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Mapping coastal erosion of a Mediterranean cliff with a boat-borne laser scanner: performance, processing and cliff erosion rate

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Abbreviations

Boatmap system® (BMS)

Digital Elevation Model of difference (DoD)

Digital Surface Model of erosion (DSMe)

Drivemap system® (DMS)

Geographic Information System (GIS)

Global Navigation Satellite System (GNSS)

Ground Sampling Distance (GSD)

Inertial Measurement Unit (IMU)

Iterative Closet Point (ICP)

Terrestrial Laser Scanning (TLS)

1 **Abstract:**

2 Terrestrial laser scanners (TLS) are well known for providing an efficient means to
3 monitor coastal cliff erosion. Cliffs along micro-tidal coasts, however, have often escaped
4 quantification because the narrow or absent coastal platforms do not offer stable and embracing
5 vantage points. To circumvent this issue, mobile laser scanning surveys from a boat can be
6 used. We present a case study from Provence-Alpes-Côte-d'Azur (Mediterranean coast -
7 southern France) to quantify cliff erosion in such micro-tidal environments. Three surveys were
8 sub-contracted over a period of 17 months to monitor a 3.5-km-long cliff of Carry-le-Rouet
9 (15km west of Marseille). Data quality was check independently using man-made planar walls
10 positioned above the cliff face, to retrieve survey precision and change detection thresholds.
11 Boat-borne mobile lidar system was capable of describing planar features with a precision of
12 3-4 cm (epoch 1 and 2) and improved to 2.6 cm (epoch 3) with point densities around 100
13 pts/m². Absolute positioning accuracy varied between 0.1 cm and 0.3 cm. Because the coastline
14 is very sinuous, we describe a method to unfold the point clouds using a continuous analytical
15 surface made of vertical planes joined by arcs of cylinders and perform the analysis in 2.5D.
16 Change was detected using a unique, conservative, threshold of 14 cm (99% quantile estimated
17 on plane change) on grids of 10 x 10 cm pixels. Integrated over the entire cliff face, the average
18 annual cliff recession rate at Carry-le-Rouet is 1.1cm/year. In 17 months, erosion was three
19 times more effective in sandstone and marls layers than in calcarenites and conglomerates.
20 Erosion varies vertically with erosion three times more effective in the lower 25 m of the cliffs
21 than above. Despite imperfections, boat-borne laser scanning system are capable of delivering
22 meaningful erosion data even in this low erosion context.

23 **Keywords:** Lidar; boat-borne laser scanning; point cloud processing; sea-cliff erosion; Mediterranean
24 coast

25

26

27

28 **1. INTRODUCTION.**

29 In recent years, a wide range of portable laser scanners has been developed and
30 significant operational improvements make them a choice equipment for field measurements

31 (Lichti et al., 2000a; Lichti et al., 2000b; Ingensand et al., 2003; Girardeau-Montaut 2005;
32 Heritage and Hetherington, 2007). Among the main geomorphological applications, the study
33 of gravitational processes such as rock falls or landslides (Kemeny and Post, 2003; Bitelli et
34 al., 2004; Teza et al., 2007; Dunning et al., 2009; Dewez et al., 2007; Abellán et al., 2010;
35 Dewez et al., 2013), and evaluation of associated geological hazards (Hunter et al., 2003;
36 Abellán et al., 2006; Jaboyedoff et al., 2009; Furlani et al., 2014) have strongly benefited from
37 these methodological developments. In particular case of inaccessible cliff face, the possibility
38 to monitor spatio-temporal changes of complex surfaces is important for the study of erosion,
39 in order to map the location, dimension and epoch of occurrence of collapse events (Lim et al.,
40 2005 ; Rosser et al., 2005 ; Young and Ashford, 2006 , 2007 ; Dewez et al., 2007 ; Collins and
41 Sitar., 2008 ; Olsen et al., 2009 ; Young et al , 2009 ; Lim et al., 2010 ; Young et al., 2010 ;
42 Dewez et al., 2013; Rohmer and Dewez, 2013; Kuhn and Prüfer, 2014). One of the applications
43 is to interpret the collapse magnitude in terms of erosion activity to appreciate the stage of cliff
44 evolution. For example an increase of rock falls erosion can “pre-date” the occurrence of larger
45 events (Rosser et al., 2007), whereas a decreasing activity may correspond to a temporal
46 “stabilization” (Perdrizzini et al., 2010).

47 Terrestrial laser scanners (TLS) are particularly suited for the survey of steep cliffs with
48 high resolution and the possibility to deal with complex geometries (Ingensand 2006; Young et
49 al, 2010). Moreover this technique is best adapted to vertical terrain configurations compared
50 to airborne laser scanners. Indeed for aerial technique, high incidence angles between vertical
51 cliff faces and laser beam are responsible for inaccuracy and the lack of vertical measures
52 (Baltsavias, 1999; Young et al., 2010; Earlie et al., 2014). For that reason coastal cliff studies
53 are generally performed with terrestrial laser scanners looking at the cliff face from the
54 beach/platform at the foot of the cliff. This setup requires, however, installing a tripod in front
55 of the cliff, which is not always feasible and especially not along micro-tidal coastline where a
56 dry coastal platform is either narrow or inexistent. We can note also that TLS is not always
57 economical over several kilometer-long sections, because of the effort to assemble all stations
58 together in a rigid reference frame (Michoud et al., 2014).

59 For these reasons, mobile laser scanning is an attractive technology that allows to scan
60 long-section with high precision (Ellum and El-Sheimy, 2002; Barber et., al, 2008; Jaakkola et
61 al., 2008; Kukko et al., 2012; Glennie et al., 2013). These systems have been adapted on boat
62 configurations in order to detect topographic changes in fluvial environments (Alho et al., 2009;
63 Vaaja et al., 2011, 2013) and more recently in coastal environments (Michoud et al., 2014).

64 This latter application, over 30-km-long coastal cliffs in northern Europe (Normandy, France),
65 has demonstrated its capability to map geomorphological features smaller than 0.5 m² (70 x
66 70cm) and to detect rock fall volume larger than 1 m³ between two acquisitions (in 2012 and
67 2013).

68 Here we discuss the example of a 3.5-km-long section of cliff in Provence, along the
69 French Mediterranean coast, near the town of Carry-le-Rouet (15km west of Marseille, [*Figure*
70 *1*]). Along this part of the coastline, potential scanning stations are scarce given the micro-tidal
71 regime. Using different mobile mapping systems for time series measurements will become
72 increasingly frequent in the future given the cost, specificity of the equipment, commercial
73 market regulations and rapid technological improvements of mobile mapping equipments. So
74 despite it not being ideal for research purposes, we describe how these different survey data
75 sets were treated and how to assess system performance. Our work is targeted at end-user
76 engineers who are not survey specialists and nevertheless need to independently check the data
77 they paid for.

78 Repeated surveys were thus performed with a similar mobile boat-borne laser scanner
79 system. In this study we address both generic issues related to the survey technique and allude
80 to site specific information concerning the geomorphic processes at work. First, the positional
81 performance of the different measurement systems and their ability to be combined to produce
82 temporal sequences of point clouds are described: (i) single survey point survey precision; (ii)
83 repeatability of the measures between successive surveys; and (iii) inter-point spacing (i.e.
84 inverse of point density) at each survey epoch. The method employed is particularly adapted in
85 the absence of external model (e.g without terrestrial laser reference). Second, given the sinuous
86 plan-form morphology of the cliff 3D point clouds cannot be readily compared and brought in
87 2.5D Geographic Information System (GIS) analysis environments for further contextual
88 analyses. We describe a transformation method based on continuous analytical surfaces made
89 of vertical planes and arcs of cylinder to unfold the coastline. The resulting surface is then
90 compatible with cliff face oriented ortho-photography and 2D geological sections drawn in GIS
91 software. Third, this processing workflow is applied to the case study of Carry-le-Rouet where
92 three boat-borne surveys have captured cliff erosion between February 2011 and July 2012.
93 Finally we discuss the boat-borne laser capacity and some first-order geomorphological
94 findings.

95

96 2. TEST SITE AND STUDY SETTING.

97 The case study is a section of the Côte-Bleue in Provence region (France), along an
98 East-West 3.5-km-long sea cliff near Carry-le-Rouet town (43°19N, 5°09E). This part of the
99 coast is sinuous and composed of a succession of 5 headlands (*[Figure 1-a)*. Cliff height is
100 comprised between 2 and 56m (relative to the NGF69 terrestrial datum, 1m DEM - Litto3D®V1
101 IGN-SHOM). The cliff exposes various lithological formations from the Upper Oligocene to
102 Lower Miocene that includes marine marly-sandy-calcareous successions with bed thickness
103 ranging from 0.3 m to 5 m and occasional occurrences of lenticular conglomerates ([Demory et](#)
104 [al., 2011](#)). The series is made of sub-horizontal to gently South-East dipping beds (2° to 10°) (*[*
105 *Figure 1-b)*. The cliff profiles present both vertical and inclined faces with well-developed
106 abrasion notches at the foot.

107 The period of the strongest waves (windstorm from SW and SE) is concentrated in
108 winter, with waves breaking on the coast between 0.5 and more than 2m of height (e.i. [Millet,](#)
109 [1990](#); [Ciavola et al., 2007](#); [Sabatier et al., 2019](#)). Rainfall is mainly concentrated in autumn in
110 the form of torrential rain ([Lionnello et al., 2006](#)). These rains can correspond to more than
111 200 mm of water falling only in 24h (Marseille-Marignane weather station, series of 1923-
112 2018).

113 The rocky shore dynamics along the French Mediterranean cliffs has not been much
114 studied and the respective contributions of marine versus continental contributions in
115 Mediterranean area are not constrained ([Furlani et al., 2014](#)). Furthermore, this part of the
116 French coast is not prone to spectacular and/or frequent cliff collapse events, such as those of
117 chalk cliffs of northern Europe (e.g. [Duperret et al., 2002](#); [Costa et al. 2004](#); [Regard et al. 2012](#);
118 [Dewez et al., 2013](#)). But risk-wise, the vicinity of the cliff is subjected to an increasing
119 residential, touristic and economic pressures. On the 6th February 2008, a rock fall of about
120 500 m³ occurred in the central part of our study area (yellow star in *[Figure 1-a)*, precisely in
121 the garden of a villa, leaving less than 2 m between the cliff edge and a swimming pool.

122 As a consequence, cliff collapse risks have become a major concern for the local
123 populations and authority and cliff collapse hazard quantification was desired in order to
124 characterize the erosion setting. We also need to evaluate if this rock fall corresponds to a rare,
125 isolated, or frequent event. We thus set out to apply the probabilistic analysis framework
126 proposed by [Dewez et al \(2013\)](#) to start assessing cliff collapse hazard.

127 [*Figure 1 about here*]

128

129 **3. DATA SETS.**

130 The temporal cliff evolution study in Carry-le-Rouet started with a first survey on 28
131 February 2011 (epoch 1), with an experimental mobile boat-borne LiDAR mapping system
132 developed by the now-defunct surveying company ATM3D. The following two other surveys,
133 30 November/1 December 2011 (epoch 2) and 7 July 2012 (epoch 3), were acquired by
134 FUGRO-GEOIDE using two different setups: the Boatmap® system (BMS); and the
135 Drivemap® system (DMS), respectively.

136 ***3.1. Description of mobile mapping system.***

137 While each of the three LiDAR mobile mapping systems implemented different
138 hardware specifications (Table 2), the instrumental concept is similar. A rigid frame on the boat
139 contains (*Figure 1-a*) a laser scanner, a pair of GNSS antennae and an Inertial Measurement
140 Unit (IMU). The accuracy of the mobile boat positioning system determines the overall
141 performance of the survey.

142

143 ***3.2. Point clouds and registration.***

144 All three point clouds were processed by FUGRO-GEOIDE survey company in
145 Montpellier (France) and delivered as X, Y, Z coordinates expressed in the national Lambert93
146 reference frame, along with raw LiDAR point intensity value. No other additional data was
147 made available. In total, the complete dataset of all three scans contains 73.2 million points
148 (Table 2). The contractor performed a multi-pass point cloud registration process using both
149 physical targets and point cloud matching with ICP algorithm (e.g. [Besl and McKay, 1992](#)).
150 Although locally variable, the quality of multi-pass registration could not be assessed because
151 the point pass identifier (whether west-to-east or east-to-west pass) was not specified in the
152 delivered file, and only a single merged point cloud was delivered to us.

153 ***3.3. Ortho-photography.***

154 A series of cliff face photographs were taken in December 2012 and shot with an
155 industrial shutter-free full frame Imperx *16 Mpix* camera fitted with a 50mm lens (Table 2).
156 These photographs were then ortho-rectified by the contractor as a 2-cm-per-pixel continuous

157 ortho-photography. These orthophotos were used for segmenting the point clouds (e.g. on-/off-
158 cliff points and cliff-growing shrubs) and producing litho-stratigraphic sections of cliff rocks (*[*
159 *Figure 1-b)*.

[Table 1 about here]

160

161 **4. POINT CLOUD: QUALITY ASSESSMENT.**

162 Point clouds delivered by subcontractors, or received from an unknown source, often
163 lack a clear description of the data quality. Here we describe an *ad hoc* procedure to retrieve
164 point cloud precision, repeatability, and effective point density empirically. The procedure
165 relies of the fortunate presence of well-distributed man-made walls close to cliff top, which
166 means at a similar distance and incidence to the lidar position as the cliff. Modeled as best-fit
167 planes, these walls serve to empirically derive point precision, accuracy and point density on
168 surface close enough to the cliff, so that statistics from modelling these planes can be
169 extrapolated to the cliff with a reasonable degree of confidence.

170 4.1. Validation metrics and procedure

171 Five walls visible in all three scans. Walls are 4m to 16m in length and 2m to 4m in
172 height. Point cloud precision of a survey corresponds to the amalgamated residuals to the best
173 fit planes (e.g. [Monserrat and Croseto, 2008](#)) (*[Figure 2-a)*). Repeatability, or accuracy, assesses
174 whether the successive surveys campaigns located the walls in the same absolute location. It is
175 assessed as the most-likely distance between the best-fit planes of epoch n with that of epoch
176 $n+1$ (e.g. [Besl and McKay, 1992](#); [Michoud et al., 2014](#)) (*[Figure 2-b)*). Because several authors
177 describe errors as not normally distributed (e.g. [Höhle & Höhle, 2009](#), [Caudal et al., 2017](#))
178 classical error propagation cannot be worked out as the sum of residual variances. The threshold
179 value above which cloud-to-cloud differences are not simply due to chance has been worked
180 out in a different fashion. Because the selected walls have remained unchanged between epochs,
181 any cloud to cloud difference observed is noise coming from imprecise measurements. We pick
182 a threshold distance as the empirical quantile at 99.9% ([Dewez et al., 2013](#)). Above this value
183 cloud-to-cloud distance has as little as 1 chance in 1000 to be noise.

184 The sum of the squared point precisions and repeatability error gives the shortest
185 distance of the erosion detection, that we call the threshold distance (*[Figure 2-c)*). Finally inter-
186 point spacing (or point density) was also computed to optimize grid pixel sizes required in a

187 later step and check the delivery for compliance with the survey specifications (e.g.
188 [Soudarissanane et al., 2011](#); [Argüelles-Fraga et al., 2013](#)).

189 To model the planar shape of the walls from XYZ Lambert93 coordinates, a Principal
190 Component Analysis (PCA) was performed. This geometrical transform is preferred to linear
191 regression solution because all X, Y and Z values are known with some degree of error. In this
192 case, the principal component analysis retrieves three components, by decreasing order of
193 variability. The first and second components are wall-coplanar coordinates; the third component
194 is orthogonal to this best-fit plane and describes the dispersion on either sides of the plane (*/*
195 *Figure 2*). We should note that wall point cloud samples were segmented well away from the
196 wall edges to avoid contamination by outliers. Unwanted residual distribution deviations could
197 exist if the walls were not true planes. The walls were indeed true planes as residuals plotted
198 versus wall-parallel coordinates did not display coherent high order polynomials trends.

199

200 ***4.1. Point precision for single survey (Pp).***

201 Point to plane distance distribution is often not normally distributed ([Höhle & Höhle,](#)
202 [2009](#)). This means that using Gaussian based metrics will not reflect the actual empirical error
203 distribution. To counteract this issue, Höhle & Hohle ([2009](#)) used robust quantile-based
204 descriptors, which match empirical distributions. This means describing the central value of a
205 distribution with the median, as opposed to the mean, and describing the dispersion with
206 quantiles of the absolute distance to the median, as opposed to the standard deviation.

207 Here we use the 99.9% quantile of the absolute deviation to the median as point
208 precision descriptor (*Figure 2a*, *Figure 3*). This quality threshold corresponds to a much smaller
209 proportion of points than the usual 5% of a 2-sigma threshold (*/ Figure 2*, *Table 3-1*) but
210 minimizes the proportion of meaningless differences given the sample size of the millions of
211 points.

212 ***4.2. Repeatability (R).***

213 Repeatability describes whether successive surveys position walls in the same location.
214 It was determined by measuring the distance between the point cloud of epoch 2 with modelled
215 planes of epoch 1. The median of this distribution delivers the value of repeatability (*Table 3-*
216 *2*).

217 [*Figure 2 about here*]

218

219 [*Figure 3 about here*]

220 **4.3. Threshold distance to detect erosion (T_d).**

221 The remaining cliff pixels exhibit a range of distances that needs thresholding to map
222 eroded blocks. Short distances indicate that the cliff has not changed much while larger values
223 depict erosion more confidently. Picking the appropriate threshold is again a matter of robust
224 statistics. The detection threshold between two point clouds depends on their accuracy, and is
225 obtained by the sum of absolute point precisions and absolute repeatability distances ([*Figure*
226 *2-c*, and *Table 3-2*).

227

228 **4.4. Inter-point spacing estimation.**

229 In a later pre-processing stage, the three point clouds are projected into 2.5D grids to
230 enable interactions with ortho-photography and further explore erosion dynamics. The choice
231 of an optimal grid pixel size is a recurrent issue in GIS. Here, we solve it by computing the
232 nearest-neighbour Euclidean distance statistics in wall-coplanar coordinates ([*Figure 4*). This
233 solution is designed for users with little computing power. An alternative would be to compute
234 the volume density in a large enough neighbourhood (e.g. 0.5 m). This option would have the
235 advantage of accounting for possible point density biases linked with lidar line of sight
236 obliquity. Our option nevertheless is equally valid since cliff face and sampling walls have
237 similar orientations. Any line of sight bias on the wall would affect point density on the cliff in
238 the same manner. Because the inter-point spacing is obviously variable in space, a minimum
239 representative inter-points spacing can be obtained by the median values (as [Michoud et al.,](#)
240 [2014](#)) which minimize influences of outliers ([Höhle and Höhle, 2009](#)).

241 [*Table 2 about here*]

242

243 [*Figure 4 about here*]

244 **5. LiDAR DATA PROCESSING.**

245 The scientific problems we wish to solve concern the total mass balance and discrete
246 block erosion over the entire cliff face. In order to do so, local, point-wise erosion can be
247 assessed with 3D cloud-to-cloud distances (e.g. [Lague et al. 2013](#)) but mass balance or scar
248 inventories still requires computing an integrated estimate of erosion, either through meshing
249 or gridding. And further, we would like to explain erosion with various methods readily
250 implemented in 2.5D GIS and currently lacking in full-3D software. The data processing
251 workflow therefore consists in a succession of 4 steps: (i) project 3D point clouds into an
252 analytical 2.5D surface (unfolding); (ii) calculate inter-epoch distances (point clouds
253 comparison); (iii) classify and check for point visibility to assess erosion and (iv) threshold
254 cloud-to-cloud distances to retrieve only meaningful erosion (*[Figure 5]*).

255 *[Figure 5 about here]*

256 **5.1. 3D to 2.5D projection method.**

257 The first step consists in projecting 3D points into an unfolded 2.5D cliff surface. Most
258 terrestrial laser scanning studies in rocky coast environments are performed along straight or
259 semi straight cliffs segments ([Lim et al., 2005](#); [Dewez et al., 2007](#) ; [Collins and Sitar, 2008](#) ;
260 [Abellán et al., 2010](#) ; [Lim et al., 2010](#) ; [Young et al., 2010](#) ; [Stock et al., 2011](#) ; [Dewez et al.,](#)
261 [2013](#) ; [Kuhn and Prüfer, 2014](#); [Michoud et al., 2014](#)) and all of them admit, sometimes
262 implicitly, that when the cliffs become truly 3D, processing is much more difficult.
263

264 Full 3D comparisons, like the M3C2 method of [Lague et al. 2013](#), requires computing
265 local plane normals over a given neighbourhood, but plane normals may misbehave at places
266 with sharp gradients. And the characteristic dimensions of cliff smoothness is spatially variable
267 (see [Feldmann et al., 2018](#)). On the other hand, it is well known that planar cliff configurations
268 close to 2D or 2.5 D allow the determination of eroded volume through DoD (Digital Elevation
269 Model of difference, [Rosser et al., 2005](#); [Abellán et al., 2010](#); [O’Neal and Pizzuto, 2011](#)). But
270 in 3D complex configurations, DoD will poorly depict strongly oblique surfaces. The coast of
271 Carry-le-Rouet is very sinuous, with a succession of headlands and bays and needs be simplified
272 (*[Figure 1-a]*).

273 To simplify the visualization and processing of 3D configuration in 2.5D, we detail a
 274 method to unfold point clouds ([*Figure 6*]). The numerical method consists in rotated XY
 275 coordinates onto a vertical surface made either of contiguous planes sections or arcs of
 276 cylinders. Elevation coordinates, Z , remain unchanged. One of two types of transformations are
 277 applied: (i) an angular rotation for planar sections ([*Figure 6-c1*]); (ii) and an angular distance
 278 calculation for cylindrical sections ([*Figure 6-c2*]).

279 - For each rectilinear section, unfolded coordinates (X_U , Y_U) of sub-cloud are obtained
 280 by applying a rotation of $-\alpha$ to the initial points (X , Y), which corresponds to the angle
 281 between the rectilinear section and the re-projected straight line ([*Figure 6-c1*]).

282 - For each circular section defined by a circle O , unfolded coordinates X_U and Y_U of sub-
 283 cloud are obtained separately ([*Figure 7*):

284 - X_U coordinate corresponds to the angular distance of the points from the
 285 initial arc section ([*Figure 7-a*):

$$286 \quad X_u = (R \times Y) \times US [2\pi] \quad (1)$$

287 with R the radius of the circle O , Y the angle between starting section and point to
 288 project, then US the unfolding sense (by convention $US = 1$ for inland section at sea, and $US =$
 289 -1 for bay section).

290 - Y_U coordinate corresponds to the distance of the points from the curviline,
 291 positive or negative ([*Figure 7-b*):

$$292 \quad Y_u = (L - R) \times US \quad (2)$$

293 with L the distance between the point to unfold (X , Y) and the center of the circle O .

294 The same transformation scheme was applied to orthorectify photographs shot in
 295 November 2011. For complementary information see the appendix A.

296

297 [*Figure 6 about here*]

298 [*Figure 7 about here*]

299 **5.2. Point clouds comparison method.**

300 After projecting all point clouds into the 2.5D space, the second step is to quantify
 301 changes in range due to cliff erosion. Many authors have argued that cloud-to-cloud distance

302 comparison was possible and desirable ([Girardeau-Montault et al., 2005](#); [Lague et al., 2013](#)).
303 Indeed, gridding or meshing prior to computing a difference is amenable to loss of information
304 or ghost volume creation. Hence, we computed a cloud-to-cloud distance between projected
305 point clouds with *Cloud Compare* software before gridding the result.

306 ***5.3. Points-cloud segmentation and visibility solution.***

307 Among all the points measured during the survey, many correspond to irrelevant
308 features: vegetation, houses and man-made features, tourists standing in front of the cliff... The
309 third processing step consists in segmenting the point clouds into object classes.

310 ***5.3.1. Classification method.***

311 Based on the American Society for Photogrammetry & Remote Sensing LAS 1.4 labelling
312 standard, a semi-manual classification of different features was performed (

313 [*Figure 8* and [*Figure 9*). We distinguish the cliff (class identifier 2), all types of
314 vegetation (tree, shrub and grass) which are combined into a single unit (class 3), and two newly
315 created classes: external part of the scene (class 64) and cliff foreground (class 65). This latter
316 class will be further processed in a second stage because it is associated with occlusion
317 problems. This classification was performed manually using orthophotos in a GIS. Mapping
318 produced continuous polygons from which the value of the class was transferred to the point
319 clouds.

320 ***5.3.2. Visibility solving method (shadow effects).***

321 Finally, because laser scanners acquire 3D data with a line-of-sight strategy, full-3D
322 objects are likely to contain unseen faces during acquisition. To limit the extent of these
323 shadows, the survey was performed in at least two passes. Shadows are detrimental for our
324 purpose as cloud-to-cloud comparisons can only compute distances between existing points,
325 and hence may locally present large values along the edges of hidden areas, unduly joining
326 background with foreground points. The classical filtering approach for this problem employs
327 the calculation of the depth-maps (or visibility-maps) from a known scanner viewpoint (for
328 more information see [Murakami et al., 1999](#); [Vögtle and Steinle., 2004](#); [Vosselman et al., 2004](#);
329 [Girardeau-Montaut et al., 2005](#)). In our case, however, mobile scanner is constantly on the move
330 and tagging a specific position with its corresponding viewpoint is very difficult. Additionally,

331 the subcontractors did not provide the space/time scanner trajectory. We therefore had to
332 develop a different approach to solve this visibility problem.

333

334 *[Figure 8 about here]*

335

336 *[Figure 9 about here]*

337 Shadows in the cliff plane were computed from a raster mask of point presence (*[Figure*
338 *10-a)*). Mask values of each epoch were labeled as a power of 2. So the sum of visibility masks
339 produces a unique identifying code which determines simultaneously when and how many
340 times points were visible (*[Figure 10-b)*). This visibility mask is then combined with the masks
341 of classified objects (cliff, vegetation and foreground) to retain only the topographic changes
342 of cliff portions. Processing quality depends on the choice of pixel size, and this choice is
343 constrained by the representative inter-point spacing discussed above (*cf. 3.4)*.

344

345 ***5.4. Threshold volume and erosion estimation.***

346 Finally, the remaining cliff pixels exhibit a range of distances that needs thresholding to
347 map eroded blocks. The minimum volume of erosion detected is thus the result of the
348 combination between the threshold distance and the surface area of one pixel size (*cf. 3.3* and
349 *3.4*, respectively).

350 In order to quantify the erosion volume and study rockfall scars properties, we need to
351 estimate the eroded surface area. As such, surface area and volume of estimation eroded
352 material is not possible with cloud-to-cloud comparisons. Some degree of integration is
353 necessary. Cloud to cloud distances of unfolded point clouds are gridded into a 2.5D, 10cm x
354 10cm, Digital Surface Model of erosion (DSMe, *[Figure 11)*). At this stage of the process,
355 DSMe is acceptable because unfolded points clouds are almost planar ([Dewez et al., 2013](#)).
356 This threshold is applied to quantify the total eroded volume.

357

358

359 *[Figure 10 about here]*

360

361 **6. RESULTS.**362 **6.1. Quality assessment.**

363 The point precision is determined as the distribution of the absolute distance between best-fit
364 wall points and their median (*[Figure 2-a &*

365 *[Figure 3)*. Distributions of absolute distances to the median are uni-modal and centered around
366 0.1cm for epochs 1 and 3. Measurements do not seem biased. At epoch 2, however, the
367 distribution is bimodal with the first mode centered around 1.1 cm, indicating an internal multi-
368 pass registration issue (

369 *[Figure 3)*. Statistical results of the precision are presented in Table 3.1. Classical point
370 measurement precisions as the 95% quantile (2-sigma) are 2.6 cm (epoch 3) and between 3 and
371 4cm (epoch 1 and epoch 2), whereas the 99.9% quantile are 4.3 cm (epoch 3) and 8.8 cm (epoch
372 1 and epoch 2).

373 Looking at the absolute difference to the median between each distributions of distance
374 to wall plan (*[Figure 2-b & Table 3-2)*, the repeatability error of the three epochs comes to
375 1 mm (between epochs 2 and 3) and presents a shift of 3 mm (between epochs 1 and 2 and
376 epochs 1 and 3).

377 The inter-point spacing is obviously variable in space. Its distributions turn out to be
378 uni-modal and asymmetric for all three scans (*[Figure 4)*. They all present similar features, but
379 the distribution mode of epoch 3 corresponds to a denser point spacing. The most frequent inter-
380 point spacing is centered around 16 cm (88% quantile), 8 cm (44% quantile) and 4 cm (38%
381 quantile) for the epoch 1, 2 and 3, respectively. The 1-sigma values (68.3% quantile) are 12,
382 11.5 and 7.1 cm which corresponds to a density of 69, 76, 178 pts/m² (epoch 1, 2 and 3). A
383 minimum representative inter-points spacing is obtained by the median values. In this case
384 inter-points spacing is 10, 9 and 5 cm corresponding to a density of 100, 123, and 400 pts/m²
385 (epoch 1, 2 and 3, respectively). For gridding, we choose an intermediate pixel size of 10 cm
386 and adopted a nearest neighbour interpolation method to fill pixels. Pixels without points
387 remained unfilled.

388 Detection thresholds as the 99.9% cloud-to-cloud distance quantile from reference walls
389 range between 13.1 cm and 18.6 cm (Table 3-2). To apply a consistent detection through time,
390 we thus pick a compromise value of 14 cm as the minimum distance to consider that erosion
391 really occurred between epoch 1 and 3.

392

393 Given point cloud characteristics and processing described, the minimum volume
394 potentially detectable is 0.0014 m³ (i.e. 1.4 liters). No smaller volumes can be detected. This is
395 not to say that erosion scars as small make sense from a geomorphological point of view. In
396 fact, the scar inventory completeness was tested with Stepp's (1972, cited and used by Dewez
397 et al., 2013) method. The probability distribution function of scar volume scales as a regular
398 powerlaw between 0.006 m³ and 0.5 m³. Volumes smaller than 0.006 m³ are not completely
399 counted because of measurements and processing limitations. For larger volumes, erosion did
400 not occur in the 17 months time frame (precisely 492 days) between the first and last survey.

401 **6.2. Erosion estimation between epoch 1 and 3.**

402 Erosion scars show up as scattered patches of erosion values (*[Figure 11]*). The
403 minimum volume of erosion detected is 1.4 liters (i.e. one pixel of 100 cm² with an erosion
404 detection threshold of 14cm). The total surface of cliff exposed is 30,141 m² where erosion
405 affected 1,107 m² (only 3.67% of the exposed cliff). To further compute erosion scars
406 properties, the grids were turned into polygon layers with a GIS software. 14,925 distinct scars
407 make up for a total volume of 323.30 m³ . In space, erosion is scattered over the cliff face (*[*
408 *Figure 11]*). The largest collapses occurred at “Cap de la Vierge” (cape H₅ with a total of 150 m³)
409 and involved the basal sandy marl units (*[Figure 11-a]*). Relative to the inventory, a
410 “substantial” collapse (4 m³) also occurred just below the repairs of the largest-known erosion
411 scar at the area near H₄ on the “Barqueroute” cliff. Apart from these large events, smaller ones
412 are scattered over the cliff face.

413

414 *[Figure 11 about here]*

415

416 **7. DISCUSSION.**

417 Although mobile laser scanning systems have been used in various other contexts (Alho
418 et al., 2009; Ellum and El-Sheimy, 2002; Barber et al., 2008; Jaakkola et al., 2008; Kukko et
419 al., 2012; Glennie et al., 2013; Vaaja et al., 2011, 2013), there are very few published studies
420 which used boat-borne mobile laser acquisition to detect coastal cliff erosion along semi-
421 straight cliffs segments (Michoud et al., 2014). Our work completes Michoud et al's (2014)
422 work for two practical and common situations: (i) in the absence of previous and external

423 validated reference data (e.g. terrestrial laser scanning) and (ii) in a sinuous configuration with
424 a succession of headlands and bays (*[Figure 1]*).

425 In the absence of validated and robust reference data, modeling point deviation from
426 planar features visible in all scans provides quality assessment in terms of internal consistency
427 (i.e. the ability to accurately represent an object with known geometry, e.g. [López et al 2014](#)).
428 From this we learned that:

- 429 - Despite being rocked and rolled by sea waves (20-30 cm of amplitude), boat-borne
430 mobile laser systems are capable of describing, in our case, planar features with a point
431 range precision of 4.3 cm (epoch 3) to 8.8cm (epoch 1 and 2) at the 99.9% quantile
432 (Table 3-1) at distances between 50 m to 300 m from the cliff face. The order of
433 magnitude of precision to be expected with these devices come between 1/1000 and
434 1/7500 of the distance to the cliff.
- 435 - Internal mis-registration may exist between successive passes in front of the cliff during
436 the same survey. Here, epoch 2 was affected by a mis-registration reaching about 3cm
437 between passes. Looking at the residuals distribution to a planar feature may help
438 identify and quantify this defect. Obviously such co-registration error strongly limits
439 the performance of the mapping system, in a particular context of low erosion rates. All
440 efforts should thrive to reach the highest precision. Even though laser scanners used at
441 epoch 2 and 3 appear to be of the same ranging precision, the instantaneous orientation
442 solution (from combined IMU/GNSS) was at fault and was not compensated through
443 software post-processing.
- 444 - Because a repeatability error - between 1 and 3 mm - could be reached (Table 3-2),
445 global compensation of the entire surveys are achievable with millimeter accuracy.
446 Consequently, the threshold distances are mostly influenced by point precision values
447 (*[Figure 2-c]*). The rather poor erosion detection thresholds, compared to terrestrial laser
448 scanning, comprised between 13.1 and 18.6cm (Table 3-2) are affected by the poor
449 overall precision of the epoch 1, and the internal bias of epoch 2. Nevertheless, this
450 finding is globally in line with the performances described by Michoud et al., ([2014](#)).
- 451 - One should note that our statistical accuracy assessment criterion, the 99.9% quantile of
452 cloud-to-cloud differences, suggested by Dewez et al., ([2013](#)) is more conservative than
453 in many others studies. For example, in the case where the median absolute deviation
454 threshold is used ([Michoud et al., 2014](#)), every point contained a large deviation than

455 the threshold. The erosion may not be always detected as such. We preferred a
456 conservative approach in a context of low erosion.

457 In a sinuous coastal configuration, point clouds need to be simplified in order to examine
458 the erosion with various methods readily implemented in 2.5D GIS such as the common DoD
459 approach (Digital Elevation Model of difference, as [Rosser et al., 2005](#); [Abellán et al., 2010](#);
460 [O'Neal and Pizzuto, 2011](#)). Therefore the key of the data processing workflow (*[Figure 5*) is
461 the unfolding method (*[Figure 6 & [Figure 7*). We are, of course, aware of the full-3D M3C2
462 algorithm developed by Lague et al. ([2013](#)), implemented in *Cloud Compare* ([Girardeau-](#)
463 [Montaut et al., 2005](#)), but computing cloud-to-cloud distances is never the end of the
464 geomorphological analysis. Erosion needs to be compared with other sources of information
465 (e.g. lithological maps), manually segmented or integrated over some meshing scheme. For
466 these operations, 2.5D GIS software remain standard tools for many users, and allow for
467 example to classify point clouds with orthophotos. Although manual processing is error prone
468 and time consuming, early tests with *Canupo* ([Brodu and Lague, 2012](#)) were not conclusive to
469 segment vegetation of epoch 1 point cloud, possibly due to the high level of noise and
470 comparatively short cliff-dwelling vegetation.

471 Finally, the goal of this work was to generate a rock fall scar inventory from the
472 Mediterranean coast of France, which had received little attention for cliff retreat so far. This
473 work was prompted by a strong societal demand. The cliff collapse risk there is high, not
474 because of the collapse hazard, but rather for the high-value assets exposed both along the top
475 and foot of the cliff (houses, beaches... see *[Figure 1-a*). This work initiated a quantitative
476 assessment of collapse hazard. With a volume of erosion detection limit of 1.4 liters (one pixel
477 of 100 cm² and a threshold erosion of 14 cm), three first-order collapse hazard information were
478 computed: (i) the overall annual cliff recession rate, (ii) the cliff face erosion map, and (iii)
479 vertical and alongshore synthetic erosion profiles:

480 -The observed average retreat rate equates to 1.1 cm/year (total eroded volume over 17
481 months divided by the exposed cliff surface area), which is one order of magnitude smaller than
482 in many coastal cliff settings discussed in the literature (see a broad literature compilation in
483 [Premaillon et al., 2018](#)). Macrotidal chalk cliffs of the English Channel erode at 10-50cm/year
484 ([Costa et al., 2004](#); [Regard et al., 2012](#); [Dewez et al., 2013](#)), mesotidal hard sedimentary cliffs
485 of NE England at 1-5cm/year ([Rosser et al. 2013](#)), and mesotidal marly-limestone cliff of
486 Atlantic coast of Portugal erode faster than 10cm/year ([Marques et al., 2006](#)). Furthermore,

487 such centimeter-scale retreat rates are in line with changes we measured between the 1920's
488 and 2010 using vertical aerial photography over the entire coastline of Provence-Alpes-Cote
489 d'Azur (Giuliano, 2015). This retreat rate is also compatible with the rare and occasional events
490 collated in the last decade.

491 - The erosion scar inventory contains 14,925 distinct patches with erosion thicker than 14
492 cm. The total erosion affected 1,107 m² of the exposed cliff (3.67%) with a low total
493 volume (about 320 m³ in 17 months) in comparison with the Normandy cliff erosion
494 e.g. 100,000 m³ in 12 months observed by Michoud et al. (2014); although this massive
495 short-term volume is affected by a huge coastal landslide in Dieppe. To further explore
496 the relationship between erosion and rock types, we follow a normalization method
497 proposed by Van Westen (1997) and used in De Guidi and Scudero (2013) whereby the
498 relative response of each lithology to erosion can be ranked and quantified. From the
499 observed erosion map, marls and sands are more prone to erosion (60% chances to be
500 eroded) compared to calcarenites and conglomerates (20% each).

501 - Alongshore (*[Figure 12-a)*), the scar volumes and surfaces are unevenly distributed and
502 no direct response can easily be picked out with respect to relative headland/bay
503 morphology. This lack of fingerprint can be due to the stochastic nature of rock falls
504 and to the short time span of our observations. We do not regard this statement as
505 conclusive and further work elsewhere will investigate this question. Finally, the
506 vertical profile of erosion (*[Figure 12-b)*) shows that erosion is focused in the lower part
507 of the cliff, between 0 and 10 m elevation. The secondary erosion peak between 20 and
508 25 m elevation is caused by a single rock fall, east of "Cap de la Vierge" (headland H₅).
509 Visual examination of scars are compatible with Rosser et al.'s (2013) suggestion that
510 collapses do propagate progressing from a basal notch at sea-level upward. So Carry-
511 le-Rouet cliffs evolve according to common processes but at a rather slow pace over our
512 17 months survey interval.

513 *[Figure 12 about here]*

514

515 **8. CONCLUSION.**

516 This paper describes methods to deal with 3D point clouds acquisition from a boat-borne
517 laser scanner along sinuous cliffs. Man-made wall planes conveniently located along the top of

518 the coastal cliff were fitted with robust planar models to empirically retrieve precision and
 519 accuracy of the surveyed point clouds. Although, full-3D change detection is now possible with
 520 recently available software, many contextual interpretations still cannot be fully performed with
 521 such software. This is why we describe a method to unfold sinuous coastline point clouds onto
 522 analytical surfaces made of vertical plane segments and cylinder arcs (unfolding method).
 523 Converting 3D to 2.5D leverages the rich GIS tools set for manual mapping, orthophoto
 524 interpretation and conventional geomorphological analysis.

525 Applied to Carry-le-Rouet over a time span of 17 months, the average recession rate
 526 comes to 1.1cm/year, when retaining only points with significant differences threshold larger
 527 than the 99.9% quantile. Such average recession rate lies at the lower end of cliff recession rates
 528 studies world-wide. Erosion was three times more effective in sand/marls than in calcarenites
 529 or conglomerates and was mostly focused in the lower part of the cliff. The model of cliff
 530 instability propagation from its base upward is also observed in Carry-le-Rouet even though
 531 further work is needed to describe it in more detail. At this short time span, cliff erosion is thus
 532 dominated by marine processes over continental processes.

533

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540 **Appendix A. Script for unfolding point clouds (R).**

541 Point cloud unfolding was coded in R ([R Core Team, 2018](#)) through the custom made
 542 Unfolding Point Cloud function. This function can treat quickly any cloud in *XYZ ASCII* format. The
 543 script requires two inputs: (i) a point cloud to process which contains the information of each sector
 544 and (ii) parameters for coastline trends (either planar or curvilinear) (Figure A-1). Angles values are
 545 obtained by the complex number method, through Complex package in R ([Becker et al. 1988](#)). The
 546 output comes in *ASCII* with both initial and unfolded coordinates.

547 *[Figure A-1 about here]*

548 #####

```

549 ##### I-UNFOLDING POINT CLOUD #####
550 #####
551 #
552 ### A- Data input ###
553 # A1- Points cloud (Figure A-1.a.1)
554 infile.pc <- file.choose() # open initial points cloud to be unfolded
555 pcloud <- as.data.frame(scan(file=infile.pc, what=list(x=numeric(),y=numeric(),z=numeric(),
556 Rr=numeric(),G=numeric(),B=numeric(),i=numeric(), Sect=numeric()), flush=T, skip=1))
557 #
558 # A2- Parameters (Figure A-1.a.2)
559 infile.pm <- file.choose()# open parameters file for unfolding operations (linear and curvilinear sections)
560 pmark<-as.data.frame(scan(file=infile.pm,what=list(ID=0, Sect=0,Type="",Ax=0.0, Ay=0.0, Bx=0.0, By=0.0, Ox=0.0,
561 Oy=0.0, R=0.0, lsect=0.0, lcum=0.0, US=0.0),skip=1))
562 pcloud$XU<-NA # to store x unfolded
563 pcloud$YU<-NA # to store y unfolded
564 #
565 ### B- Loop for unfolding ###
566 for (j in 1:length(pmark$Sect)){
567 # B1- Type of section
568 type <- as.character(pmark$Type[j])
569 #
570 # B2- Selection of parameters related to the section (Figure A-1.a.2)
571 xA <-pmark$Ax[j] # X coordinate of start of the section
572 yA <-pmark$Ay[j] # y coordinate ...
573 xB <-pmark$Bx[j] # x coordinate of end of the section
574 yB <-pmark$By[j] # y coordinate ...
575 lcum <-pmark$lcum[j] # lcum : cumulated length at the beginning of the section
576 lsect <-pmark$lsect[j] # lsect : section length
577 xO <-pmark$Ox[j] # x coordinate of the center of the circle
578 yO <-pmark$Oy[j] # y coordinate ...
579 R <-pmark$R[j] # radius of the circle
580 US <- pmark$US[j] # sense for unfolding
581 #
582 # B3- Selection of points belonging to the section
583 lgs <- pcloud[which(pcloud$Sect==j),]
584 #
585 # B4- Unfolding
586 if (type=="line"){
587 lgUnf <- unfol.line(lgs, xA, yA, xB, yB, lcum)
588 } else if (type == "curve"){
589 lgUnf <- unfol.curve(lgs, xA, yA, xO, yO, R, US, lcum)
590 } else {
591 }
592 #
593 # B5- Data storing
594 pcloud$XU[which(pcloud$Sect==j)] <- lgUnf$XU
595 pcloud$YU[which(pcloud$Sect==j)] <- lgUnf$YU
596 } #
597
598 ### C- Data output (Figure A-1.b) ###
599 #
600 output.file <- paste(dirname(infile.pc), "/unfolded24.txt", sep="")
601 write.table(pcloud, output.file, row.names=F)
602 #
603 #####
604 ##### II-FUNCTIONS #####
605 #####
606 #
607 unfol.line <- function(lgs, xA, yA, xB, yB, lcum){
608 # Translation of origin
609 lgUnf <- data.frame(XU=lgs$x - xA, YU=lgs$y - yA)
610 # Rotation
611 alpha <- Arg(complex(real=(xB-xA), imaginary=(yB-yA)))
612 rot <- matrix(c(cos(alpha), sin(alpha), -sin(alpha), cos(alpha)),ncol=2, nrow=2, byrow=T)
613 temp <- t(rot %*% t(cbind(lgUnf$XU, lgUnf$YU)))
614 # Translation back to lcum

```

```

615   lgUnf$XU <- temp[,1] + lcum
616   lgUnf$YU <- temp[,2]
617   return(lgUnf)
618 }
619 #
620 ##END##
621 #####
622

```

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Table 1. Technical specifications of the three boat mobile mapping systems (ATM3D, Boat-Map[®] and Drive-Map[®]).

BOAT MOBILE MAPPING SYSTEM			
Epoch	1 (February 2011)	2 (November 2011)	3 (July 2012)
SYSTEM	ATM3D	BOAT-MAP[®]	DRIVE-MAP[®]
Number of points	10.6*10 ⁶	18.7*10 ⁶	43.9*10 ⁶
1. Positioning sensors (GNSS & IMU)			
<i>GNSS brand</i>	<i>NOVATEL</i>	<i>TRIMBLE</i>	<i>TOPCON</i>
GNSS sampling frequency [Hz]	1	1	20
Brand (IMU)	<i>LandINS (IXSEA)</i>	<i>FSAS (NOVATEL)</i>	<i>TOPCON</i>
IMU sampling frequency [Hz]	200	200	100
Rolling/pitch precision [°]	0.005	0.008	0.02
Bend precision	0.010	0.023	0.04
2. Mapping sensors (LASER scanner)			
LASER scanner brand	<i>LMS Z390i (RIEGL)</i>	<i>Iiris HD ER (OPTECH)</i>	<i>VQ 250 (RIEGL)</i>
Aperture angle [°]	80	40	360
Measurement rate [pts.s ⁻¹]	11000	10000	300000
Distance range [m]	1-400	3-1800	1.5-200
Angular resolution [°]	0.002	0.00115	0.0018
σ angular measured [°]	0.001	0.00458	0.001
σ distance measured [mm]	4	7mm-100m	5
3. Camera			
Camera brand	-	<i>Imperx-16M-G(IMPERX)</i>	-
Focale length [mm]	-	35	-
Sensor length [mm]	-	36.07*24.05	-
Pixel size [Mpx]	-	4872*3248	-

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871 *Table 2. Synthesis of point clouds quality. 1. Single epoch quality of the three epochs (statistical*
 872 *point precision and modal value); 2. Inter epoch quality of the three epochs (point precision,*
 873 *repeatability and threshold distance). * The 95 and 68.3 quantiles would be the equivalent of*
 874 *classical 2-sigma and 1-sigma thresholds if the distribution were truly Gaussian.*

1. Single epoch quality of three point clouds: point precision [cm]				
Epoch		1 (February 2011)	2 (November 2011)	3 (July 2012)
N walls [pts]		7630	8968	23232
Quantile of 99.9		8.8	8.8	4.3
absolute 95.0 (2σ*)		3.1	3.8	2.6
distance 68.3 (1σ*)		1.4	2.2	1.1
[cm] 50.0		1.0	1.6	0.7
Modal value [cm]		0.1	1.1	0.1

2. Inter-epoch quality of three point clouds (see [Figure 2])

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a. Sum of the squared point precision [cm]				+	b. Repeatability distance [cm]				=	c. Threshold distance [cm]			
	Epoch 1	Epoch 2	Epoch 3			Epoch 1	Epoch 2	Epoch 3			Epoch 1	Epoch 2	Epoch 3
Epoch 1	-	-	-		Epoch 1	-	-	-		Epoch 1	-	-	-
Epoch 2	17.6	-	-		Epoch 2	0.29	-	-		Epoch 2	17.9	-	-
Epoch 3	13.1	13.1	-		Epoch 3	0.31	0.13	-		Epoch 3	13.4	13.2	-

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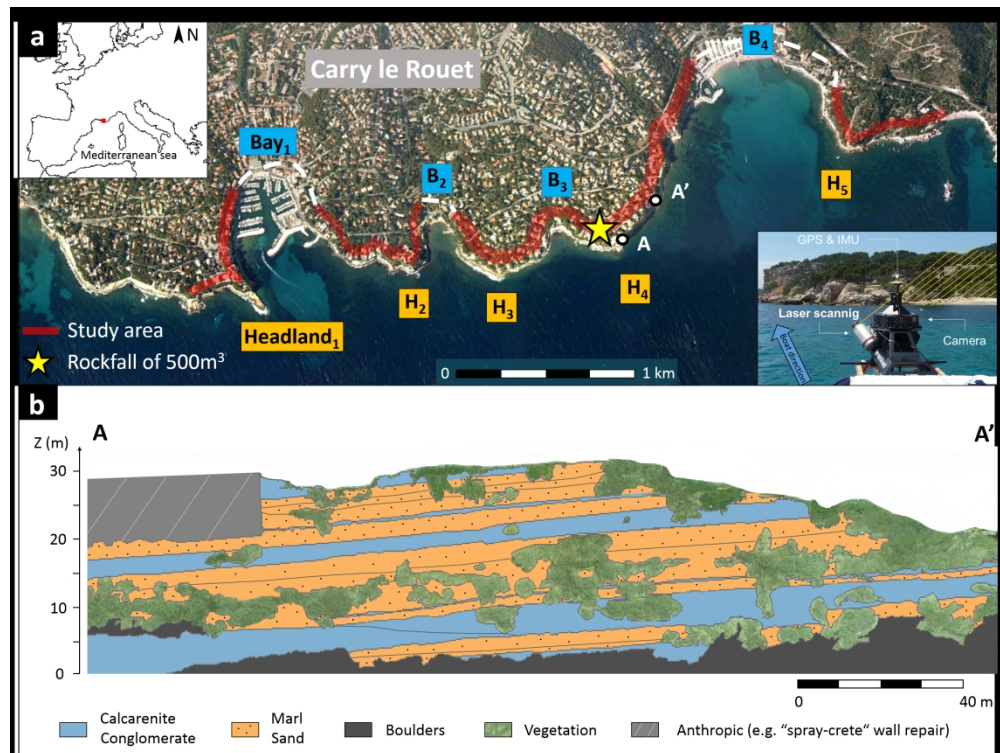


Figure 1. Study site of Carry-le-Rouet along the micro-tidal Mediterranean coastline (15km west of Marseille, southern France). a- Map view of the sinuous coastline composed of 5 headlands and 4 bays and study area; b- Front view of the section AA' and geological interpretation of the Oligo-Miocene sedimentary stack setting drawn from ortho-photography. The "spray-crete" wall repair corresponds to the northern end of a rockfall section of about 500m³ of that occurred on February 6, 2008.

507x380mm (150 x 150 DPI)

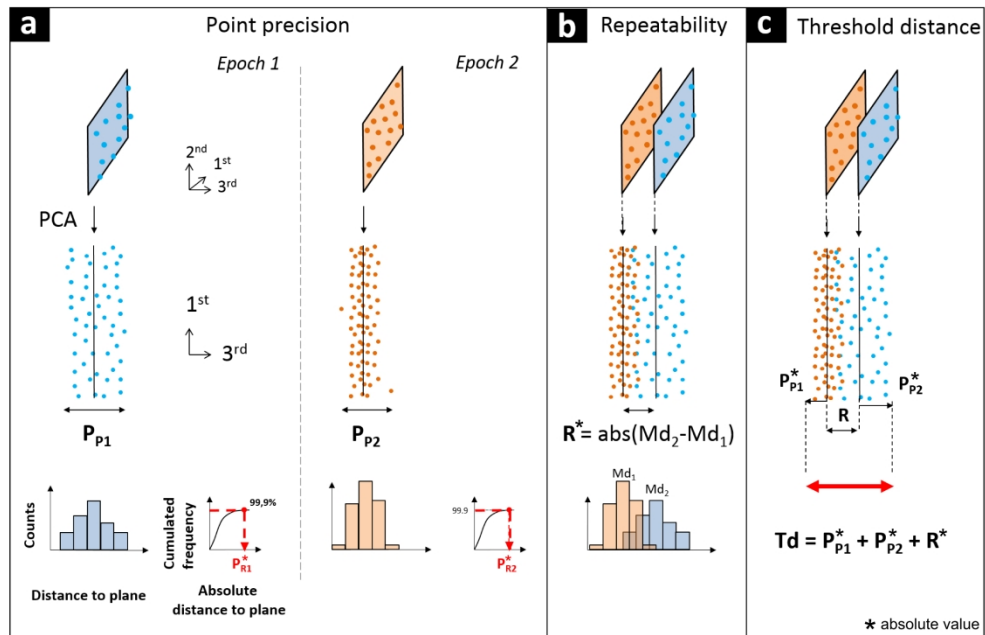


Figure 2. Quality assessment principle applied to a planar object. Point precision (PP), repeatability distance error (R); and threshold distance (Td) assessment through the third component (3rd) of Principal Component Analysis applied to diachronic wall measurements (example for epoch 1 and 2). 3rd component corresponds to distance to wall plan model. a- Point precision (PP1 and PP2) values are obtained as the 99.9% quantile of the cumulated frequency of the absolute 3rd component. b- Repeatability error (R) corresponds to absolute difference of median of the 3rd component values (Md_1 and Md_2). c- Threshold distance (Td) is the total uncertainty of the detection between two epochs.

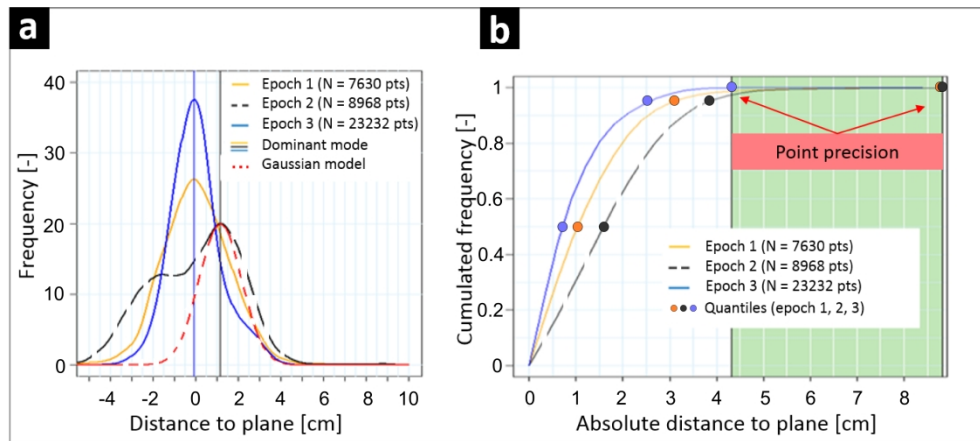


Figure 3. Point precision (PP) assessment. a- Frequency density (bandwidth of 3mm) of PCA third component deviation to the median. Dominant modes (density curve maximum) are marked by vertical lines. The red short-dashed curve represents a Gaussian distribution centered on the dominant mode of the epoch 2. b- Cumulated frequency of absolute deviation from the median. The plain dots represent the 50%, 95% and 99.9% quantiles of each survey. Epoch 2 is more skewed to the right than epochs 1 and 3.

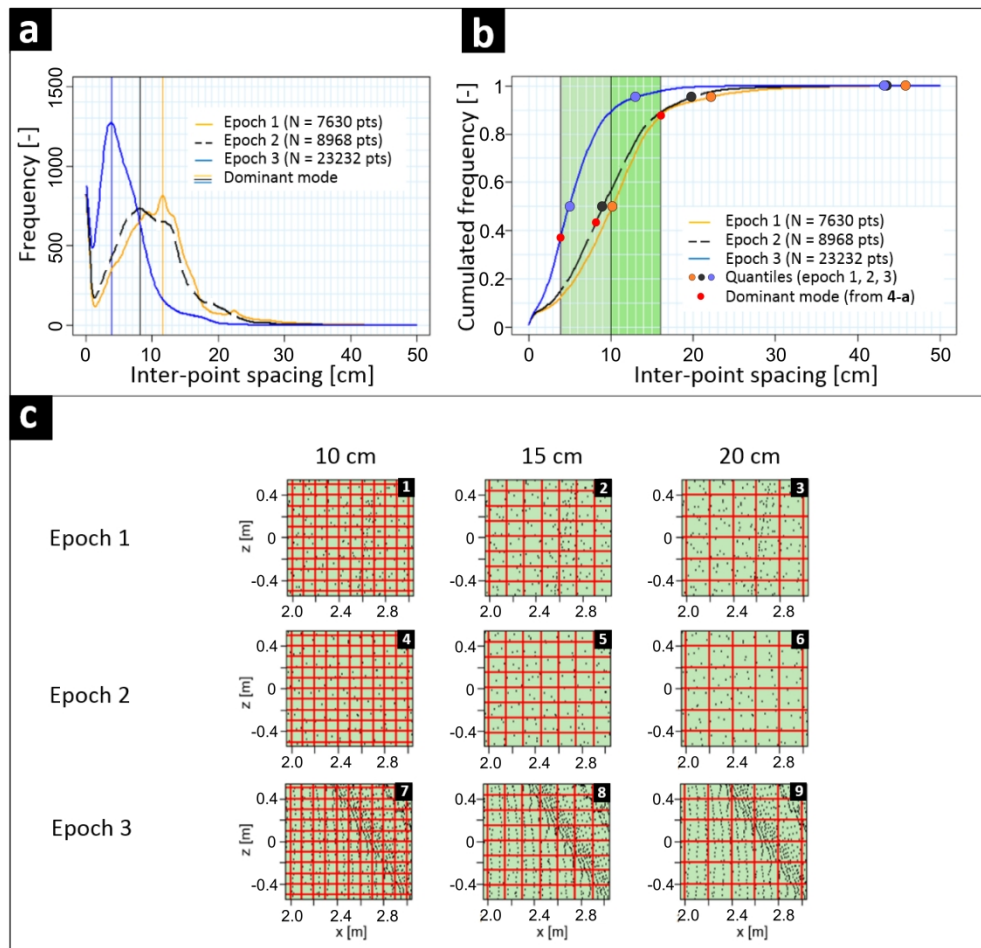


Figure 4. Inter-point assessment determined by a projection of 2.5D grids for the three epochs. a- Frequency density of inter-point Euclidian spacing in a wall-coplanar reference frame (bandwidth = 0.5mm). Dominant modes are defined by vertical lines. b- Cumulated frequency of the inter-point spacing. c- Example of different grid cell size (10, 15, 20cm) applied to point clouds from a wall extracted for the three epochs.

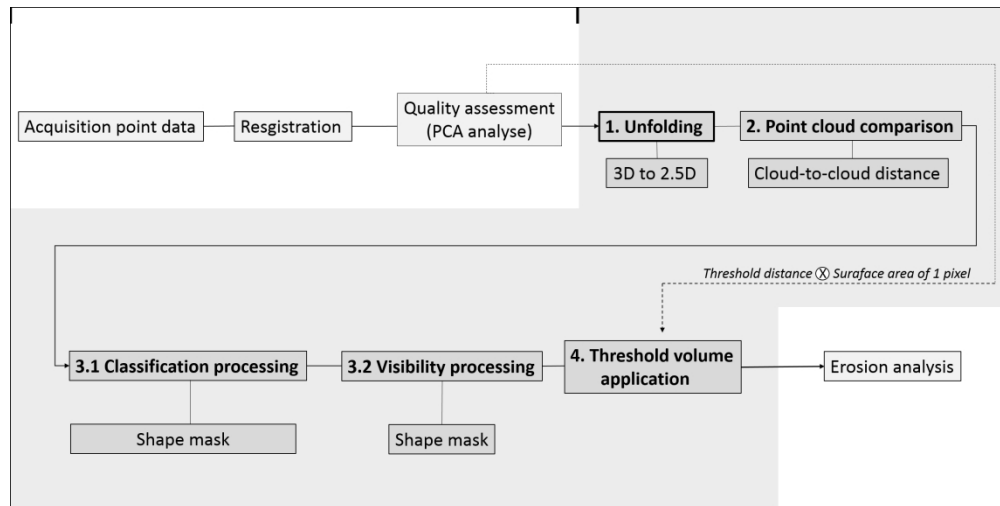


Figure 5. Flow diagram of LiDAR data processing (from data acquisition to erosion analysis). Grey polygon indicates LiDAR data processing based on unfolding method.

438x220mm (150 x 150 DPI)

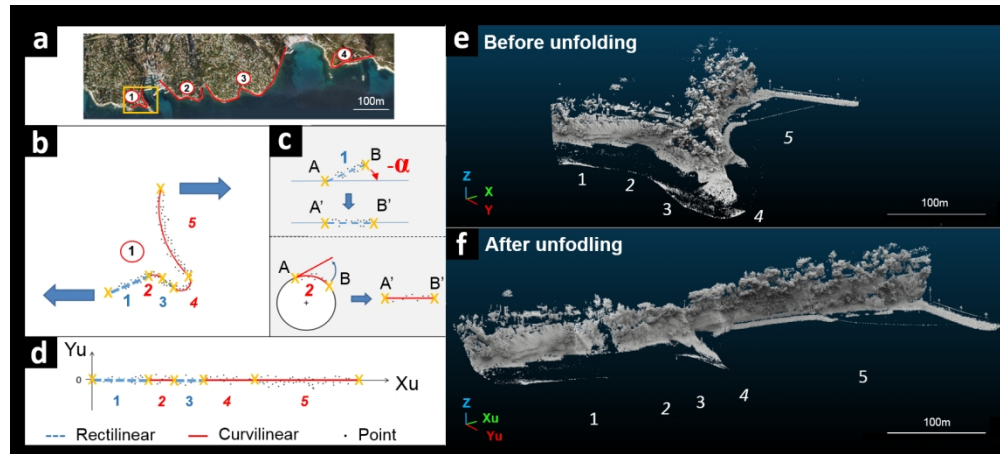


Figure 6. Projection method applied to a complex sinuous point cloud, example of area 1. a- Map view of the general trend of coastline defined through GIS. Map projection is defined in the same system as point clouds. b- Focus of sinuous area 1. General trend and point cloud are segmented into linear (dashed blue line) and curvilinear sections (solid red curve). c. Two types of transformation are applied to sub-point cloud, c.1- angular rotation for rectilinear, and c.2- angular distance calculation for curvilinear section. d. Point cloud unfolded and re-projected in unfolded coordinates along a straight line. e- & f- View of point cloud before and after unfolding.

293x132mm (150 x 150 DPI)

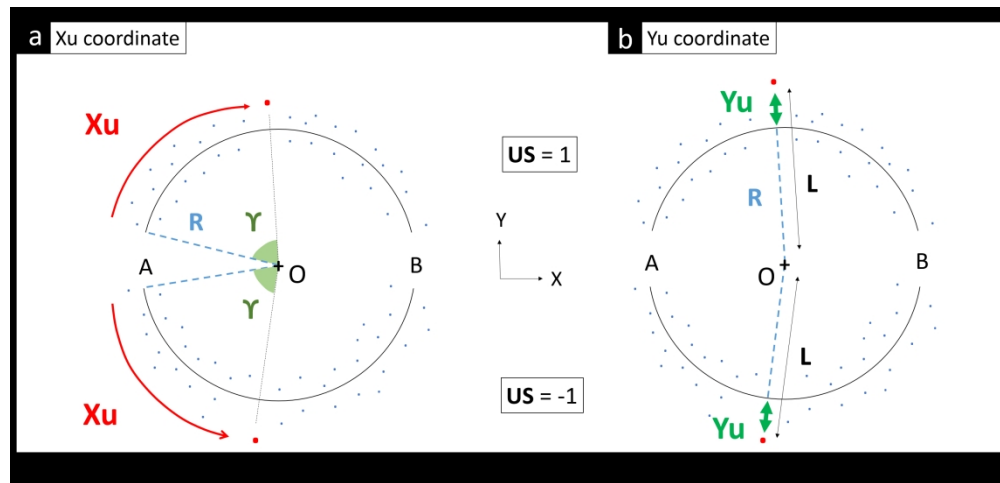


Figure 7. Unfolding method of curvilinear section defined by a circle. Unfolded coordinates XU and YU of sub-clouds are obtained separately. a- XU coordinate corresponds to the angular distance of the points from the initial arc section (A). b- YU coordinate corresponds to the distance of the points from the curvilinear section (AB).

511x245mm (150 x 150 DPI)

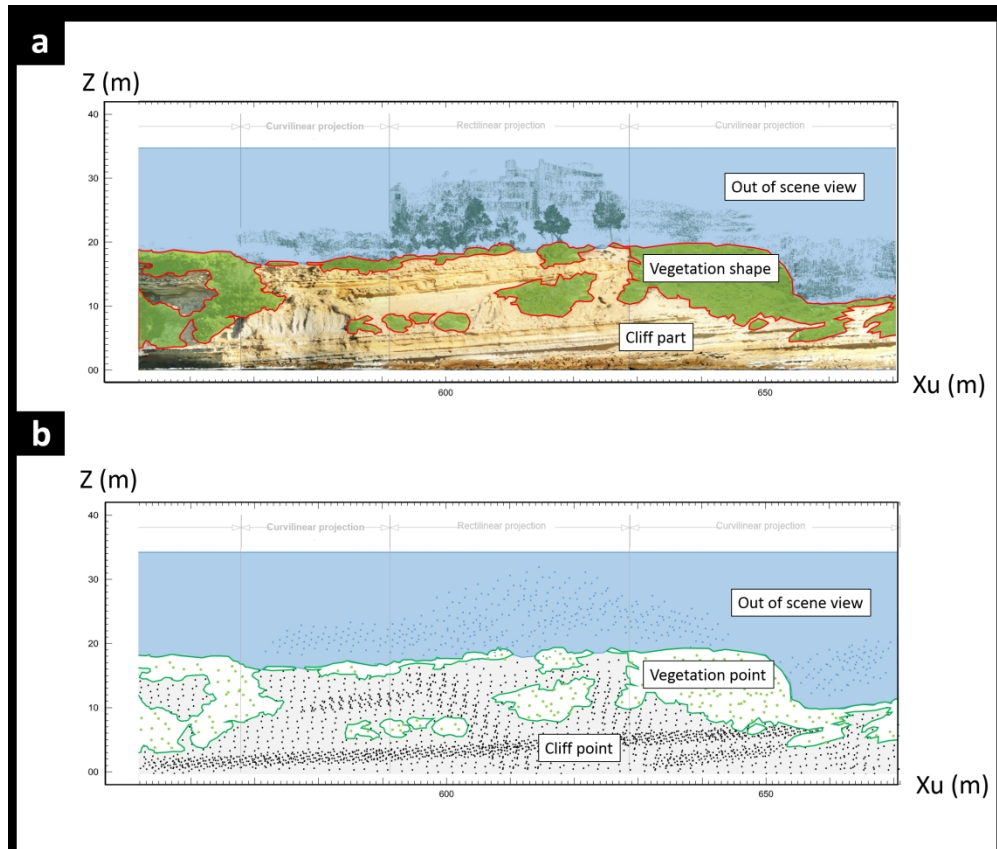


Figure 8. Semi-automatic classification by mask application to an unfolded point cloud. a- Example of a section of an ortho-photography digitalized by three polygons which correspond to "out of scene view", "vegetation" and "cliff". b- Mask segmentation applied by superposition of polygons on the front view (X_u , Z) of unfolded point cloud (in same projection).

408x345mm (150 x 150 DPI)

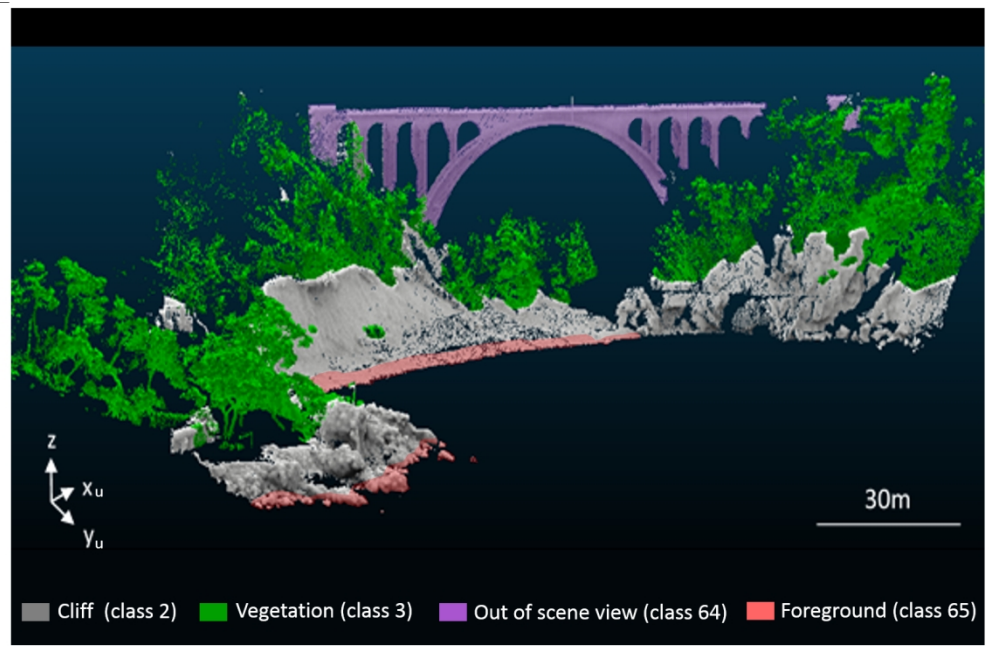


Figure 9. Point cloud processed (unfolded and classified). Example of the eastern section of epoch 3.

281x185mm (150 x 150 DPI)

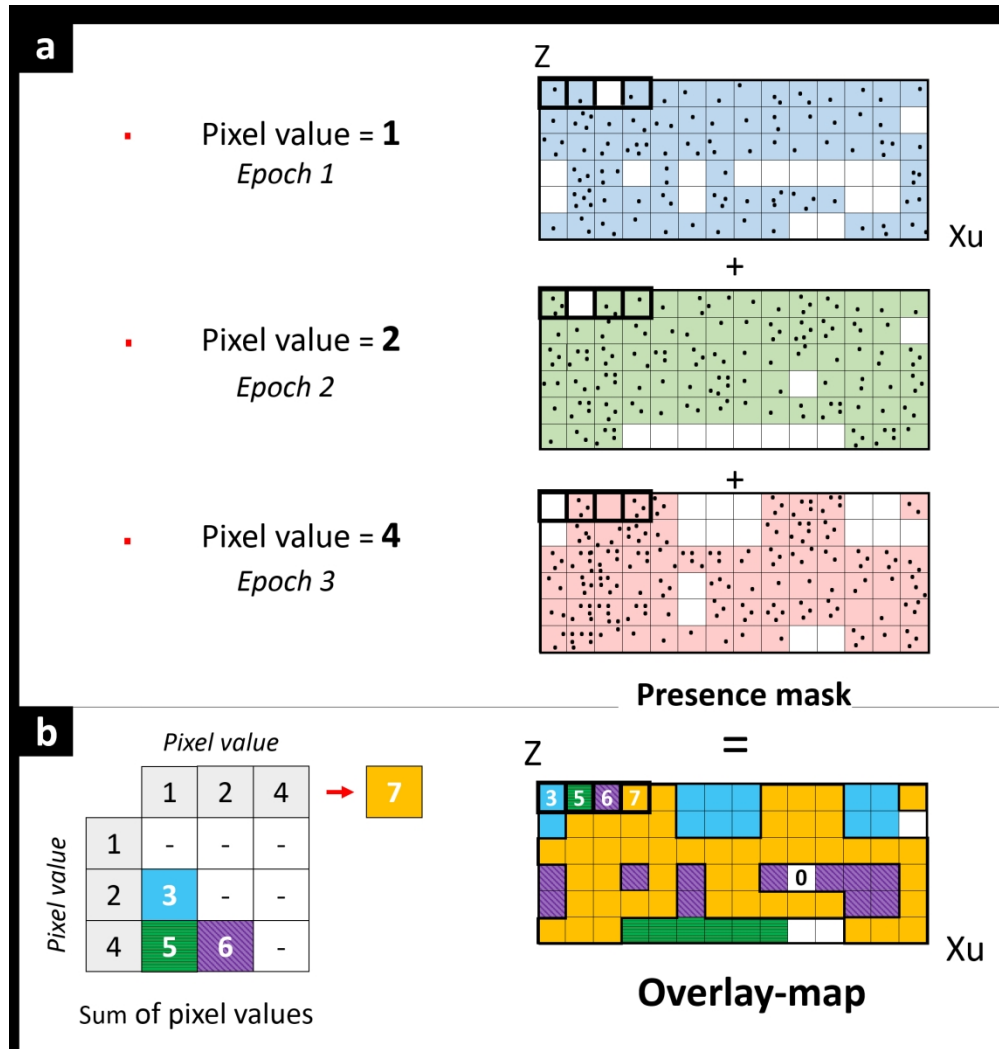


Figure 10. Overlay-map generation in two steps. a- Point presence mask creation for the three epochs. Pixel label is incremented at each epoch. b- Overlay map generated by the sum of the point presence mask. The nominal pixel value shows distinct visibility between the three epochs.

362x378mm (150 x 150 DPI)

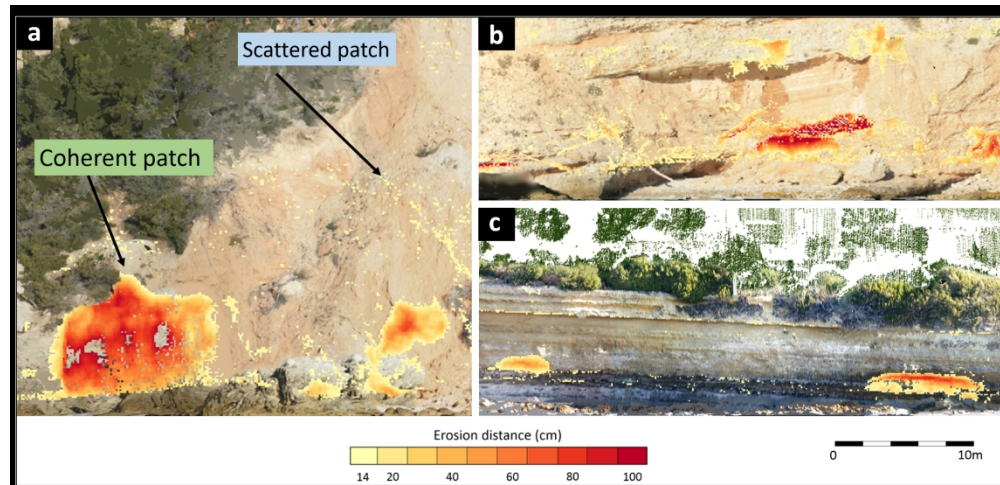


Figure 11. Examples of Digital Surface Model of erosion (DSMe) overlaid on ortho-photography. Erosion scars show up as coherent and scattered patches of absolute distance values.

545x262mm (150 x 150 DPI)

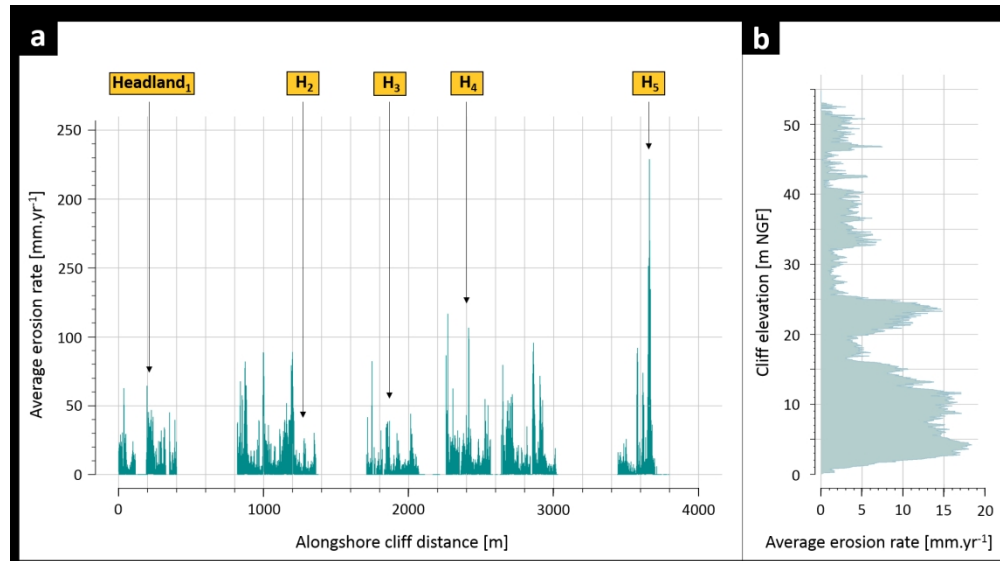


Figure 12. Average erosion rates integrated along-shore (a) and vertically (b). a. All headlands flagged from west to east. The easternmost headland, H5 (“Cap de la Vierge”), locally focused erosion with three large events; b. The vertically integrated profile shows a basal section, up to 15m in height affected by erosion rates above 10mm/year while the upper part of the cliff only reaches 5mm/year.

344x192mm (150 x 150 DPI)

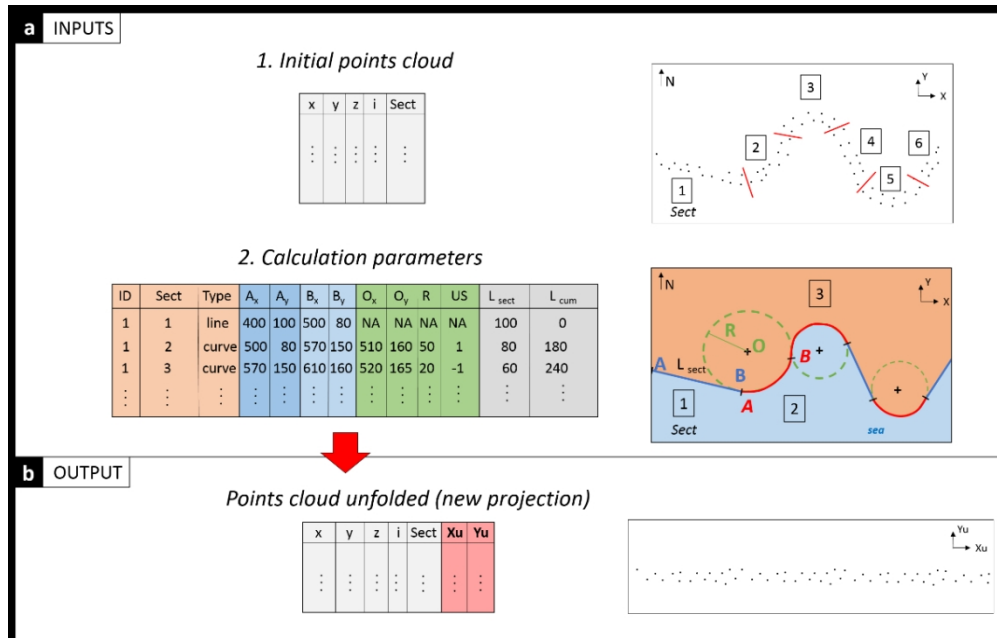


Figure A-1. Concept of unfolding point cloud (inputs and output configuration). a- Processing requires two inputs: 1 Initial point cloud containing the xyzi and sector identifier (Sect) to unfold, 2 Calculation parameters for each sector, whether linear and circular transformation; b- Output is a table which contains initial xyz and new curvilinear continuous coordinates.