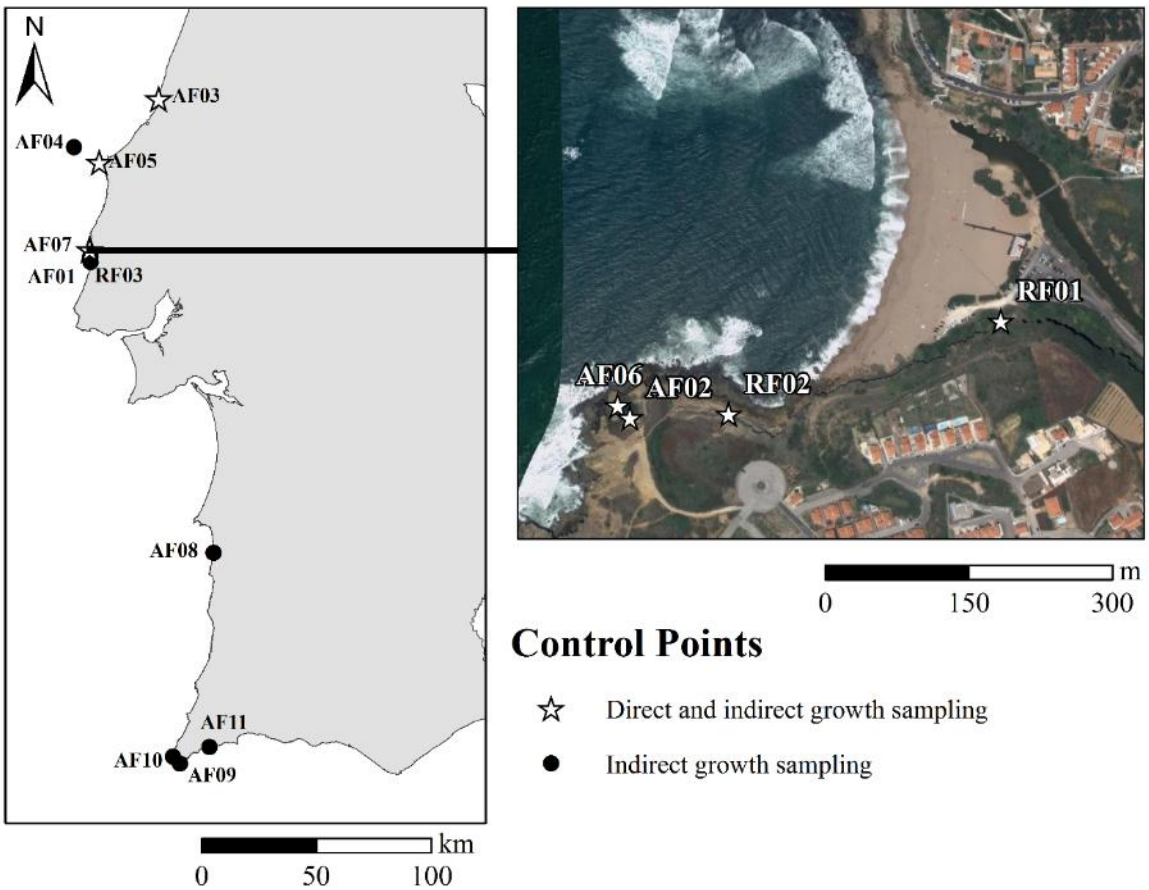

Figure S6: Location of control points where indirect and direct lichen growth were sampled. Maps built with Esri© ArcMapTM 10.5.1.7333, source of satellite images: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

AF03 S. Miguel de Arcanjo Fort: 1645

The AF03 control point is located at an ancient fort named S. Miguel de Arcanjo. The fort was built around 1577 to protect the bay and port from pirates and pillages (Almeida, 1946; Machado, 2009). The earlier and unfinished version of the fort revealed inadequate defensive capabilities. For this reason, the fort was later rebuilt, remodeled and expanded, and reached its current configuration in 1645 (Almeida, 1946; Machado, 2009). Lichens were sampled in the cornerstones of the N-facing wall (surface aspect 330° N) of the fort at 15 m above mean sea level (amsl) and 24 m from the coastline (Figure S7). The control surface was vertical and comprised of clastic limestone. Lichen size measurements and photographic record for cover measurements were undertaken in 13-11-2015. The site was re-visited in 25-01-2020 to photograph lichen thalli for direct lichen growth measurements.

Figure S7: (a) (b) Location of the AF03 control point in S. Miguel de Arcanjo Fort over a satellite image (Maps built with Esri© ArcMapTM 10.4, source of the satellite image: Esri, Digital Globe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community).(c) Corner-stones used in lichen cover measurements; vertical scale corresponds to 0.6m and horizontal scale to 0.8m. (d) Detail of a lichen thallus on the corner-stone.

AF04 S. João Baptista Fort: 1678

AF04 control point is in S. João Baptista Fort on Berlenga Grande island, offshore central Portugal. The fort was built as a convent around 1520. It was abandoned around 1570 and later, in 1640, rebuilt and turned into a fort (Direção Geral dos Edifícios e Monumentos Nacionais, 1953). Since then, S. João Baptista Fort suffered a severe attack and was rebuilt in 1678, as stated in an inscription located over the main door (Direção Geral dos Edifícios e Monumentos Nacionais, 1953). The fort is mainly made of granite, except for the crystalline limestone main door frame, inscription stone, and coat of arms. The door frame comprises a narrow vertical surface facing North (surface aspect of 315°N), at 5m amsl and

10m from the coastline, which is covered with lichens of the species *Opegrapha durieui*. Lichen size measurements and photographic record for lichen cover measurements were undertaken in 31-07-2016 along the limestone stones limiting the upper left side of the door (Figure S8).

Figure S8: (a) Location of the AF04 control point in Berlenga Grande island (image source: "Berlenga Grande Islands." 455993m E and 4362855m N Universal Transverse Mercator WGS84, Google Earth, Image from October 30, 2006, Accessed on August 8, 2016). (b) Sampling location (source of the satellite image: Esri, Digital Globe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. (c) Sampling location. (d) Detail of the lichens covering the surface of the door-frame. Vertical scale 0.42m; horizontal scale 0.19m.

AF05 Baluarte Redondo: 1558

The AF05 control point is in Baluarte Redondo, a small round fort located on the W coast of Portugal, corresponding to the oldest defensive structure in the dataset (Mateus, 1999). As stated in an inscription over the main door, the construction of this structure ended in 1558 (Mateus, 1999). The main door of the fort comprises clastic limestone blocks forming a vertical surface facing 12°N at 14m amsl and 27m from the coastline. Photographic record for lichen cover measurements was undertaken on 17-06-2015, on the left side of the main door. Lichen size was measured on 05-08-2016 (Figure S9). Baluarte Redondo fort has been subject to improvements, such as cleaning, plastering, and painting. The maintenance of this structure resulted in the death of lichens and subsequent stone discoloration. The time of exposure considered in this control point might be overestimated, given that the dates of reconstruction and cleaning are unknown. The site was re-visited in 26-01-2020 to photograph lichen thalli for direct lichen growth measurements.

Figure S9: (a) Location of the AF05. (b) Location of Baluarte Redondo fort (Maps built with Esri© ArcMapTM 10.4, source of the satellite images: Esri, Digital Globe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community). (c) Main door (vertical scale 1m). (d) Surface used in lichen cover measurements (vertical scale 1.2m, horizontal scale 0.2m).

RF01: Cliffs in S. Lourenço beach: 2011-2012

RF01 control point corresponds to a rock-fall scar in the south limiting cliffs of S. Lourenço beach (N of Ericeira). A large boulder of clastic limestone was detached from the cliff-face at 14m amsl and 132m from the coastline (Figure S10a, c, f, and g). This movement generated a vertical surface facing North (surface aspect 335°). Based on field observations and photographic records, it was possible to time-constraint the mass movement between September 2011 and 30-05-2012. Direct observation of the control surface occurred on 20-

09-2013. No visible lichens were covering the surface exposed after the rock-fall, contrasting with older surfaces of the cliff covered with patina and presenting small lichen thalli. The site was re-visited in 19-01-2020, when new lichen thalli were photograph for direct growth measurements.

Figure S10: (a) Location of RF01 and RF02 control points over digital orthophotos (IGEO, 2010). (b) RF02 Rock-fall scar circled in red. (c) RF01 Rock-fall scar and resulting boulder circled in red. (d) RF02 rock-fall scar (vertical scale corresponds to 1m). (e) Detail of lichen cover in RF02 (vertical scale is 0.2m, and the horizontal scale is 0.4m). (f) Part of RF01 surface. (g) Detail of the contrast in lichen cover between the RF01 fresh and older surfaces (vertical scale corresponds to 1m).

RF02: Cliffs in S. Lourenço beach: 2005-2006

RF02 control point comprises a rock-fall scar located further west from RF01, still in the south limiting cliffs of S. Lourenço beach. Movement of a clastic limestone boulder was detected on photographs. Detailed observations of changes occurring in this location, made by Paulo Henriques (geologist in the Portuguese Authority for Civil Protection - Autoridade Nacional de Protecção Cívil), lead to the time constriction of the rock-fall between 1-11-2005 and 10-06-2006. The cliff-face fresh surface is vertical, facing N (surface aspect is 10°), at 9 m amsl, 17m away from the coastline (Figure S10a-b and d-e). Lichen size sampling and photographic records were undertaken on 20-09-2013. The site was re-visited in 19-01-2020 to photograph lichen thalli for direct lichen growth measurements.

AF06 Fencing wall in Santa Susana's Fort: 1657-1777

AF06 control surface is located in the fencing wall of Santa Susana Fort (Figure S11). The fort was built in 1657 to protect the land from pirate attacks (Costa, 1997). By 1777 the Fort was reported to be missing plaster, and its condition was improved in 1831 (Costa, 1997). A part of the fort was demolished between 1944 and 1949, and a new building was built in its place (Costa, 1997). The comparison of the current architectural plant with the original, available in Costa (1997), showed that the northern wall of the fort maintained its configuration. Field observation confirmed the existence of an older and preserved section of the fencing wall missing plaster, made of pilled clastic limestone cobles (Figure S11a and b). The fencing wall forms an N-facing (surface aspect 350°) near-vertical surface (slope of 72°). Lichen size and cover measurements were undertaken on 26-12-2013 on the pilled cobles. The site was re-visited on 26-01-2020 to photograph lichen thalli for direct growth measurements.

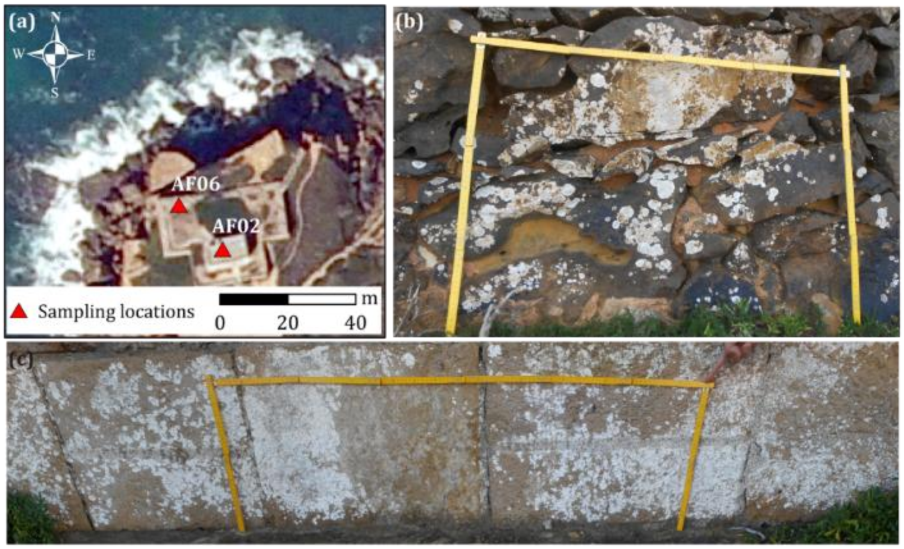

Figure S11: (a) Location of AF06 and AF02 control points in Santa Susana Fort over digital orthophotos (IGEO, 2010). (b) Detail of lichens covering surface AF06 (vertical scale corresponds to 0.6m and horizontal scale to 0.8m).(c) Detail of lichens covering surface AF02 (vertical scale 0.4m; horizontal scale 1.2m).

AF02 Santa Susana Fort: 1944-1949

The remaining part of the Santa Susana fort is younger than the fencing wall and dated from 1944-1949 (Costa, 1997). The N-facing (surface aspect 350°) vertical wall of the fort, located at 18m amsl and30 m away from the coastline, comprises clastic limestone blocks (Figure S11c). Lichen size measurements and photographic record for cover measurements were undertaken over these blocks on 26-12-2013. The site was re-visited on 19-01-2020 to photograph lichen thalli for direct growth measurements.

RF03 Cliffs in Ribeira de Ilhas beach: 1980-1989

RF03 control surface is a massive clastic limestone rock-fall scar facing north (surface aspect 352°) in the cliffs limiting Ribeira de Ilhas beach (Figure S12). The surface is located at 37m amsl and 55m away from the coastline. The rock-fall movement was detected by comparing aerial photographs from 1980 and 1989 (Figure S12b and c). Lichen size measurements and photographic record for lichen cover measurements on this surface were undertaken on 07-11-2013.

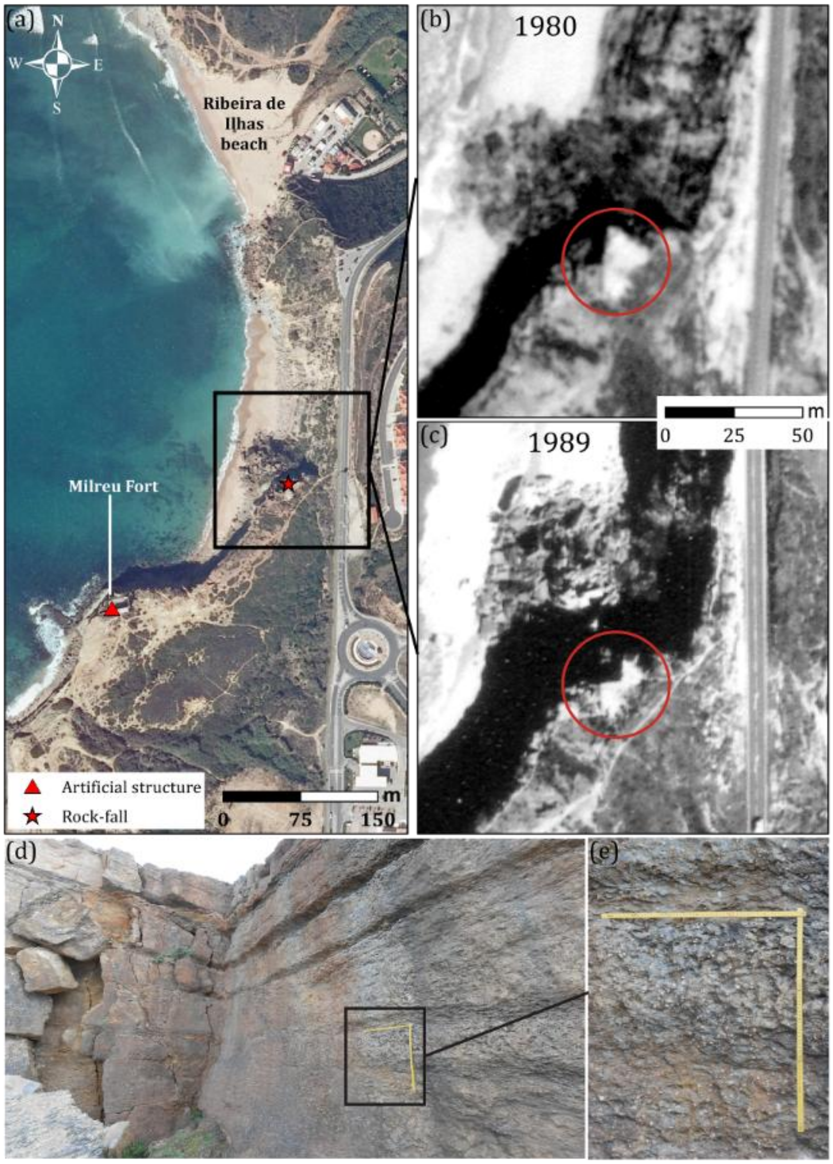

Figure S12: (a) Location of RF03 rock-fall scar and Milreu Fort (AF07 control point) over digital orthophotos (IGEO, 2010). (b) Aerial photograph from 24-05-1980 with a red circle limiting the general area of the RF03 rock-fall. (c) Aerial photograph from 18-04-1989 with a red circle limiting the general area of the rock-fall. (d) RF03 surface. (e) Lichens covering surface RF03 (vertical and horizontal scales 0.6m).

AF07 Milreu Fort: 1657-1777

Control point AF07 is in Milreu Fort, located over a cliff edge at 21m amsl and 34m away from the coastline (Figure S13). The fort was built to protect the land from piracy attacks (Costa, 1997). The most likely age of this fort is 1657 (Costa, 1997). This fort was reported to be missing plaster in 1777, and reconstruction occurred in 1831 (Costa, 1997). Differences in building materials used during reconstruction are easily detected: plaster was replaced by concrete, and patched walls were made of bricks instead of limestone quarry (Figure S13b).

Lichen size was measured on 30-01-2014 over unplastered clastic limestone cobbles that comprise the N and E-facing walls, which have become exposed sometime between 1657 (date of construction) and 1777. Photographic record for lichen cover measurements was undertaken on 07-11-2013, at the base of the N-facing wall over building blocks, likely exposed since 1957 (Figure S13b and c).

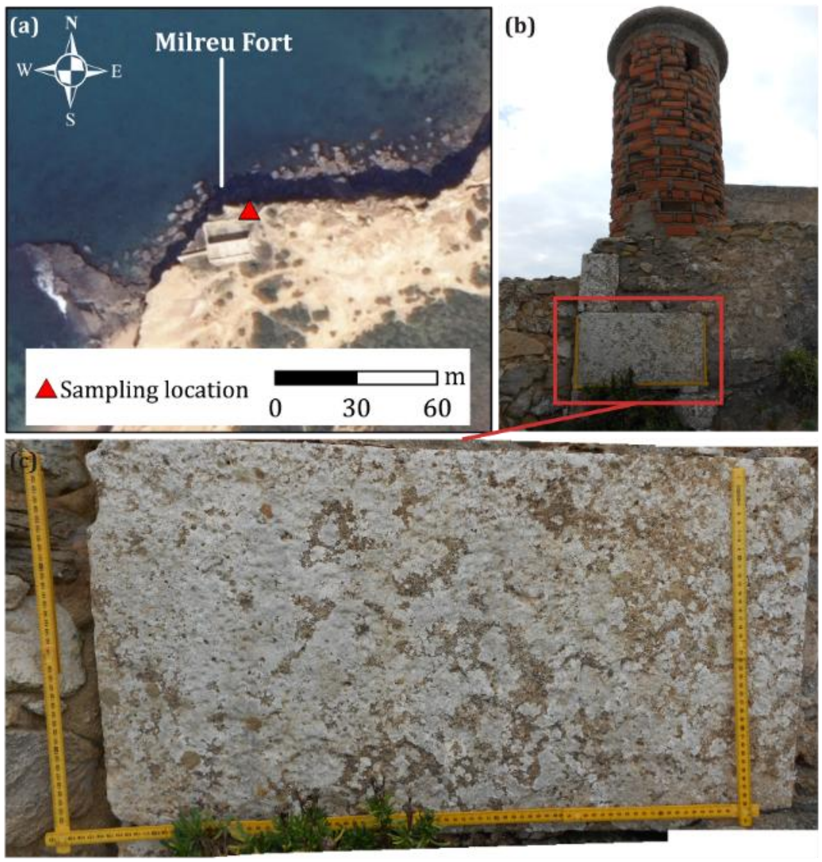

Figure S13: (a) Location of the AF07 control point over digital orthophotos (IGEO, 2010). (b) Cornerstone used in lichen cover measurements (vertical scale 0.2m; horizontal scale 0.8m). (c) Lichens covering the surface of the cornerstone (vertical scale 0.2m; horizontal scale 0.8m).

AF01 Concrete wall in Ericeira: 1980-2000

AF01 control point corresponds to an artificial wall at 20m amsl and 20m away from the coastline, re-built between 1980 and 2000 (Figure S14). Changes in the configuration of the wall were detected by comparing aerial photographs. Lichen size measurements and photographic record for lichen cover measurements were undertaken on 18-02-2014, over the N-facing section of the wall (surface aspect 6°), made of concrete (Figure S15 c and d).

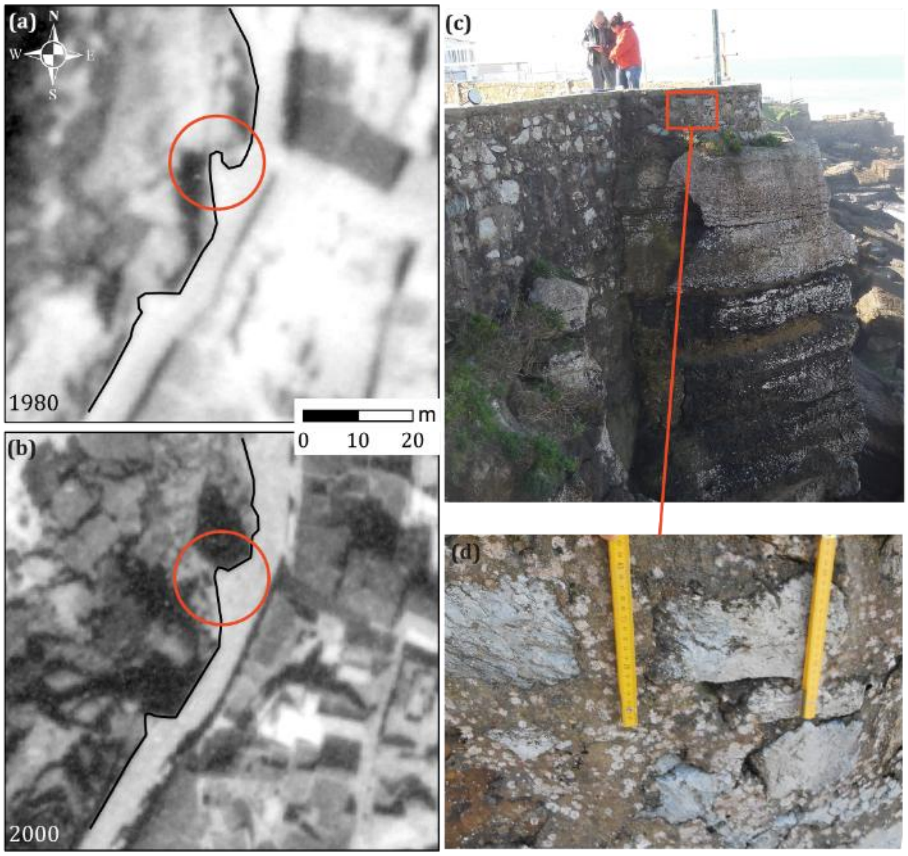

Figure S14: (a) Location of AF01 control point over an aerial photograph from 24-05-1980; red circle is limiting the general area of the artificial wall, here represented by the black line. (b) Aerial photograph from 24-02-2000. (c) AF01 control surface. (d) Lichens covering the surface (vertical scales 0.2m).

AF08 Pessegueiro Fort: 1588-1690

The construction of Pessegueiro Fort, where AF08 control point is located (Figure S15), began in 1588 (Quaresma, 2007). The construction was repeatedly interrupted and resumed under the direction of several engineers, was abandoned in 1608 (Quaresma, 2007; Guedes, 1989), and finally completed in 1690 (Quaresma, 2007*;* Severino, 2014). Sampling was focused on walls of the fort’s trench made of aeolianite blocks. Lichen size measurements were undertaken in the NW and SW walls of the trench, facing the fort (surface aspect ranging from 20° to 130°), on 03-08-2016. Photographic record for lichen cover measurements was undertaken in the walls of the fort’s SW trench, facing NE.

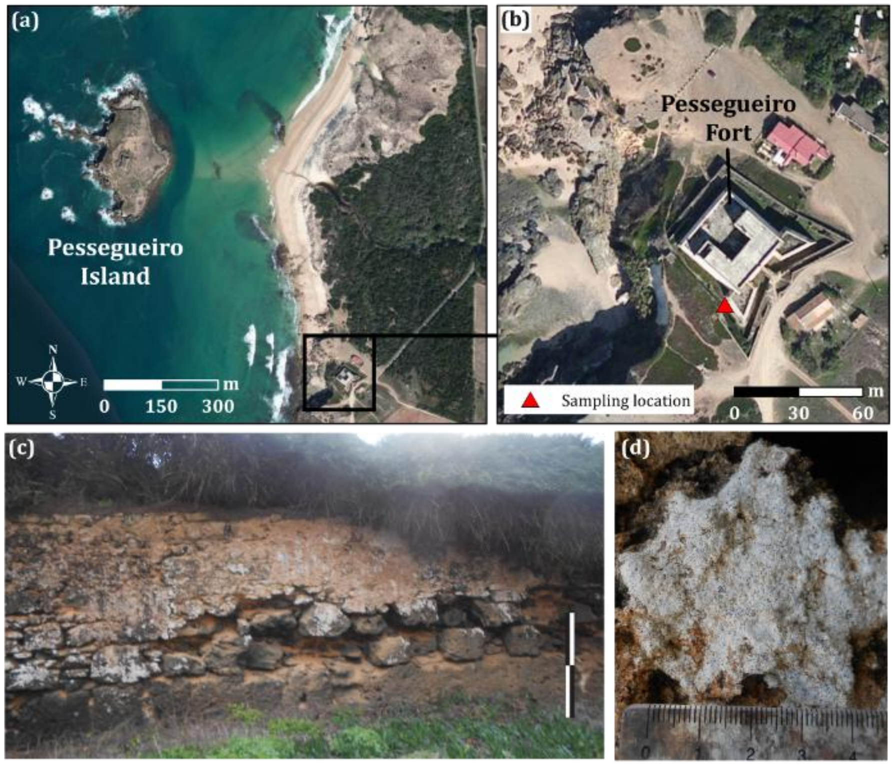

Figure S15: (a) AF08 control point. (a) Location of the control point in Pessegueiro Fort. (b) Lichen size and cover sampling location (Maps built with Esri© ArcMapTM 10.4, source of the satellite images: Esri, Digital Globe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community). (c) Wall of the southern trench used in lichen cover measurements (vertical scale 1m). (d) Detail of a lichen in the trench wall.

AF09 Belixe Fortress: 1632

AF09 control point is located on Belixe Fort, in the SW tip of mainland Portugal (Figure S16a). This structure was built during the XV-XVI centuries, to be destroyed by pirate Francis Drake in 1587, and later rebuilt in 1632 (Severino, 2014; Direção Geral dos Edifícios e Monumentos Nacionais, 1960). The 1755 earthquake caused some damages to the fort, later to be reconstructed by Direção Geral dos Edifícios e Monumentos Nacionais (General Directorate of National Buildings and Monuments) between 1940 and 1960 (Direção Geral dos Edifícios e Monumentos Nacionais, 1960). Photographs taken before and after the reconstruction show an unharmed and untouched bulwark, in the lower eastern section of the fortress. Photographic record for lichen cover measurements was undertaken on 26-01-2014 and lichen size measurements on 3-08-2016. Both variables were sampled over pilled shelly limestone cobles on the vertical N-facing wall of the fort (surface aspect 354°), at 52m amsl, and 70m away from the coastline (Figure S16b-d).

Figure S16: (a) Location of the control point AF09 Belixe Fortress. (b) Sampling location (Maps built with Esri© ArcMapTM 10.4, source of the satellite images: Esri, Digital Globe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community). (c) Eastern part of Belixe Fortress bulwark (vertical scale 1m). (d) Area of the bulwark used in lichen cover measurements (vertical scale 0.2m and horizontal scale 0.8m).

AF10 Sagres Fortress: 1793

AF10 is in Sagres Fortress, in the SW tip of mainland Portugal (Figure S17a). This structure is dated from the XV century, evidenced by archaeological remains (Silva, 2013) and by extensive historical documents that mention the existence of a village attributed to this location (Direção Geral dos Edifícios e Monumentos Nacionais, 1960). However, the current configuration of the bulwark is different from the portrayed in historical documents (Direção Geral dos Edifícios e Monumentos Nacionais, 1960; Mesquita, 2000). The original bulwark and gateway were destroyed by pirate Francis Drake in 1587 and by two earthquakes (27-12-1722 and 1-11-1755) (Direção Geral dos Edifícios e Monumentos Nacionais, 1960; Mesquita, 2000; Silva, 2013). Reconstruction with the current configuration finished in 1793, as stated in an inscription in the coat of arms (Direção Geral dos Edifícios e Monumentos Nacionais, 1960; Mesquita, 2000; Silva, 2013). Since then, improvement works were carried out by Direção Geral dos Edifícios e Monumentos Nacionais, including the extension of the gateway, during 1940-1960 (Direção Geral dos Edifícios e Monumentos Nacionais, 1960; Mesquita, 2000). The crystalline limestone quarry that composes thw gateway was removed during reconstruction and later re-used, maintaining at least part of the lichen cover, shown in photographs taken immediately after improvement works, available in Direção Geral dos Edifícios e Monumentos Nacionais (1960).

Photographic record for measurement of lichen cover was undertaken on 26-01-2014, over a vertical surface facing NE (surface aspect 50°) at 37m amsl and 102m away from the coastline, over the limestone quarry surrounding the main entrance of the fort (Figure S17b-d). Initial observations indicated that many thalli were dead, possibly due to stone cleaning during reconstruction. The absence of lichens and the presence of stone discoloration in other limestone blocks throughout the fort wall strongly supports this interpretation. Lichen size and cover were measured in limestone stones with preserved thalli, located on the right side of the gateway of Sagres Fortress. Species identification was only possible for two of the five largest thalli measured in this location, given the absence of preserved reproductive structures. Lichen size measurements were undertaken on 03-08-2016. An underestimation of percentage cover is expected due to lichen removal during stone cleaning. Also, given that most individuals were dead, possibly due to reconstruction during 1940-1960, it was assumed that lichens stopped growing in 1950.

AF11 S. Luís Almádena Fort: 1632

AF11 control point, in S. Luís de Almádena Fort, is on the S-facing coast of Portugal (Figure S18a). The fort is in ruins, although it is possible to identify most of the original architecture (Severino, 2014). The fort was built in 1632 to defend the coastline, particularly the fishing settlements frequently attacked by pirates (Coutinho, 1997). Photographic record for lichen cover measurements were undertaken on 26-01-2014 over unplastered clastic limestone cobbles comprising the N-facing (surface aspect 328°) walls of the fort, at 69m amsl and 97m from the coastline (Figure S19b and c). Sampling for lichen size was undertaken in the same wall on 03-08-2016.

Figure S17: (a) Location of Sagres Fortress. (b) Sampling location in Sagres Fortress (Maps built with Esri© ArcMapTM 10.4, source of the satellite images: Esri, Digital Globe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community). (c) Photo of the gateway (vertical scale 1m). (d) Area selected for measurements of lichen cover (vertical scale 1m and horizontal scale 0.2m).

Figure S18: (a) Location of AF11 control point in S. Luís de Almádena Fort (Maps built with Esri© ArcMapTM 10.4, source of the satellite images: Esri, Digital Globe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community). (b) View of the northern wall of the Fort (vertical scale 2 m). (c) Detail of the wall surface used in lichen cover measurements (vertical and horizontal scales 1m).

Summary

The information regarding control points is summarized in Table S2. Lichen coalescence was frequently observed in surfaces with a long time of exposure, making the identification and measurement of individual lichens a complicated task. This was the case in control points AF11, AF08, AF07, and AF05. Furthermore, in some forts, lichens were found and measured over unplastered limestones, such as AF06, AF07, AF11, and AF08. Unplastering resulted from deterioration of plaster applied originally over the construction material. In these cases, it was considered that exposure occurred immediately after construction, except for AF07 and AF06 sampling locations, where 18th-century historical documents on the state of preservation of the forts aided to constrain the age of exposure of stones (Costa, 1997). The age of exposure can be overestimated in these cases.

In AF10 and AF05 sampling locations, the limestone blocks comprising the doorframes have been partially cleaned; this is evidenced by the large number of dead organisms and stone discoloration. In both locations, the date of the most recent cleaning operation is unknown. In the case of the AF10 control point, lichens were assumed to have stopped growing following major reconstruction undertaken around 1950 (between 1940 and 1960). Maintenance of AF05 repeatedly occurred due to the continuous use of that defensive structure, precluding the establishment of the most recent date of stone cleaning.

Table S2: Control points used in the construction of the lichen growth curve for the species *Opegrapha durieui*. RF stands for rock-fall and AF for artificial structure. *Time of exposure ended before date of measurement due to stone cleaning during reconstruction. DD-decimal degrees; amsl-above mean sea level

Control Point	Longitude (DD)	Latitude (DD)	Altitude (m amsl)	Distance from the coastline (m)	Lithology	Surface aspect and slope	Date		Time	Lichen sampling
							Exposure	Sampling		
RF01	-9.42069	39.0110	14	132	Clastic limestone	355°, vertical	01-09-2011 to 30-05-2012	20-09-2013	1.7	Size and cover
RF02	-9.42395	39.0101	9	17		10°, vertical	01-11-2005 to 10-06-2006	20-09-2013	7.6	
AF01	-9.41870	38.9626	20	20	Concrete	6°, vertical	24-05-1980 to 24-02-2000	18-02-2014	23.6	
RF03	-9.41867	38.9848	37	55	Clastic limestone	352°, vertical	24-05-1980 to 18-04-1989	07-11-2013	29	
AF02	-9.42514	39.0101	18	30	Clastic limestone	350°, vertical	1944 to 1949	26-12-2013	67	
AF03	-9.08534	39.6045	15	24	Clastic limestone	330°, vertical	1645	13-11-2015	370	
AF04	-9.51019	39.4116	5	10	Crystalline limestone	315°, vertical	1678	31-07-2016	338	

Control Point	Longitude (DD)	Latitude (DD)	Altitude (m amsl)	Distance from the coastline (m)	Lithology	Surface aspect and slope	Date		Time	Lichen sampling
							Exposure	Sampling		
AF05	-9.38124	39.3527	14	27	Clastic limestone	12°, vertical	1558	17-06-2015	457	Cover
								05-08-2016	458	Size
AF06	-9.42529	39.0102	17	19	Clastic limestone	350°, 72°	1657 to 1777	26-12-2013	296	Size and cover
AF07	-9.42046	38.9838	21	34	Clastic limestone	Variable	1657 to 1777	30-01-2014	297	Size
							1657	07-11-2013	356	Cover
AF08	-8.79105	37.8281	13	51	Aeolianite	Variable	1690	09-02-2014	324	Cover
								03-08-2016	326	Size
AF09	-8.98254	37.0274	52	70	Shelly limestone	354°, vertical	1632	26-01-2014	382	Cover
								03-08-2016	384	Size
AF10	-8.94814	37.0009	37	102	Crystalline limestone	50°, vertical	1973*	26-01-2014	157	Cover
								03-08-2016		Size
AF11	-8.80429	37.0668	69	97	Clastic limestone	328°, vertical	1632	26-01-2014	382	Cover
								03-08-2016	384	Size

Changes in lichen cover area, percentages and standard deviation with control area increments

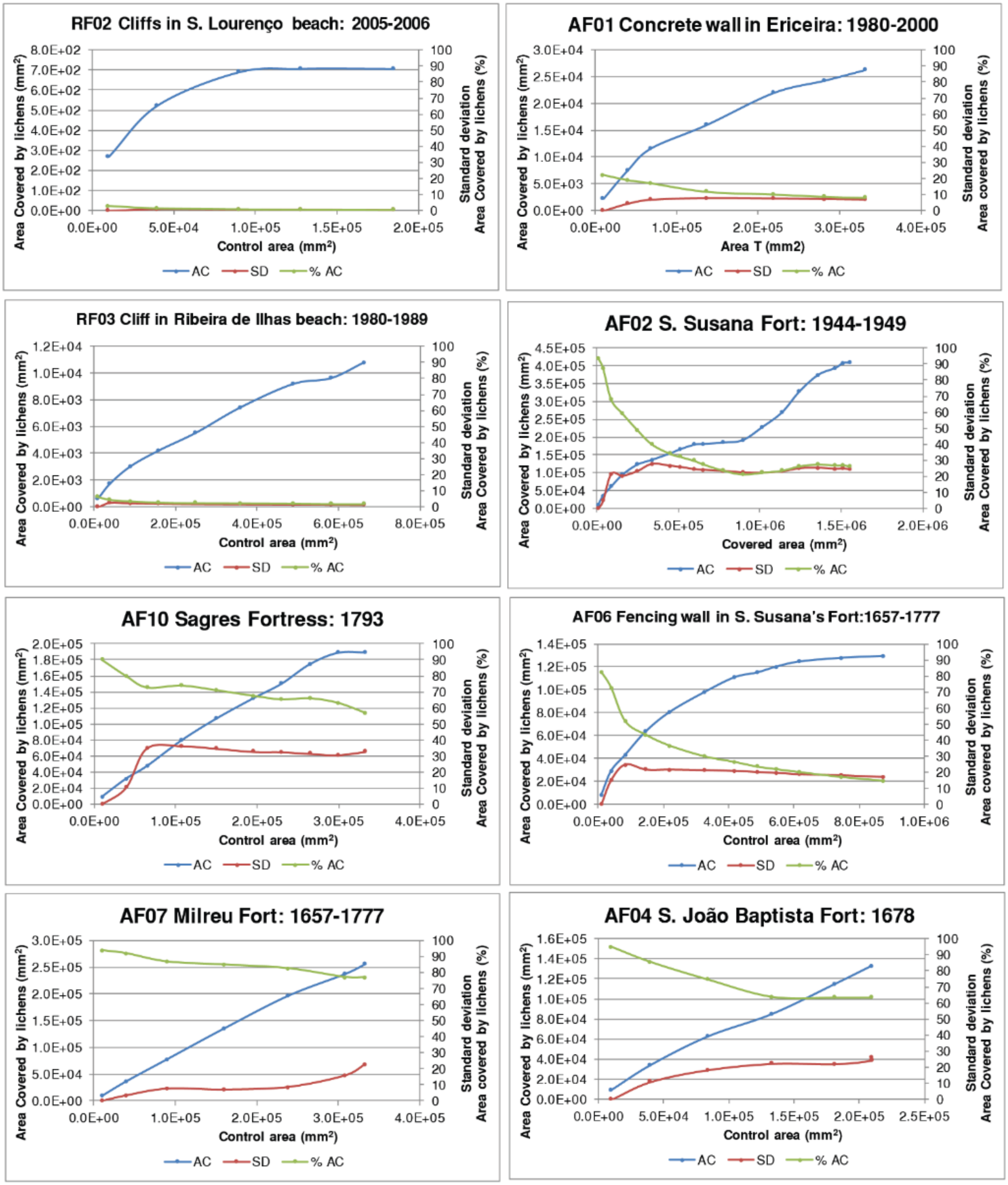

Figure S19: Plots showing changes in area covered by lichens, percentage of area covered and standard deviation, with increments in the control area

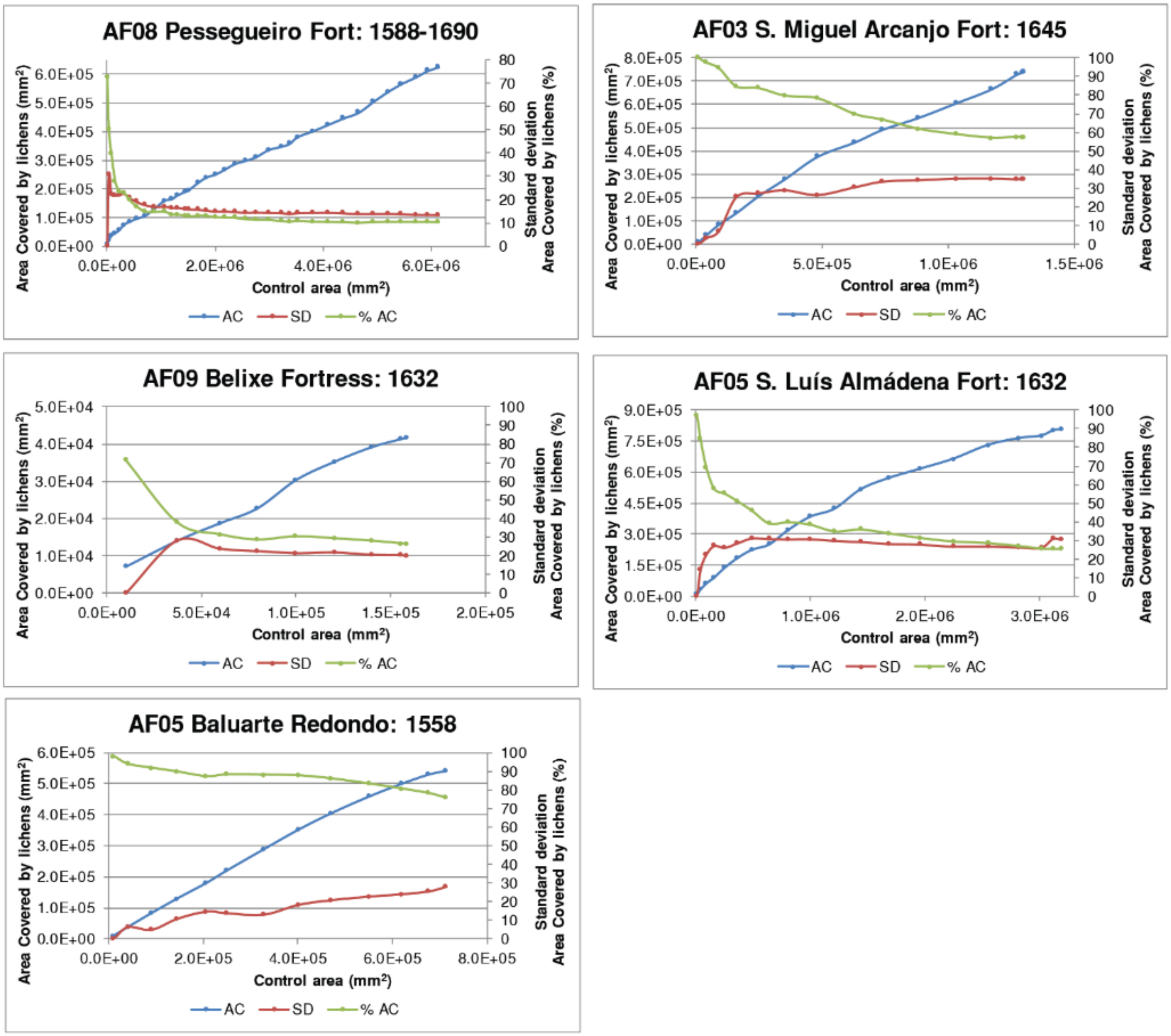

Figure S19: (cont.) Plots showing changes in area covered by lichens, percentage of area covered and standard deviation with increments in the control area

Table S3: Bioclimatic variables, averaged for the years 1970-2000, in each control point, extracted from the WorldClim Version2 climate dataset (Fick and Hijmans, 2017).

Control Point	Temperature (°C)	Water vapor pressure (kPa)	Solar radiation (kJ m^{-2} day^{-1})	Precipitation (mm)
RF01	15.43	1.44	16098	53.50
RF02	15.43	1.44	16098	53.50
AF01	15.28	1.43	16188	55.08
RF03	15.46	1.43	16223	53.00
AF02	15.43	1.44	16098	53.50
AF03	15.12	1.41	15802	56.92
AF04	15.49	1.42	15718	52.58
AF05	15.43	1.43	15734	50.42
AF06	15.43	1.44	16098	53.50
AF07	15.46	1.43	16223	53.00
AF08	16.09	1.45	17183	46.50
AF09	16.23	1.47	17440	40.67
AF10	16.63	1.49	17500	39.58
AF11	16.78	1.46	17459	41.42

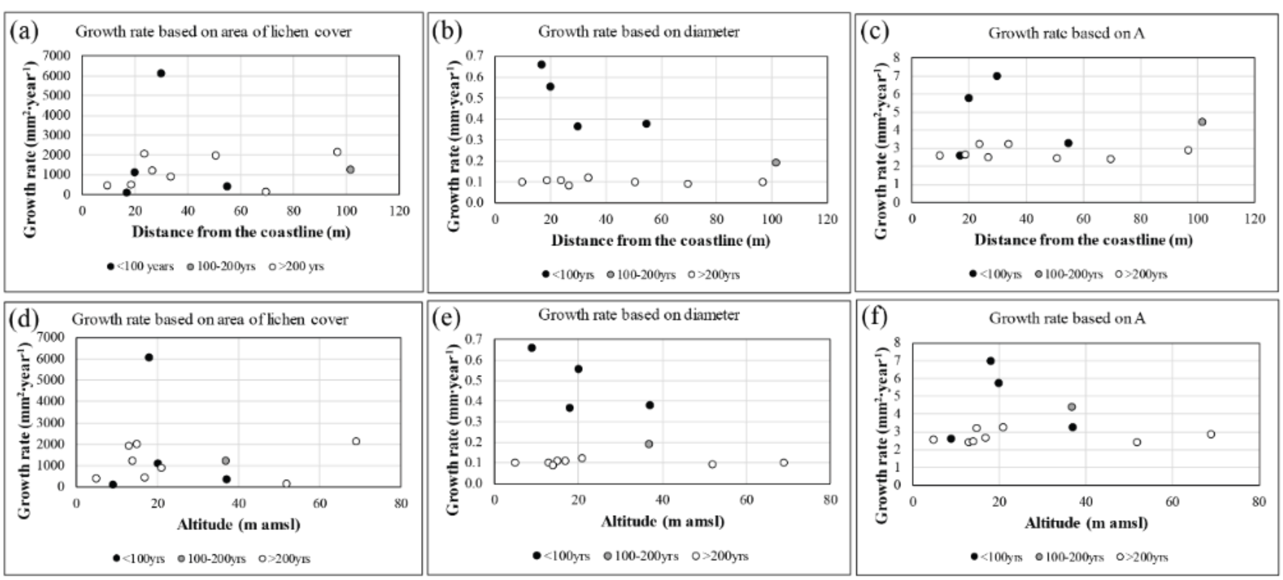

Figure S20: Scatter plots relating distance from the coastline (a-c) and altitude (d-f) with growth rate obtained from different lichen size parameters (lichen cover over a 100×100 mm control area, lichen diameter and area of the largest inscribed circle, respectively).

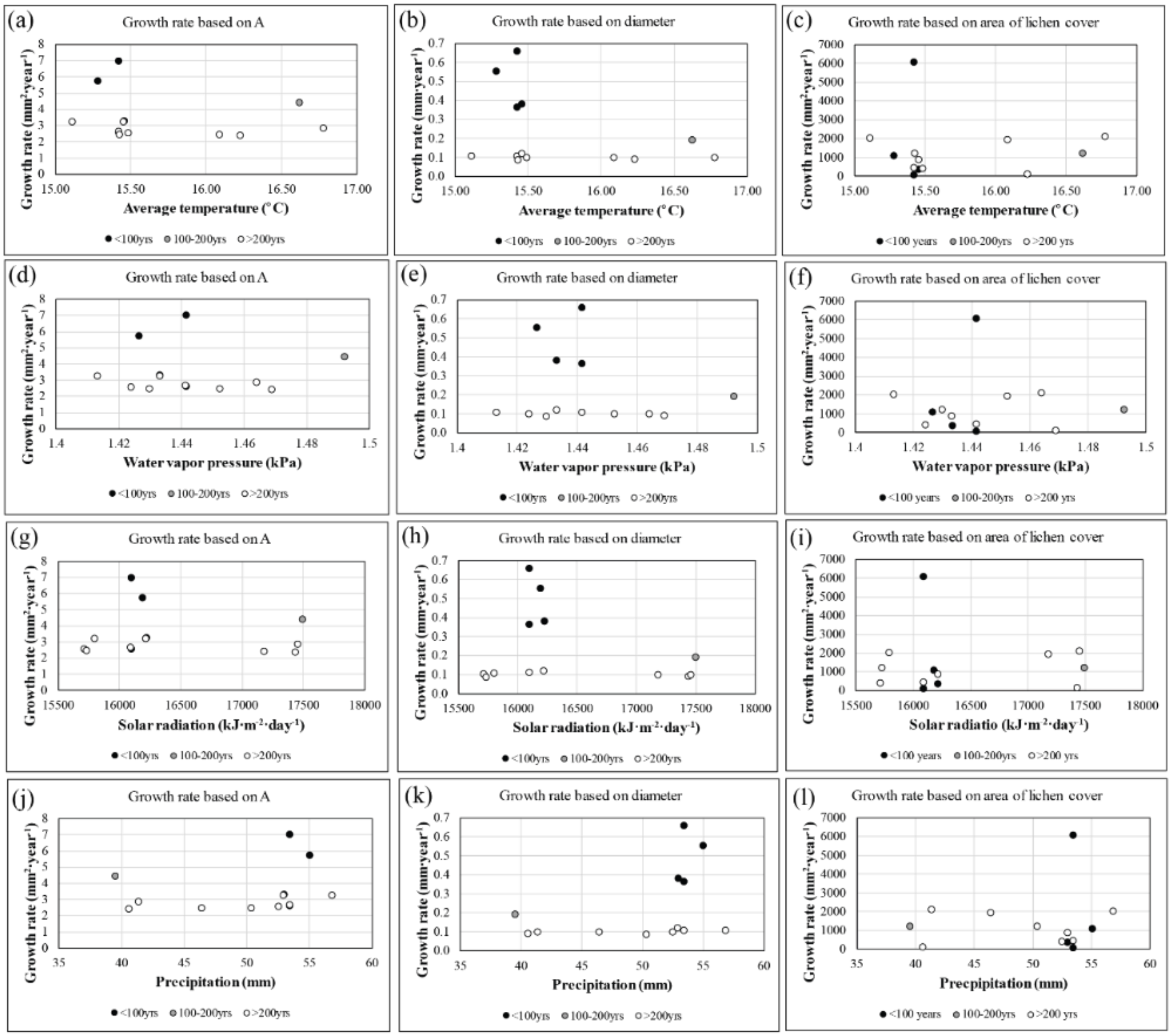

Figure S21: Scatter plots relating average temperature (a-c), water vapor pressure (d-f), solar radiation (g-i) and precipitation (j-l) with growth rate, obtained from different lichen size parameters (lichen cover over a 100×100 mm control area, lichen diameter and area of the largest inscribed circle, respectively).

Direct measurements of lichen growth

RF01: Cliffs in S. Lourenço beach: 2011-2012

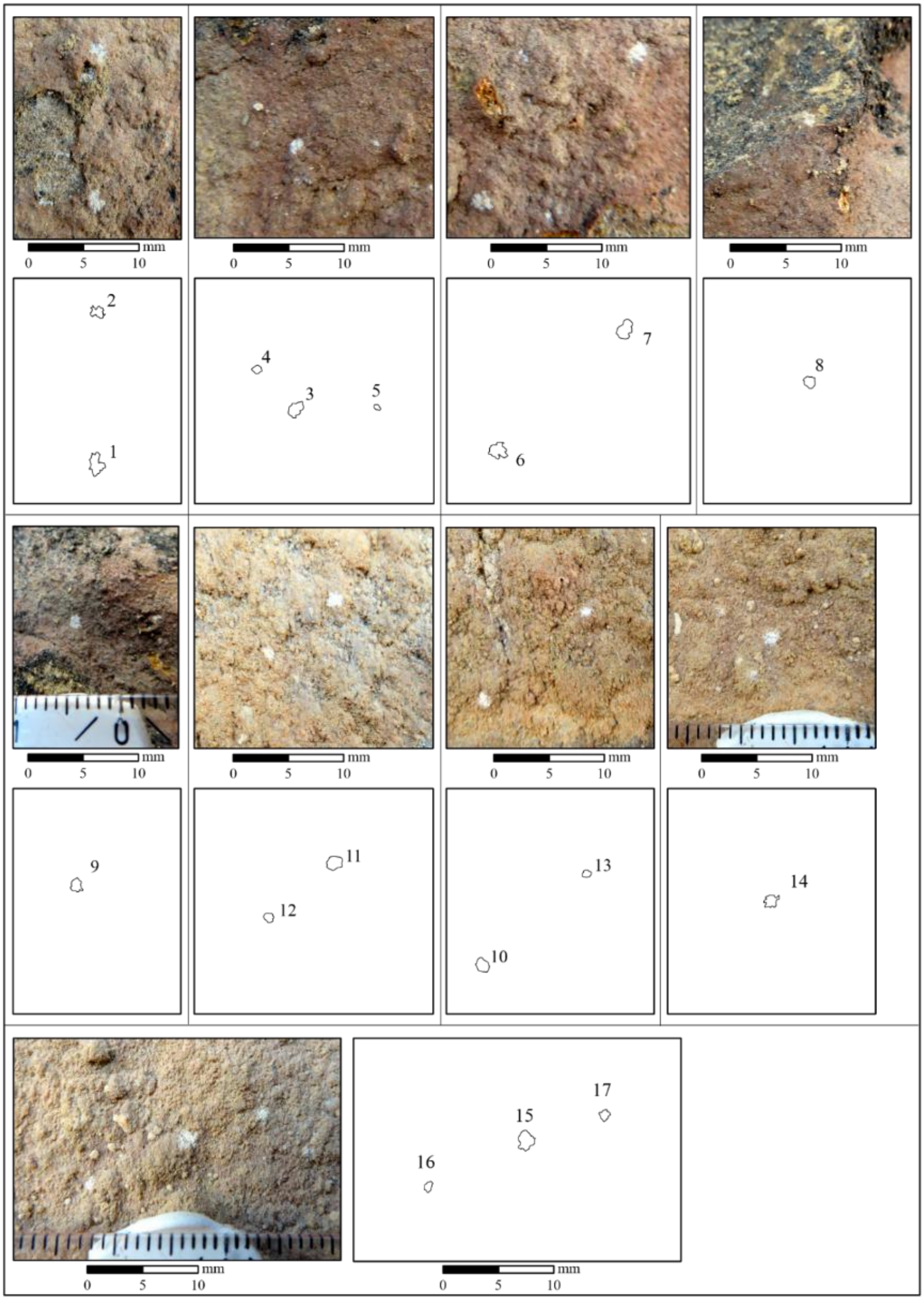

Figure S22: Photographs of lichens found in RF01 control point in 2020 and outline of lichen thalli.

RF02: Cliffs in S. Lourenço beach: 2005-2006

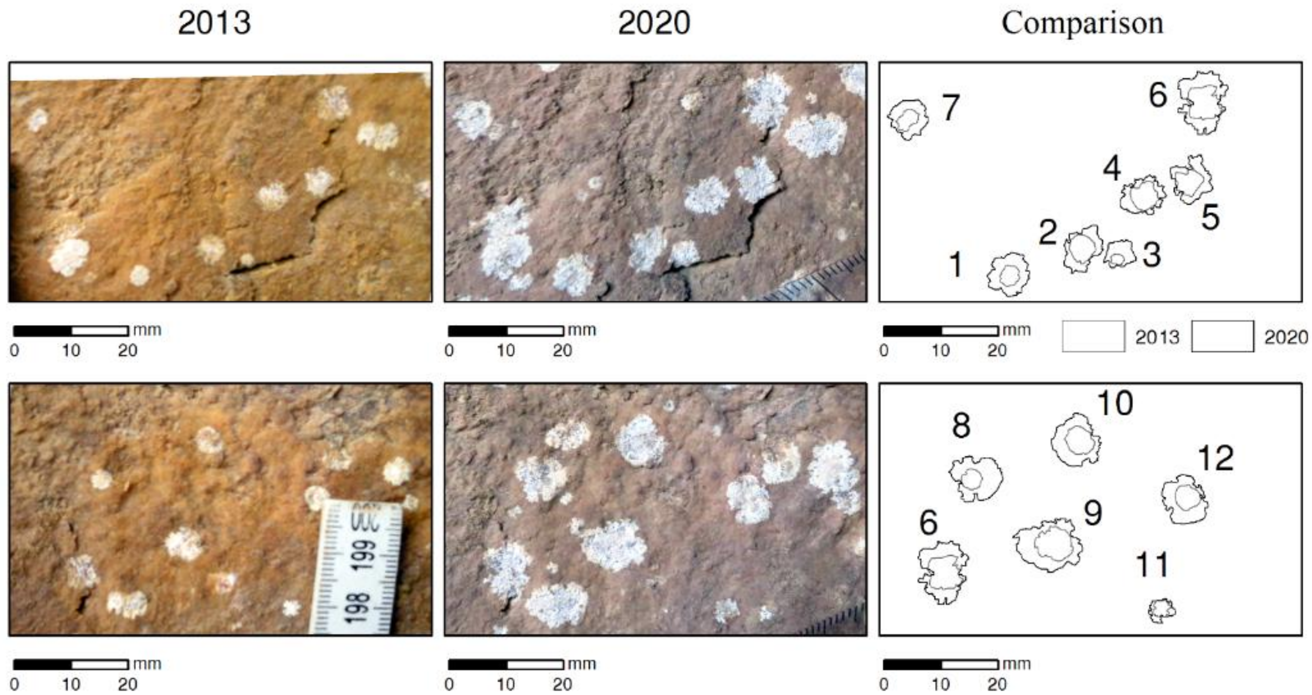

Figure S23: Photographs of lichens used for direct measurement of growth in 2013 and 2020 in RF02 control surface and comparison between the outline of lichen thalli.

AF02 Santa Susana Fort: 1944-1949

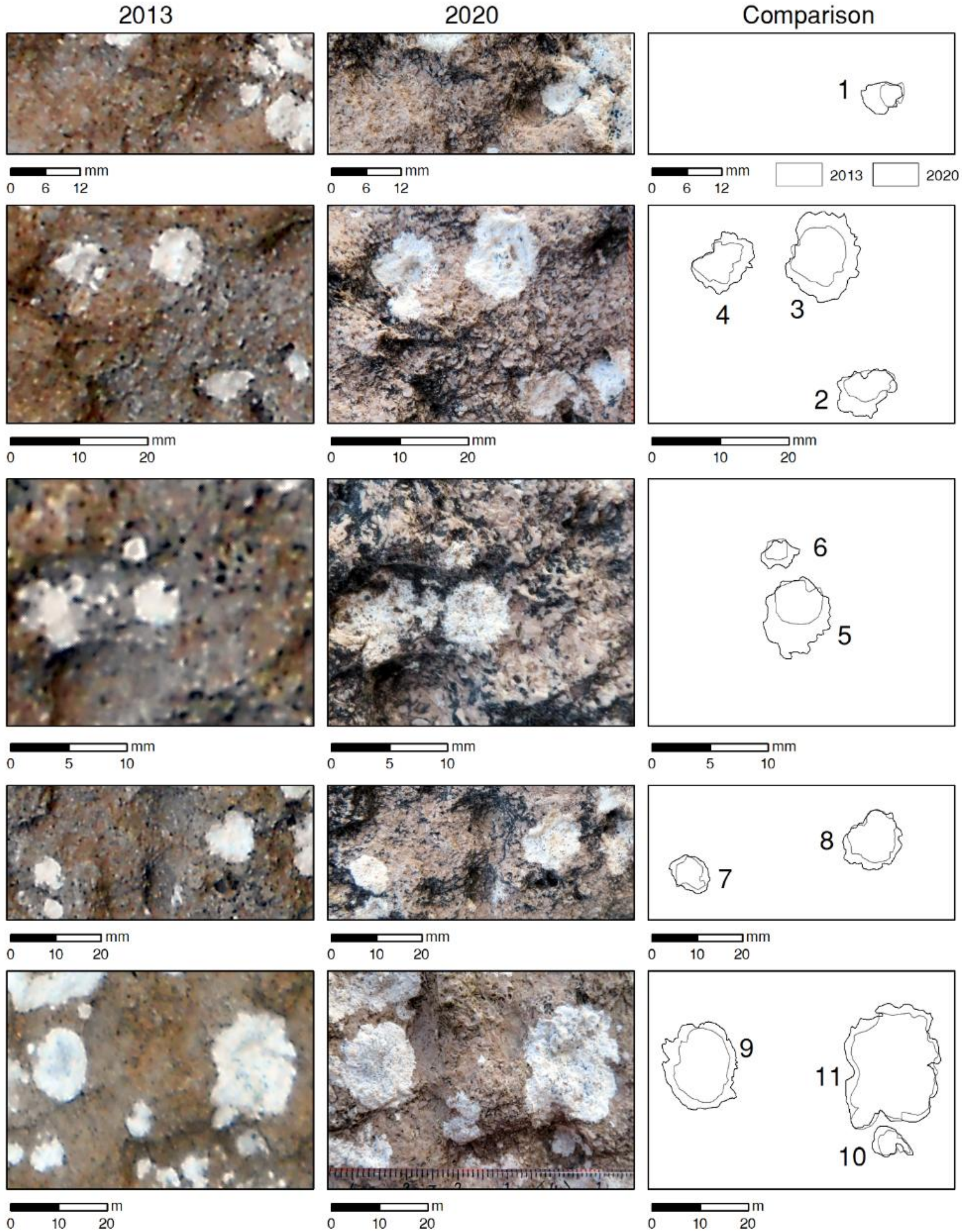

Figure S24: Photographs of lichens used for direct measurement of growth in 2013 and 2020 in RF02 control surface and comparison between the outline of lichen thalli.

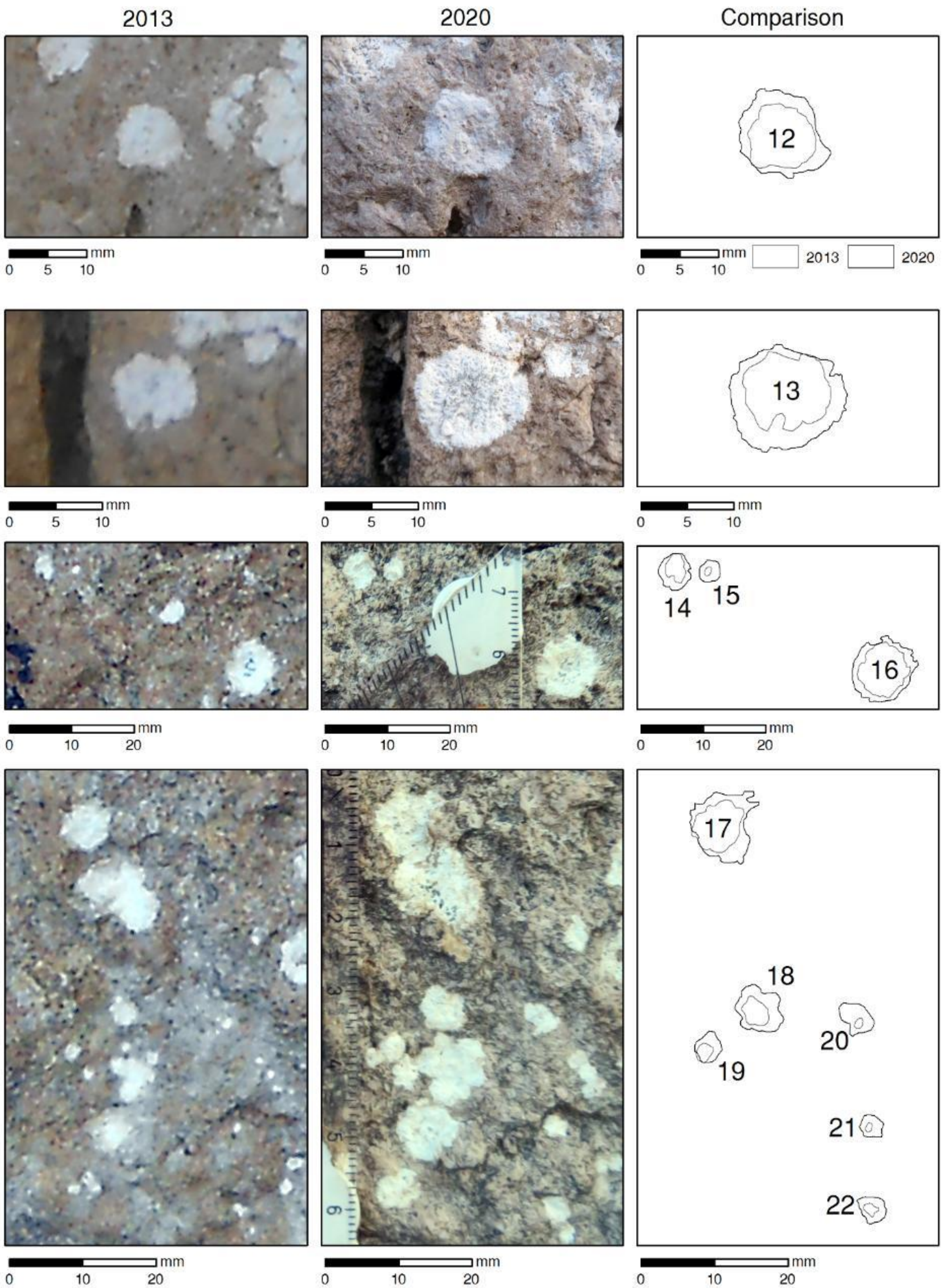

Figure S25: Photographs of lichens used for direct measurement of growth in 2013 and 2020 in RF02 control surface and comparison between the outline of lichen thalli.

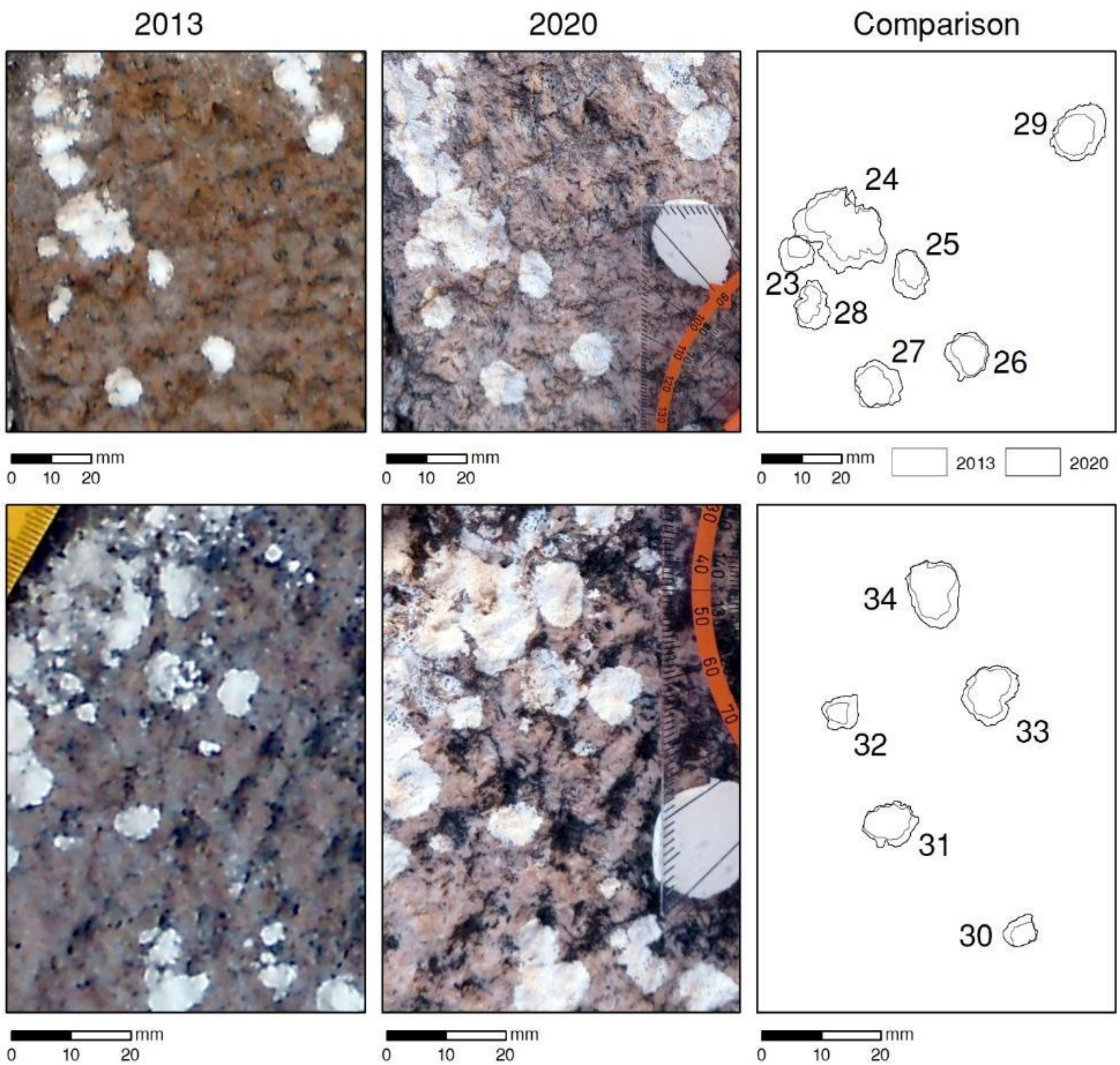

Figure S26: Photographs of lichens used for direct measurement of growth in 2013 and 2020 in RF02 control surface and comparison between the outline of lichen thalli.

AF03 S. Miguel de Arcanjo Fort: 1645

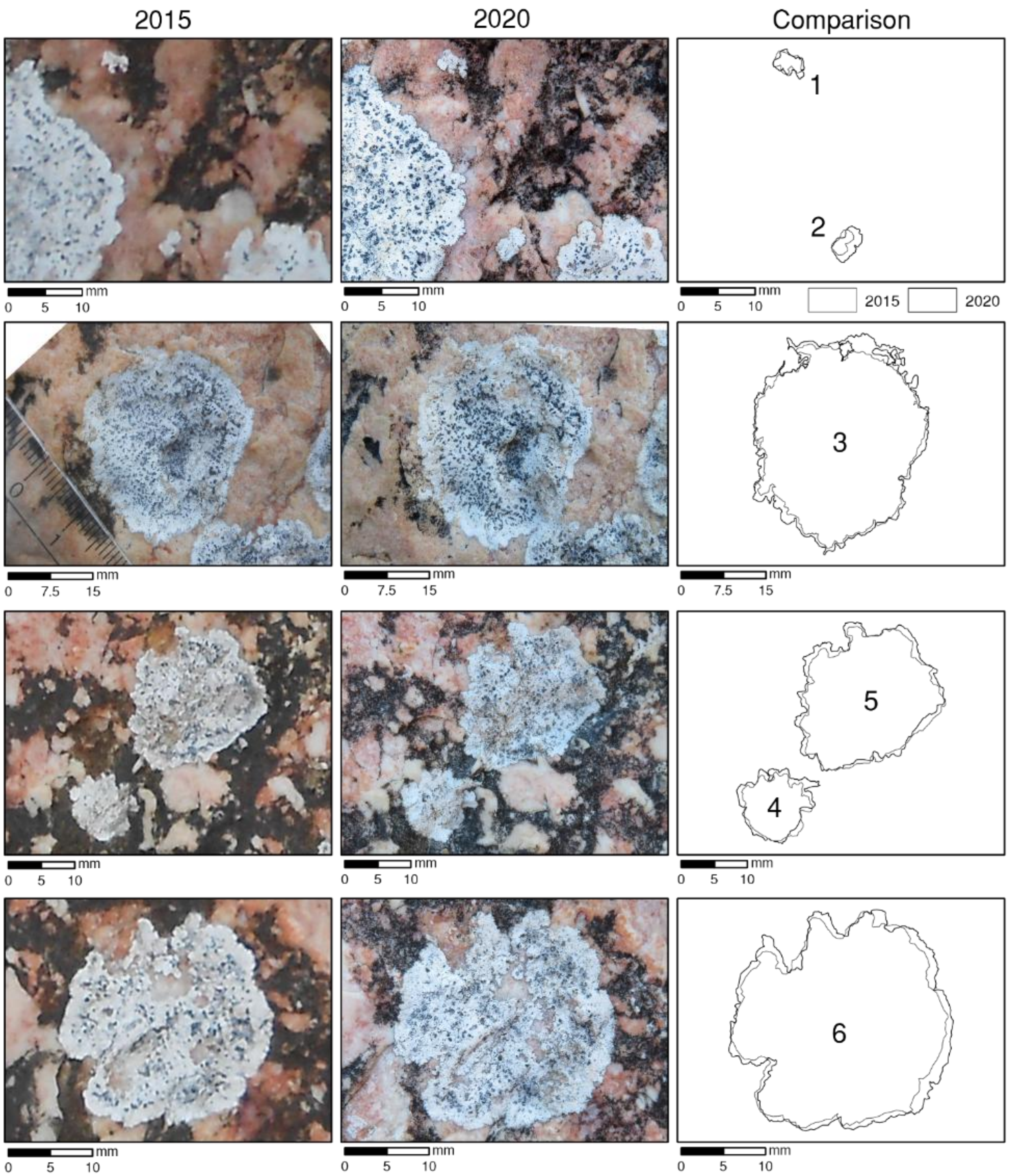

Figure S27: Photographs of lichens used for direct measurement of growth in 2015 and 2020 in AF03 control surface and comparison between the outline of lichen thalli.

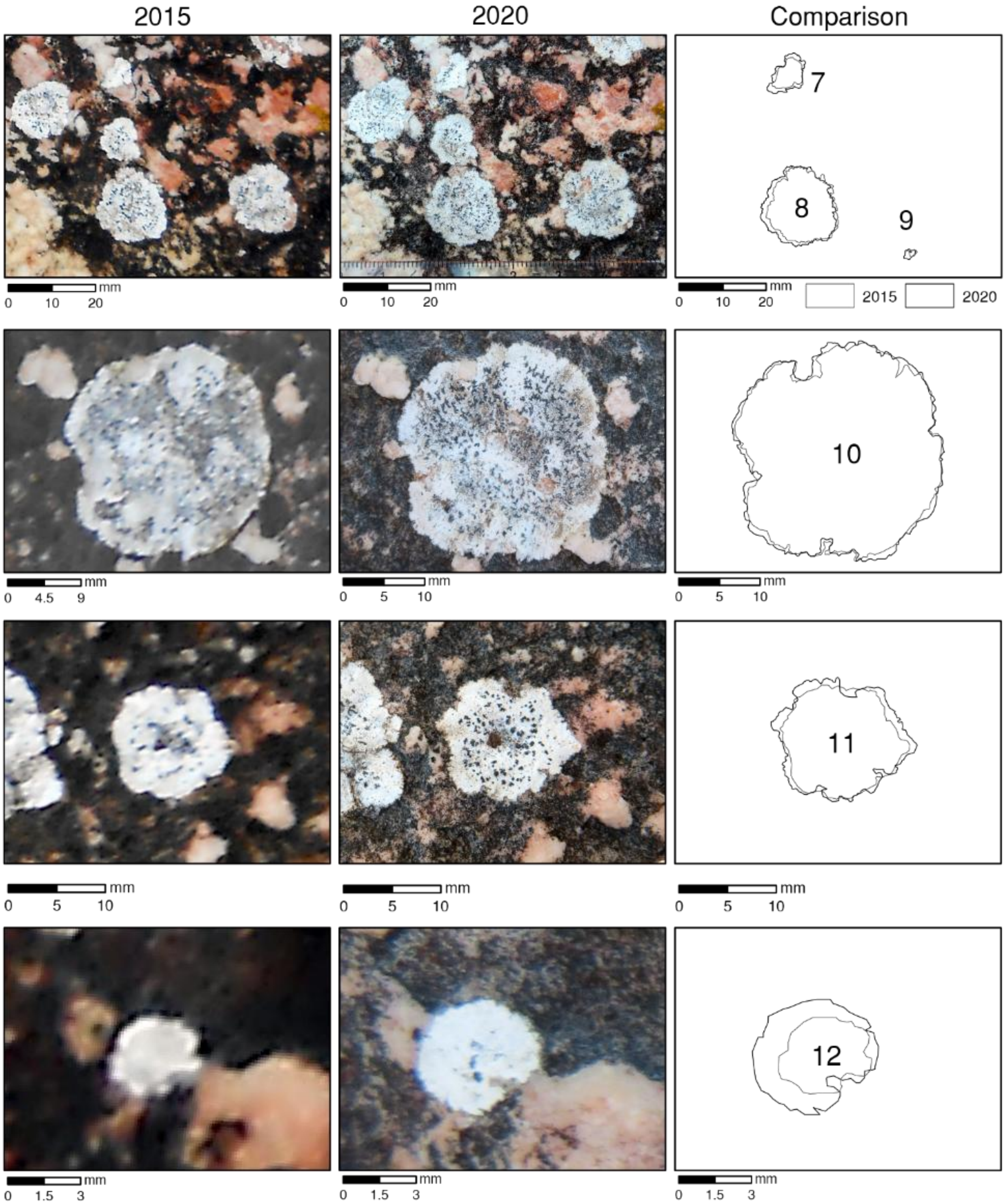

Figure S28: Photographs of lichens used for direct measurement of growth in 2015 and 2020 in AF03 control surface and comparison between the outline of lichen thalli.

AF06 Fencing wall in Santa Susana's Fort: 1657-1777

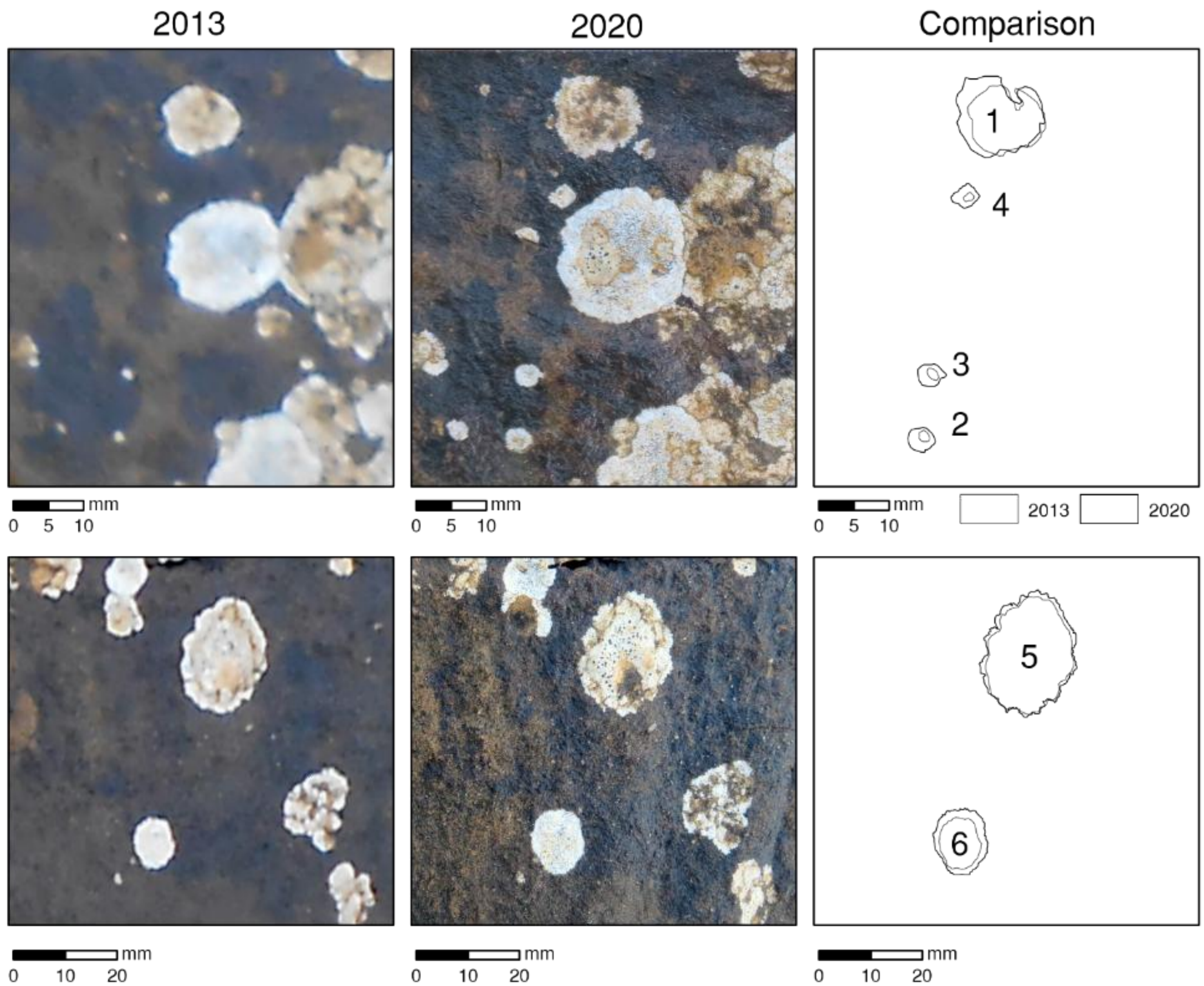

Figure S29: Photographs of lichens used for direct measurement of growth in 2013 and 2020 in RF06 control surface and comparison between the outline of lichen thalli.

AF05 Baluarte Redondo: 1558

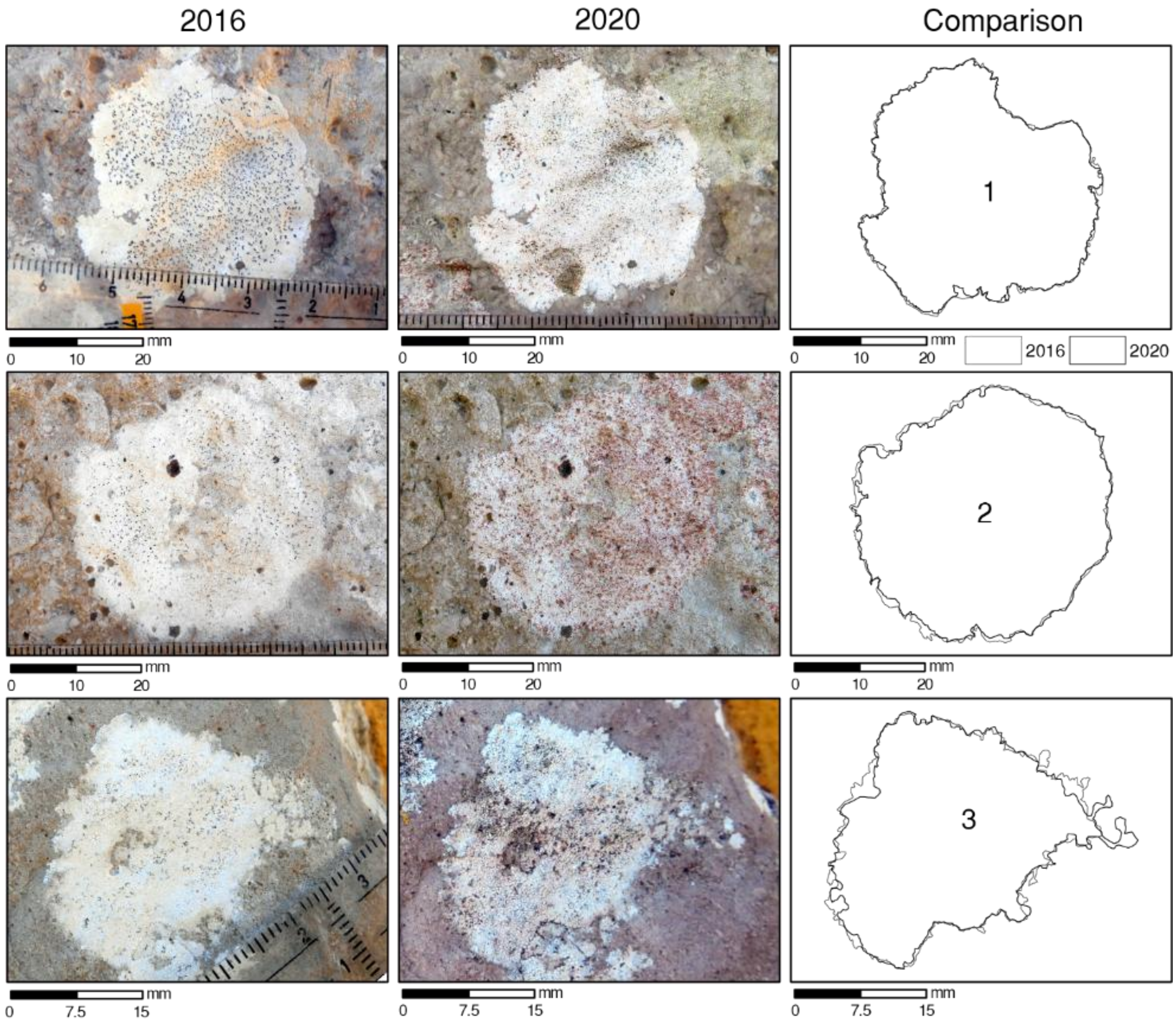

Figure S30: Photographs of lichens used for direct measurement of growth in 2016 and 2020 in AF05 Baluarte Redondo control point and comparison between the outline of lichen thalli.

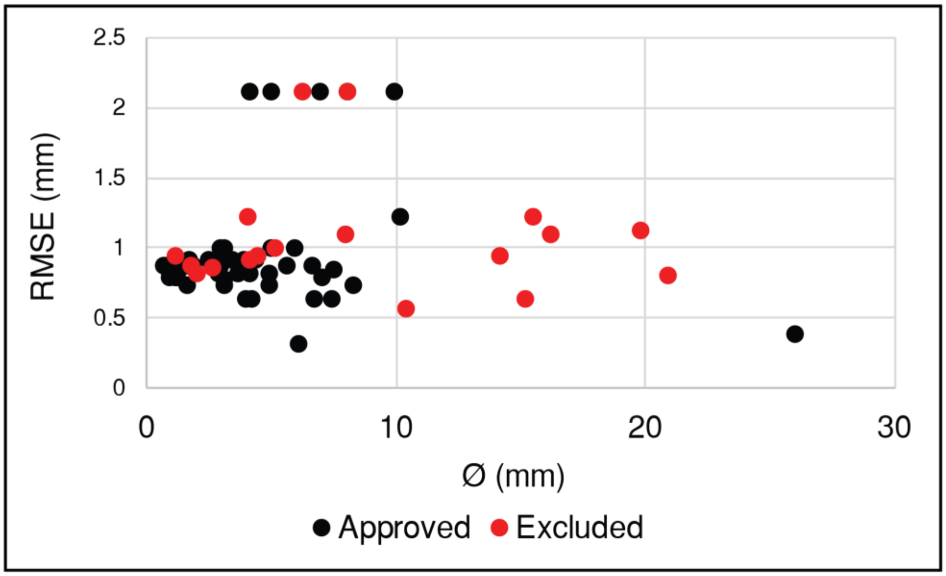

Figure S31: Scatter plot of the georeferencing RMSE against the largest inscribed circle of the thalli. Data excluded due to RMSE > changes in Ø are represented in red, and the remaining dataset is represented in black.

Age estimation of boulder stabilization

Table S4: Boulder mass, lichen age parameters, and estimated ages obtained with the Ø and *A* growth models. BCE-Before Common Era; CE-Common Era. Shaded cells overlap the 1755 tsunami. * boulders with two overlapping lichen populations.

Boulder ID	Mass (t)	Ø (mm)	*A* (mm^2)	Sampling year	Ø-based model		*A*-based model	
					Estimated age	Prediction interval	Estimated age	Prediction interval
B1614	2.24	48.2	1825	2015	25BCE	3165BCE-1211CE	1348CE	1201-1494CE
B1540	1.91	46.4	1691	2015	406E	2017BCE-1373CE	1398CE	1257-1538CE
B1536	5.26	39.2	1207	2015	1394CE	521-1756CE	1580CE	1456-1704CE
B1543	0.64	36.4	1041	2016	1587CE	996-1835CE	1644CE	1523-1765CE
B1556	20.56	31.6	784	2015	1787CE	1481-1918CE	1739CE	1621-1857CE
B1542	10.47	27.0	573	2015	1891CE	1726-1961CE	1819CE	1701-1936CE
B1306	0.50	25.6	515	2016	1913CE	1776-1971CE	1842CE	1724-1959CE
B1544	13.89	25.0	491	2015	1919CE	1793-1974CE	1850CE	1732-1967CE
B1473	0.66	23.4	430	2012	1935CE	1832-1979CE	1869CE	1751-1988 CE

Boulder ID	Mass (t)	Ø (mm)	*A* (mm^2)	Sampling year	Ø-based model		*A*-based model	
					Estimated age	Prediction interval	Estimated age	Prediction interval
B1492	0.26	20.6	333	2012	1958CE	1887-1989CE	1906CE	1786-2025CE
B1362	0.09	19.2	290	2012	1967CE	1908-1993CE	1922CE	1802-2043CE
B1517	0.24	18.2	260	2012	1973CE	1920-1995CE	1933CE	1813-2054CE
B1333*	0.10	18.6	272	2016	1975CE	1920-1998CE	1933CE	1813-2054CE
B1532	0.28	18.2	260	2016	1977CE	1924-1999CE	1937CE	1817-2058CE
B1509*	4.85	17.2	232	2012	1978CE	1931-1997CE	1944CE	1823-2065CE
B1496	0.26	17.0	227	2012	1978CE	1933-1998CE	1946CE	1825–2067CE
B1493	3.52	16.8	222	2012	1979CE	1935-1998CE	1948CE	1826–2069CE
B1367	1.79	16.2	206	2012	1982CE	1941-1999CE	1954CE	1832–2075CE
B1504*	1.03	16.2	206	2012	1982CE	1941-1999CE	1954CE	1832-2075CE
B1140	1.74	14.8	172	2012	1987CE	1953-2001CE	1967CE	1844–2089CE
B1481	5.88	13.0	133	2012	1992CE	1965-2003CE	1981CE	1858–2105CE
B1143	0.43	12.6	125	2012	1993CE	1967-2004CE	1984CE	1861-2108CE
B1280	1.06	13.0	133	2016	1996CE	1969-2007CE	1985CE	1862-2109CE
B1512	0.71	12.4	121	2012	1994CE	1968-2004CE	1986CE	1862-2109CE
B1451	2.80	12.2	117	2012	1994CE	1969-2004CE	1987CE	1864-2111CE
B1406	0.56	8.8	61	2012	2000CE	1984-2007CE	2008CE	1883-2133CE
B1452	2.00	8.8	61	2012	2000CE	1984-2007CE	2008CE	1883-2133CE
B1502	3.17	7.6	45	2012	2002CE	1988-2008CE	2014CE	1889-2140CE
B1515	0.15	6.2	30	2012	2004CE	1992-2008CE	2020CE	1894-2146CE
B1144	1.15	5.8	26	2012	2004CE	1993-2008CE	2021CE	1895-2147CE
B1533	5.01	6.6	34	2015	2006CE	1994-2011CE	2021CE	1896-2147CE
B1264	0.90	3.6	10	2012	2006CE	1997-2009CE	2028CE	1901-2154CE

Geometric relationship between Ø and *A*

The relationship between the radius and the area of a circle is quadratic and represented by the following equation:

$$A = \pi r^2$$

For a given increase in circle size, the increment in radius (and diameter) is smaller than the area increase. In Figure S32, the increase in radius (or diameter) between t_1 and t_2 (represented by the grey portion of the circle) and between t_2 and t_3 (represented by the hatched portion of the circle) is the same (diameter increase of 10mm). However, the increase in area is 30% higher for the larger circle (of 54978mm^2 from t_1 to t_2 and of 70686mm^2 from t_2 and t_3).

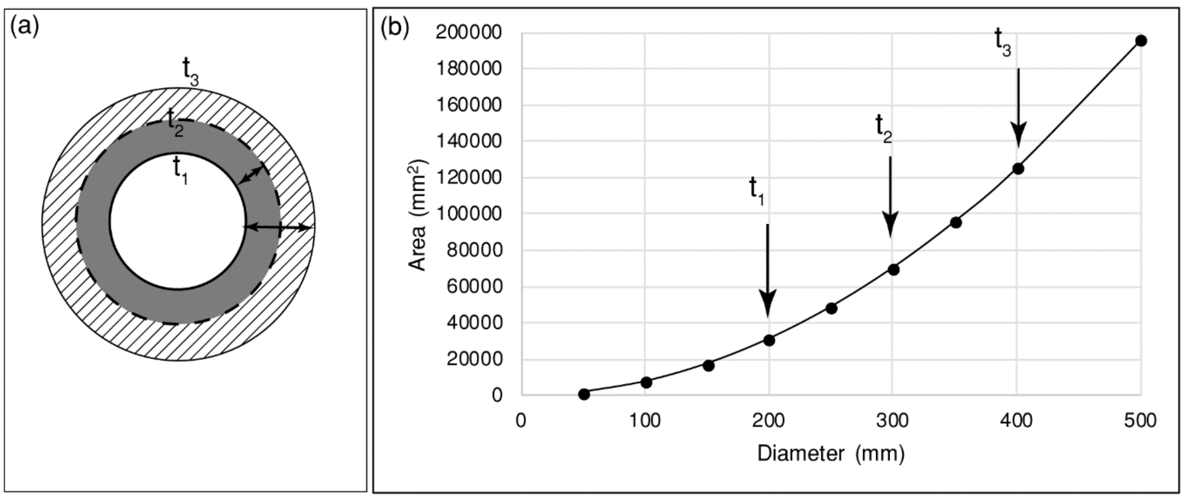

Figure S32: Representation of the relationship between the area and diameter of a circle. (a) 10mm diameter increase between t1 and t2 and t2 and t3. (b) The increase in area is progressively higher with diameter increase.

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