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1 **Examining high-resolution survey methods for monitoring cliff erosion**
2 **at an operational scale**

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17 **Examining high resolution survey methods for monitoring cliff erosion** 18 **at an operational scale**

19 This paper aims to compare models from terrestrial laser scanning (TLS),
20 terrestrial photogrammetry (TP), and unmanned aerial vehicle photogrammetry
21 (UAVP) surveys to evaluate their potential in cliff erosion monitoring. TLS has
22 commonly been used to monitor cliff-face erosion (monitoring since 2010 in
23 Normandy) because it guarantees results of high precision. Due to some
24 uncertainties and limitations of TLS, TP and UAVP can be seen as alternative
25 methods. First, the texture quality of the photogrammetry models is better than
26 that of TLS which could be useful for analysis and interpretation. Second, a
27 comparison between the TLS model and UAV or TP models shows that the mean
28 error value is mainly from 0.013 to 0.03 m, which meets the precision
29 requirements for monitoring cliff erosion by rock falls and debris falls. However,
30 TP is more sensitive to roughness than UAVP, which increases the data standard
31 deviation. Thus, UAVP appears to be more reliable in our study and provides a
32 larger spatial coverage, enabling a larger cliff-face section to be monitored with a
33 regular resolution. Nevertheless, the method remains dependent on the weather
34 conditions and the number of operators is not reduced. Third, even though UAVP
35 has more advantages than TP, the methods could be interchangeable when no
36 pilot is available, when weather conditions are bad or when high reactivity is
37 needed.

38 **Keywords:** Coastal cliff erosion; monitoring; terrestrial laser scanning; terrestrial
39 photogrammetry; UAV photogrammetry; Normandy

40 **1 Introduction**

41 Changes to coastal cliffs are complex because of the sudden and stochastic natures of
42 erosion in time and place and the diversity of movements (rock falls and debris falls
43 according to the typology of Varnes). Despite contributions to research into
44 geomorphological processes on rocky coasts in recent years, the respective contribution
45 of the triggering factors responsible for erosion is still difficult to determine (Naylor et
46 al. 2010; Lim et al. 2011; Letortu et al. 2015a; Laute et al. 2017).

47 As quantifying changes in unstable and subvertical cliff face is difficult and
48 sometimes dangerous, in situ data are mainly collected by remote-sensing methods.
49 Data with a horizontal or quasi-horizontal point of view (side scanning a vertical
50 structure as the cliff face) allow all changes to be observed because the data capture cliff
51 face changes which reflect failures and deposits anywhere on the cliff profile (contrary
52 to cliff top and cliff base). High spatial resolution and high temporal repetitiveness are
53 essential to reveal patterns of cliff failure (location, time) and therefore to better
54 understand and forecast the processes responsible for cliff erosion (e.g. Collins and Sitar
55 2008; Hampton 2002; Vann Jones et al. 2015; Young 2015).

56 Different methods terrestrial Laser Scanning (TLS), Aerial Laser Scanning
57 (ALS), Mobile Laser Scanning, Unmanned Aerial Vehicle Photogrammetry (UAVP),
58 Terrestrial Photogrammetry (TP) are available for cliff monitoring depending on the
59 precision, the spatial and temporal scales, and costs (e.g., Young et al. 2010; James and
60 Robson 2012; Michoud et al. 2014). As reported in James and Robson (2012), for
61 restricted areas (ranges of 10–500s of meters) terrestrial laser scanners or TP can be
62 used. Over larger areas, aerial photogrammetry, aerial laser scanners, and space-based
63 radar and photogrammetric techniques are possible.

64 Within the framework of the “Service National d’Observation DYNALIT”
65 (French National Service Observation for the study of coastal and coastline dynamics),
66 we survey the cliff-face evolution in Petit Ailly site in Varengeville-sur-Mer
67 (Normandy, France) to quantify fine-scale changes, to visualize the modalities of
68 evolution and to contribute to the debate about the agents responsible for the retreat of
69 the chalk cliffs. Since October 2010, a 3D monitoring of the cliff face has been
70 performed by terrestrial laser scanner (an active remote-sensing instrument) at very high
71 spatial resolution and with pluricentimeter precision (± 0.03 m) every 3-4 months

72 (Letortu et al. 2015b). It enables reliable, homogeneous, frequent and perennial
73 monitoring of rock falls and debris falls. However, the TLS routine is expensive and
74 cumbersome and therefore requires several operators. UAVP and TP surveys may be
75 efficient alternatives offering data of equivalent quality.

76 Is the accuracy of close-range techniques, such as TP and UAVP, sufficient in
77 comparison with the more expensive and cumbersome TLS routine for monitoring cliff-
78 face erosion? The answer to this question involves many topics: (1) the resolution
79 and/or ground sampling distance (2) the spatial coverage (3) the accuracy and precision
80 of the datasets for diachronic surveys of individual and mass movements, and (4) an
81 easy-to-use acquisition protocol for the site configuration and data processing. If the
82 different techniques achieve the same level of data quality, these methods could be
83 interchangeable, depending on weather conditions and people availability, without any
84 impact on the monitoring results.

85 Thus, this article presents an original comparison for such environment of three
86 high-resolution remote-sensing methods implemented for 28 January 2016: (1)
87 measurement by TLS and two photogrammetric methods based on Structure from
88 Motion/Multi-View Stereophotogrammetry (SfM-MVS) techniques from (2) UAV
89 photographs and (3) terrestrial photographs. After a brief description of the study area,
90 this paper details the survey methodology. Finally, the results of the cliff-face
91 monitoring are presented and discussed.

92 **2 Study area**

93 The study takes place near Dieppe, in Seine-Maritime (Normandy) in the northwestern
94 part of France and along the Channel. Geologically, the Upper Normandy coastal cliffs
95 (60-70 m high on average) extending from Cap d'Antifer to Le Tréport (100 km) are

96 made of various chalk with flints of Upper Cretaceous (Pomerol et al. 1987; Mortimore
97 and Duperret 2004). The different stages of chalk (from the oldest to the newest:
98 Cenomanian, Turonian, Coniacian, Santonian and Campanian) present slight variations
99 in facies and fine sedimentary discontinuities, inducing some subtle resistance contrasts.
100 Over these chalk strata, the usual residual flint formation (Laignel 1997; Costa et al.
101 2006) have been replaced by a bed of clay and sand sediments about 10-30 m thick of
102 Paleogene age (Bignot 1962), especially in Sainte-Marguerite-sur-Mer, Varengeville-
103 sur-Mer, and Sotteville-sur-Mer (Figure 1). The Seine-Maritime cliff coast is
104 characterized by the regressive dynamics, coming out as instantaneous falls affecting all
105 or part of the cliff. A monitoring of the regressive dynamics of the cliff top between
106 1966 and 2008 shows a retreat rate of 0.15 m/year with high spatial variability in Upper
107 Normandy (Letortu et al. 2014).

108 The SNO DYNALIT site of Petit Ailly is located along Cap d'Ailly
109 (<https://www.dynalit.fr/fr/falaises/ailly-puys>). More precisely, it lies on either side of
110 the Petit Ailly dry valley in Varengeville-sur-Mer (Figure 2). This site is made up of
111 Santonian chalk, covered by a bed of clay and sand of Paleogene age, prone to erosion.
112 It has a high erosion rates calculated from TLS surveys: from October 2010 to June
113 2017, the erosion rate is 0.38 m/year with a fallen volume of 12965 m³ (± 155 m³) due to
114 rock falls and debris falls. Nevertheless, these average retreat rates are not
115 representative of the erosion which occurs suddenly caused by rockfalls. For example,
116 in February 2014, a rock fall of approximately 5000 m³ resulted in a cliff-top retreat of
117 11 m in a few seconds.

118 The studied cliff face is characterized by (1) its verticality (from 70° to
119 overhang); (2) its height (about 30-40 m); (3) its spatial extent (250 m long); (4) debris
120 falls, which are individual movements of blocks or flakes (up to decimeters), and rock

121 falls, which describe large-scale mass movements from all or part of the cliff face; and
122 (5) its limited accessibility (rock falls, tide constraints, difficulty in setting up targets at
123 the cliff top).

124 **3 Methods**

125 **3.1 Data collection**

126 *3.1.1 Terrestrial laser scanner data collection and ground control points*

127 A terrestrial laser scanner is an optical active remote-sensing technology that can
128 measure the position (distance and angle) of a point relative to the device using the time
129 of flight of laser pulses reflected by the point to be measured.

130 The instrument used in this study is a Riegl® VZ-400 (Figure 2(6)) emitting a
131 laser pulse in the near-infrared (1550 nm), which records unique echo digitization but
132 allows the digitized echo-signals (waveform data) to be processed in Riegl® software.
133 This instrument provides scan data acquisition with theoretical 0.005 m accuracy and
134 0.003 m precision at a range of 100 m. The measurement range can reach up to 600 m
135 while the measurement rate can reach up to 122,000 measurements per second with a
136 wide field of view of 100° vertical (from 30° to 130°) and 360° horizontal (Riegl 2014).
137 Moreover, the Riegl® VZ-400 is equipped with a Nikon D800 camera, which provides
138 photographs. These pictures can be used to drape a 2D image on the 3D point cloud but
139 are not an absolute requirement for topographic measurement. In Varengeville-sur-Mer,
140 the two scanner stations are positioned on the beach at about 75 m from the cliff face.
141 TLS acquisition involves a 360° horizontal and 100° vertical scan with an angular
142 resolution of 0.04° in both directions, providing a dense 3D point cloud (more than 22.5
143 million points) and five photographs in 9 min (20 % overlap by default). These

144 instruments are heavy, 20 kg for the scanner and 1 kg for the Nikon camera, and require
145 complementary equipment (a tripod, cases, batteries, targets and a total station).

146 To carry out georeferencing and obtain repeated surveys of high accuracy, the
147 data acquisition process requires additional equipment: reflective targets (10cm high
148 cylinders, 0.15 kg, Figure 2(4)) used as ground control points (GCPs) and a total station
149 to measure them (Figure 2(2)). Contrary to the GPS, the total station measures points
150 close to the cliff front without a mask effect. The Trimble M3 total station is precisely
151 positioned at a single location previously known by raw data GPS post-processing.
152 Knowing the reflective targets absolute coordinates enables the point cloud acquired in
153 a relative coordinate system to be projected in an absolute coordinate system (Lambert
154 93 and associated RGF93 and IGN69, official reference system in France; EPSG:
155 2154). For the TLS survey at Petit Ailly, laser scans were performed from two stations
156 with 15 targets as GCPs (Figure 3). To reduce the alignment error of the point cloud,
157 targets are numerous and with different distances from the scanner (as long as they all
158 remain visible).

159 *3.1.2 Terrestrial photo collection*

160 Terrestrial photographs are acquired with a Nikon D800 reflex camera (1 kg) with a
161 focal length of 35 mm, taking 36 Mpix photos. To collect data on the cliff front, as
162 recommended by James and Robson (2012), images of the area of interest are acquired
163 from different positions. As depicted in Figure 5a, the camera orientations are not
164 parallel but rather converge on the scene. The procedure to collect digital photographs is
165 quite easy to implement. It involves short distances between the acquisition positions
166 (around 2–3 m when taking photos at ~20 m from the cliff foot) and photos taken at
167 angular intervals of 10–20°, over a wide range of angles. To obtain a high-quality

168 dataset, photographs should overlap by at least 60 % (ideally, a point should be seen at
169 least three times) and must capture the area with at least two shooting angles. In 23 min,
170 the whole cliff section (250 m long) was covered by a dataset of 153 photographs
171 collected along the baseline depicted in Figure 3. The overlap enables that any point in
172 the studied cliff face being present in six to more than nine photographs.

173 *3.1.3 UAV photo collection*

174 The drone survey is implemented using an electric hexacopter UAV, called DRELIO 10
175 (multi-rotor DS6 platform assembled by DroneSys). A collapsible frame enables it to be
176 folded for easy transportation. With a 0.8m diameter, the DRELIO 10 weighs less than
177 4 kg and can handle a payload of 1.6 kg. The flying time is about 20 min. On a tilting
178 gyro-stabilized platform, a Nikon D800 reflex camera with a focal length of 35 mm is
179 set up. The camera takes 36 Mpix photographs in intervalometer mode every 2 s. The
180 DJI[®] software iOSD runs the flight control. For delicate steps of the take-off and
181 landing, the pilot prefers to control the UAV thanks to ground station software.

182 The dataset is collected along the yellow baseline depicted in Figure 3. As
183 shown in Figure 5b, data at the cliff top were collected by the camera that is in the nadir
184 position. To collect data on the cliff front, the camera was forward-pointed and tilted at
185 25°. In this case, the flight has to be performed in manual mode to keep the camera
186 turned toward the cliff face. The flight lasted around 8 min. In this configuration, the
187 dataset is composed of 110 oblique and nadir images (that will be processed together),
188 any point in the studied cliff face being present at least in 9 photographs.

189 *3.1.4 GCPs for TP and UAVP*

190 Like the TLS survey, TP and UAVP need GCPs (targets) to record the models in a
191 reference coordinate system and to achieve models of the highest quality, in terms of

192 both geometrical precision and georeferencing accuracy. The absolute coordinates are
193 provided by additional equipment : the total station (previously described). In order to
194 obtain a high-quality final model (James and Robson 2012) and help to mitigate doming
195 effects caused by an incorrect camera model and radial distortion (James and Robson
196 2014), a large number of GCPs is recommended. The GCPs need to be distributed
197 throughout the area of interest (Javernick et al. 2014; Smith et al. 2014) without linear
198 configurations. They should ideally cover both the margins and the center of the area of
199 interest, with a good range of values in each spatial dimension. However, in a cliff
200 context, access to the cliff face is dangerous due to frequent rock falls. It can therefore
201 be difficult to ensure targets are clearly visible while guaranteeing the safety of the
202 person installing them at the top of the cliff. The lack of targets on the upper part of the
203 cliff face may create distortion. To avoid this concern, the photograph acquisition
204 protocol was implemented cautiously. The UAV camera was forward-pointed and tilted
205 at 25° with photographs at different distances from the cliff face to reduce distortion.
206 For TP, a great variety of viewing angles of terrestrial photographs was taken to limit
207 the doming effect (Jaud et al. 2017b). A total of 17 targets were used for TP with
208 different configurations: 9 were vertically positioned on the area of interest (center of
209 orange crosses, 40 cm high, painted on the lower part of the cliff face, Figure 2(5))
210 while 8 targets (circular disks, 23 cm in diameter, Figure 2.1) were horizontally
211 positioned on the beach (Figure 3). For UAVP, 22 targets (circular disks, 23 cm in
212 diameter, Figure 2(1)) were horizontally positioned on the beach, on the lower part of
213 the valley slope and on the cliff top (Figure 3).

214 **3.2 Data processing**

215 *3.2.1 Terrestrial laser data processing and absolute error quantification*

216 The main steps in the TLS data processing are (1) georeferencing and point cloud
217 assembly (RiscanPRO® software); (2) manual point cloud filtering including areas
218 without overlap with previous TLS data, noise and vegetation (Fledermaus®); and (3)
219 Delaunay 2.5D meshing (best fit plane, Cloudcompare®).

220 The scanning survey of each position is recorded as a 3D point cloud (x,y,z) in a
221 reference system relative to each position of the scanner in the field. The accuracy of
222 georeferencing is carried out by comparing the position of the control points in the
223 model with the GCPs precisely measured on the field using the Root Mean Square Error
224 method (measuring the differences between values predicted by a model and the values
225 really observed) (Kaiser et al. 2014; Eltner et al. 2016). This accuracy assessment is
226 only valid if the point cloud is considered consistent (distortion due to atmospheric
227 effects is neglected). For the first and second stations, the standard deviations of fit
228 residues are 0.0091 and 0.0093 m, respectively. The absolute error on the data
229 (accuracy) is the sum of the TLS instrumental errors, the total station measurement
230 errors, and topographic inaccuracies during georeferencing. The theoretical instrument
231 accuracy of the TLS is very high (± 0.005 m at a range of 100 m), so the main source of
232 error comes from the total station survey, which measures the target positions with
233 accuracy from 0.01 to 0.03 m.

234 In a context of recurrent TLS surveys, a procedure of accuracy assessment has
235 been implemented. It is based on the comparison of the position of 3 fixed points
236 (surveyor nails located on the descending road to the sea) measured by the total station
237 during the 18 successive missions carried out within the framework of the DYNALIT
238 observatory. The 6 July 2011 topographical survey is defined as a reference because the

239 survey conditions were optimal. Identified thanks to their dispersion from the reference
240 data, the poor measurements are removed. The validated data have a maximum
241 dispersion ellipse of 0.018 m in x, 0.019 m in y and 0.033 m in z (Figure 4).

242 For diachronic comparisons to quantify local erosion rates, the point clouds are
243 adjusted relative to this point cloud of reference (6 July 2011) using a best fit algorithm.
244 To keep the consistency of this protocol, the comparison between TLS data and
245 photogrammetric data is also based on a best fit adjustment.

246 *3.2.2 Photograph data processing and precision*

247 The procedure for deriving 3D point clouds from photographs is based on the SfM-
248 MVS workflow. The SfM-MVS algorithm is implemented by Agisoft® PhotoScan
249 Professional (version 1.2) (Figure 5). The positions of the GCPs are imported into
250 Agisoft® PhotoScan and, concurrently, the GCPs are pointed out on the photographs to
251 compute the georeferenced 3D point cloud.

252 The 3D surface reconstruction is divided into two main steps:

- 253 • Camera alignment by bundle adjustment. Tie points are detected and matched on
254 overlapping photographs so as to compute the external camera parameters
255 (position and orientation) for each picture. From 17 to 22 GCPs (targets located
256 on the cliff front and on the beach for TP; targets on the beach for UAVP) are
257 tagged to georeference data and refine the internal parameters of the camera.
- 258 • From the estimated camera positions and the pictures themselves,
259 stereophotogrammetric equations allow the software to compute the position of
260 each tie point, so as to build a dense point cloud.

261 There is no direct measurement of accuracy from TP or UAVP because the
262 surveyor nails (fixed in a horizontal position) are not always visible in these datasets.
263 TLS data are considered the reference dataset for comparison in this paper, so, as
264 previously mentioned, TP and UAVP point clouds have been fitted to TLS data.
265 Therefore, the measure of precision of the photogrammetric reconstruction for TP and
266 UAVP datasets is assessed relative to the synchronous TLS dataset. The best fit RMS
267 error is of 0.04 m between TP and TLS and UAVP and TLS.

268 ***3.3 Data comparison***

269 First of all, TLS and photogrammetric methods (UAVP and TP) differ in the nature of
270 collected data and so resulting products. The main advantage of UAVP and TP is that
271 they provide textured models of better quality than the TLS model. When scanning a
272 site, by default, the TLS takes only five photographs for a 360° horizontal angle (with
273 an overlap of 20%). This is not enough to create, from all angles, a textured model
274 taking into account the terrain (Figure 6b). It is possible to increase the overlap but
275 because of fixed points of view of TLS stations, it would be hard to match the
276 photogrammetric model. In fact, the process of SfM-MVS itself involves the use of
277 ten(s) of high-resolution photographs, thus enabling the algorithm to choose perfectly
278 the relevant photographs to texture each parcel of the model (Medjkane et al. accepted).
279 It thus constitutes an important asset for the morphological analysis and interpretation
280 of landscapes (Figure 6c and d).

281 A first comparison of raw data is provided in Table 1. For the TP dataset,
282 because the photographs were taken closer to the cliff face than for the other datasets,
283 more photographs were needed to cover the area of interest so the sampling distance on
284 the cliff face was greater than for UAVP (Table 1). The volume of data was so large

285 that it was not manageable; it had to be processed in chunks. The steps for a more
286 advanced quantitative comparison were

- 287 (1) Cleaning the point cloud around the cliff face to obtain a good surface overlap;
- 288 (2) Subsampling TP and UAVP datasets to obtain manageable ones. The distance
289 sampling was a point every 0.06 m to have the same mean sampling as the TLS
290 point cloud, considered the reference;
- 291 (3) Fitting TP or UAVP models to the TLS point cloud used as the reference with
292 Cloudcompare and 3DReshaper software; and
- 293 (4) Comparison of the subsampled fitted point clouds (TP_SF, UAVP_SF) with the
294 TLS mesh (2.5D Delaunay mesh).

295 After dataset subsampling (0.06 m) of TP and UAVP models, quick filtering
296 around the cliff face and the beach and a fitting between TP or UAVP models and the
297 reference data (i.e. the TLS point cloud), the final point clouds can be quantitatively
298 compared (Table 2).

299 As in many papers (Westoby et al. 2012; Kaiser et al. 2014; Eltner et al. 2015;
300 Smith et al. 2016), we consider TLS models as the reference although they may also
301 have bias. As declared by Kromer et al. (2015), “the ability to detect change by
302 comparing a series of point clouds is controlled by the point cloud accuracy, precision,
303 survey design and terrain factors.” For the TLS point cloud, these parameters are, as
304 Kromer et al. (2015) point out:

305 the scanner target distance (Teza et al. 2007), vegetation (Su and Bork 2006),
306 incidence angle (Sturzenegger and Stead 2009; Lato et al. 2010; Pesci et al. 2011),
307 surface reflectance (Csanyi and Toth 2007), surface roughness (Lague et al. 2013),
308 atmospheric conditions (Beckmann 1965), heterogeneity in point spacing (Raber et
309 al. 2007), alignment error (Oppikofer et al. 2009) and instrument specifications
310 (Pirotti 2013). Some of these factors contribute to the random Gaussian point-to-

311 point noise (precision), and others contribute to a systematic error (Lichti and
312 Skalous 2010).

313 However, we consider the TLS dataset the reference in this relative comparison
314 because (1) within the TLS dataset, measurement errors related to the accuracy of the
315 laser are constant (0.005 m at a range of 100 m) while errors inherent in georeferencing
316 are transmitted to the whole cloud; (2) vegetation is scarce on the cliff face; (3) the
317 incidence angle is close to the normal direction and so the noise and systematic error of
318 the TLS point cloud are likely to be low.

319 For a quantitative data comparison, four calculation algorithms can be used
320 (Kromer et al. 2015): (1) M3C2 (2) mesh to point or mesh to mesh change detection (3)
321 spatial filtering (with calibration) and (4) space-time filter (with calibration). We used
322 mesh (for the TLS dataset) to point (photogrammetry datasets) because (1) the spatial
323 distribution of density from TLS, TP, and UAVP is different leading to an
324 overassessment of the distance between points; (2) the shortest distance calculation
325 enables change in different directions to be interpreted; and (3) noise is reduced through
326 the creation of the mesh of TLS data.

327 **4 Results and discussion**

328 ***4.1 Global quality assessment***

329 The characteristics of the resulting point clouds differ from one method to another
330 (Table 2). As shown in Figure 7:

- 331 • The spatial distribution of the density is highly variable within the TLS point
332 cloud due to the positions of the TLS stations. The most homogeneous densities
333 are unsurprisingly UAVP and TP not only because of subsampling but also

334 because of the *modus operandi*, with a moving point of view during data
335 collection. UAVP has the most homogeneous density due to the automatic
336 snapping every 2 s.

- 337 • The best spatial coverage is observed for the UAVP model with no occlusion.

338 With the subsampled fitted (SF) point clouds, the comparisons of TP_SF and
339 UAVP_SF datasets with the TLS dataset highlight the low error value (millimeter to
340 centimeter values), which is relevant to observe debris falls. The mean error value is
341 mainly from 0.013 m to 0.03 m (Figure 8c and d). However, artifacts on datasets have
342 values superior to 1 m. These artifacts could be partially due to the error-assessment
343 method overestimating the error when the point cloud density is drastically different
344 between the compared datasets (because of occlusion).

345 Over the whole datasets, the mean error value is of 0.005 m for the TP model,
346 whereas it is of 0.014 m for the UAVP one. Thus, the TP model is more precise than the
347 UAVP one relative to the TLS reference. Nevertheless, the standard deviation is lower
348 for the UAVP_SF model than for the TP_SF one, so the dispersion of the measurement
349 error is lower (Table 3). In our comparison, the most important issue is to have a low
350 measurement error dispersion in order to obtain a reliable dataset (Figure 8a and b), and
351 so, for this purpose, the UAVP dataset appears to be the most relevant.

352 During data acquisition, the three datasets may suffer from occlusion due to
353 terrain factors (rock falls, overhanging areas, hollow areas, vegetation, and caves).
354 Occlusion is minimized with the TP and UAVP surveys relative to the TLS surveys
355 because the SfM-MVS survey covered the whole cliff face thanks to a greater number
356 of points of view. The UAV flight provides the largest number of cliff-face views and
357 can avoid the concern about overhanging. With the TLS surveys, time limitations
358 determine the number of possible tripod set-ups meaning that gaps may occur in the

359 final point cloud owing to occlusion. In such a context, a small number of targets are an
360 important issue because decreasing the duration per station will improve the spatial
361 coverage and the accuracy of the TLS surveys (Jaud et al. 2017a).

362 *4.2 Local quality assessment*

363 In the previous data comparison, when a point in one dataset is situated in a zone
364 without data (due to occlusion) in the compared dataset, the point to mesh distance is
365 measured relative to the nearest point, introducing an overestimation of the error. To
366 avoid this, we defined strips of the cliff face (Figure 9) considered to be without
367 artifacts in the error assessment (without vegetation, rock falls, complex morphology,
368 occlusion, etc.).

369 First, for all cliff-face strips, both data comparisons give nearly the same mean
370 error (0.015 m for TP-TLS comparison and 0.016 m for UAVP-TLS comparison) and
371 standard deviation values (0.031 and 0.026 m, respectively, for TP-TLS and UAVP-
372 TLS comparisons). So, without occlusion, the results from both methods seem to be
373 comparable.

374 Second, the mean error values are similar between the whole cliff face and strips
375 for UAVP (0.014 and 0.015 m, respectively). The standard deviation is slightly lower
376 for the strips than for the whole cliff face (0.026 against 0.037 m) due to surface
377 homogeneity, which limits overestimation. For TP, the results are different. The mean
378 error value is higher for the strips than for the whole cliff face (0.016 and 0.005 m,
379 respectively), whereas the standard deviation is lower for the strips than for the whole
380 cliff face (0.031 and 0.05 m, respectively). This means that occlusion significantly
381 affects the TP results. UAVP appears to be a more reliable and stable method whichever

382 surface is studied (cliff-face morphology, vegetation, etc.) whereas TP is much more
383 sensitive to roughness.

384 *4.3 Elements for choosing a relevant survey method*

385 According to our results, the choice of a suitable method for cliff erosion monitoring
386 depends on many criteria that are summarized in Table 4.

387 The main advantages of TLS are the precision of the data and the low dispersion
388 due to the consistency of the dataset (including the georeferencing step). Another
389 advantage is the long battery life, which enables many surveys to be carried out,
390 especially if the distance between stations can be increased to cover a larger area and a
391 single target can be used per survey (visible from every TLS station). The main
392 disadvantages of TLS remain the very expensive purchase and maintenance costs and
393 the weight. TLS field campaigns have low ability to implement survey because the
394 stations have to be close to the area of interest and the instrument is heavy (50 kg
395 including instruments, cases, batteries, a tripod and targets) and cumbersome. Easy
396 access to the area is necessary. Moreover, the weather conditions are a restraining factor
397 (in addition to tide times) since the instrument is highly sensitive to rain, wind, and fog,
398 which may be frequent in coastal areas (Table 4). The alternative of a hand-held mobile
399 laser scanner, which has been recently used for cliff-erosion monitoring (James and
400 Quinton 2014), could overcome the portability concern but the purchase of new material
401 is not desirable.

402 The main strengths of TP are very long battery life, very low sensitivity to bad
403 weather, very good ability to implement survey, and low cost. Because this method
404 needs a light instrument, which has a low energy consumption, the survey can be done
405 with the highest battery life. Thanks to these major advantages, the survey can be highly

406 reactive and easily carried out before/during/after a morphogenesis event. The main
407 weaknesses are the dispersion of the data and the processing duration (Table 4).

408 The main strengths of UAVP are the modus operandi, which can be adapted to
409 the configuration of the study area (very high flexibility in the ability to capture the
410 interest area) and very high speed of data acquisition. With a UAV pilot, sites that are
411 difficult to access can be monitored since the take-off and landing can be in the
412 hinterland. With a suitable flight plan, the distance-to-target can be varied to avoid
413 occlusion due to topographic complexities (Abellan et al. 2016). However, having a
414 pilot available (a key skill) can be a major constraint and weather conditions have to be
415 dry, with neither strong wind nor fog. Mild weather conditions may be a limiting factor
416 in coastal zones. Moreover, as TP, the duration of data processing may be longer than
417 for the TLS data (Table 4).

418 In the context of the observatories, the camera network (photo or video) could
419 be a complementary approach. More precisely, this instrumentation would not be used
420 for a precise quantification of observed changes but seems more suitable for a site of a
421 hundred meters maximum to capture erosion events because of its higher temporal
422 resolution. In fact, the time sampling of the TLS, PT, and UAVP surveys does not
423 provide this kind of information. The precise time of the observed change is important
424 to constrain the driving forces and, if possible, identify the triggering factor. Moreover,
425 with this information, a quantification survey can be planned when necessary. Thus,
426 video monitoring, combined with the precise quantification of changes thanks to TLS,
427 UAVP or TP, could improve the understanding of the agents and processes responsible
428 for cliff erosion and failure forecast. However, deployments of video cameras are not
429 possible everywhere because of the site configuration. A camera network needs to be

430 installed on a fixed support (e.g., on large rocks that can protect cameras from waves,
431 spray and abrasion) with a suitable view angle (embayed coast).
432 Each of the techniques presented in this paper has different strengths and weaknesses.
433 The choice of the instrument(s) (it could be a combination) to carry out monitoring
434 depends on the required precision, the costs, the site configuration (accessibility, height,
435 danger, morphology, etc.), the time, the people and skills available, as well as the
436 weather conditions and legal framework (for UAV).

437 **5 Conclusion**

438 Because the precision of a centimeter range (mean error value from 0.013 to 0.03 m) is
439 reached by the TP and UAVP, these can be seen as complementary methods to TLS
440 cliff erosion monitoring in Normandy. However, it should be remembered that TP is
441 sensitive to roughness, which can increase the standard deviation of data. Moreover, in
442 order to obtain textured models of good quality, SfM-MVS models are clearly better
443 than those of TLS. Because the TLS survey is cumbersome and expensive, the lower
444 costs of TP or UAVP seem attractive. However, it is important to bear in mind that the
445 choice is specific to accuracy expectations; the site configuration (accessibility, height,
446 danger, morphology, etc.); the time available to do the survey; the people and skills
447 available; financial resources; weather conditions and the legal framework (for UAV).
448 For our cliff erosion survey, TLS remains a good option because the methodological
449 framework can be improved (e.g. a single target) but UAVP is an interesting alternative:
450 (1) with a large spatial coverage in a few minutes with numerous viewpoints that avoid
451 occlusion; (2) a lighter weight and a higher flexibility in the ability to capture interest
452 areas than TLS; and (3) easy site access because the take-off and landing can occur in
453 the hinterland. However, this method needs a qualified pilot and if the area of interest is

454 near sensitive stakes (houses, airports, etc.), it could take time to obtain the flight
455 authorization. Another main weakness is its high sensitivity to weather conditions
456 (especially wind and rainfall), which can delay many surveys in the coastal zone.
457 Therefore, if a reactive method is needed, TP could be a good option. Despite some
458 drawbacks, SfM-MVS has changed topographic data collection in a wide range of
459 environmental settings and should have a bright future because of technical
460 developments in the devices and software.

461

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602 California." *Geomorphology* 228: 200–212.

603

604 **Tables**

Method	Number of points	Surface (m²)	Average density per m² on the cliff face	Sampling distance on cliff face for the raw point cloud
Terrestrial photogrammetry (TP)	124,757, 214	13,897	8,977	Irregular: mean of 1 point every 0.0105 m
UAV photogrammetry (UAVP)	59,418,289	15,535	3,824	Regular: mean of 1 point every 0.016 (mean)

Terrestrial laser scanning (TLS)	2,553,230	14,190	178	Irregular: mean of 1 point every 0.06 m (mean)
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605 Table 1. Main characteristics of raw datasets

		TLS	TP_SF	UAVP_SF
Main characteristics	Number of points	2,264,742	2,030,389	2,160,790
	Mean density (per m²)	293 (± 159)	183 (± 17)	171 (± 15)
	Density interval per m²	1-657	1-355	1-396
Advantages		Few occlusions (except caves where the TLS station is not well positioned)	Homogeneous density (less than UAVP because manual snapping is more irregular)	Homogeneous density and there are no occlusions at cliff top and cliff foot
Disadvantages		Heterogeneous density due to TLS stations and there are some occlusions due to rock fall and hollow terrain	Occlusions (overhanging areas at cliff top, rock fall at cliff foot)	

606 Table 2. Characteristics, advantages and disadvantages of the TLS, TP and UAVP point
607 clouds (after subsampling and cleaning)

	TP point cloud vs. TLS mesh		UAVP point cloud vs. TLS mesh	
	Mean error	Standard deviation	Mean error	Standard deviation
Whole cliff face	0.005	0.05	0.014	0.037

608 Table 3. Mean error and standard deviation values (m) between TP and UAVP whole
609 cliff-face point clouds vs. TLS mesh

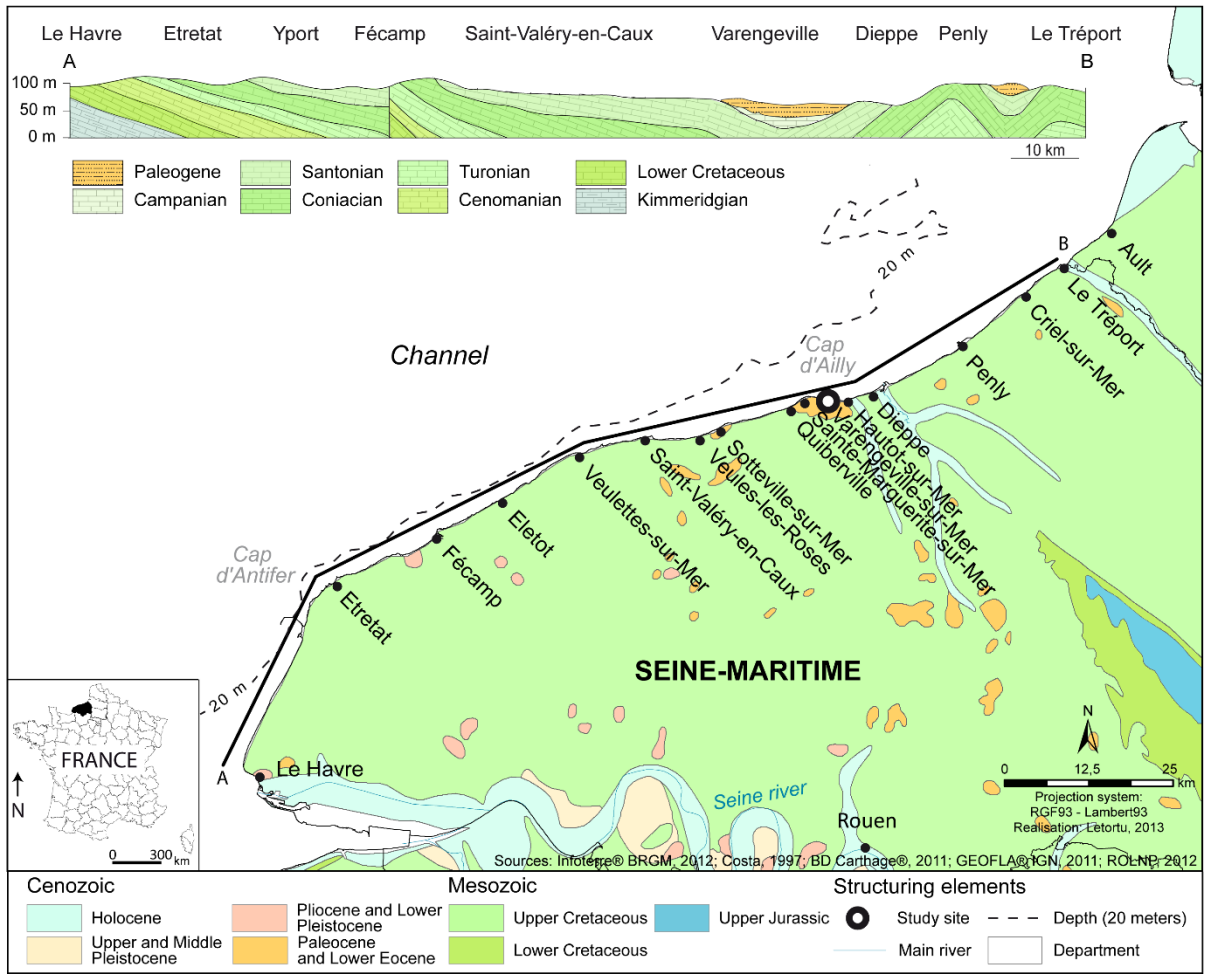
	TLS (Riegl® VZ-400 or similar)	TP (Nikon D800 or similar)	UAVP (DS6 + Nikon D800 or similar)

Precision	high	low	high
Purchase and maintenance costs	very expensive (purchase: 150 k€)	cheap (purchase: 1.5 k€)	expensive (purchase: 10 k€)
Weight (instruments and targets)	very heavy (33 kg)	light (5 kg)	heavy (9 kg)
Battery life	long	very long	short
Speed of data acquisition	low	low	very high
Sensitivity to occlusion	high	high	very low
Sensitivity to bad weather (rainfall, wind)	high	very low	high
Number of man/days	high	low	high
Ability to implement survey (targets, pilot, station location)	poor	very good	good
Flexibility in the ability to capture the interest area (overhanging, caves, etc.)	low	low	very high
Level of acquisition skill needed	high	high	very high
Acquisition duration	long	long	short
Processing duration	long	very long	very long

610 Table 4. Summary of strengths (significant strengths in green in the online version, light
611 gray in the print version) and weaknesses (significant weaknesses in red in the online
612 version, dark gray in the print version) of TLS, TP and UAVP methods for Normandy
613 cliff erosion monitoring

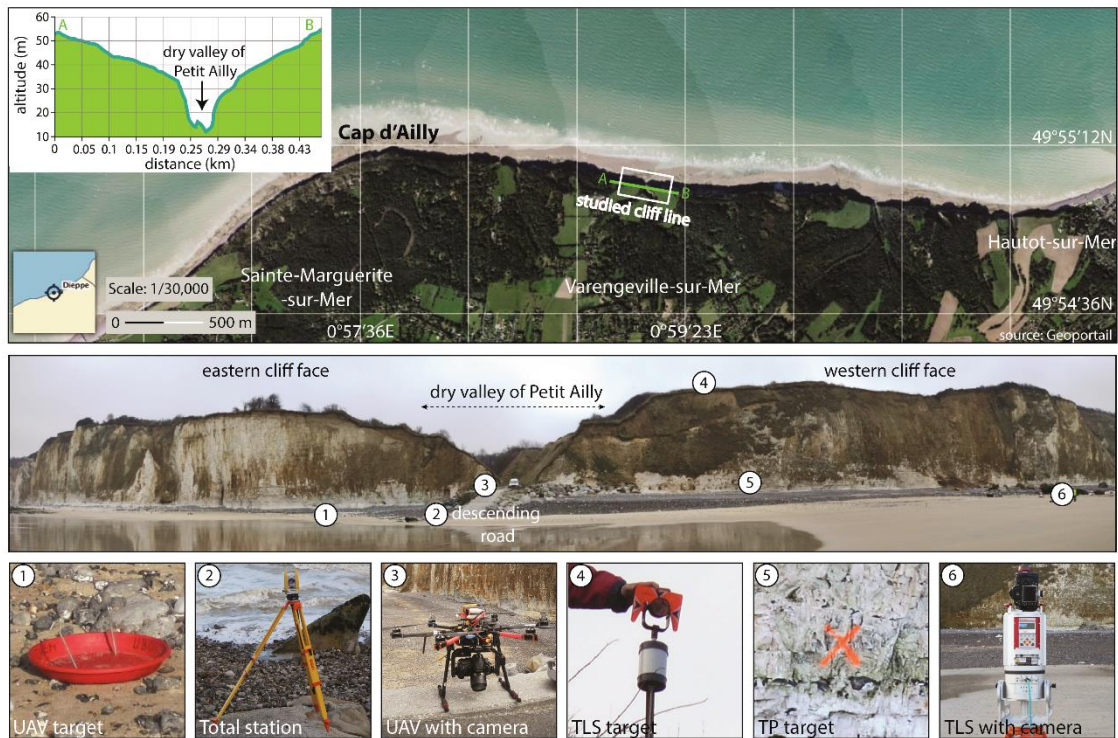
614

615 **List of figures**



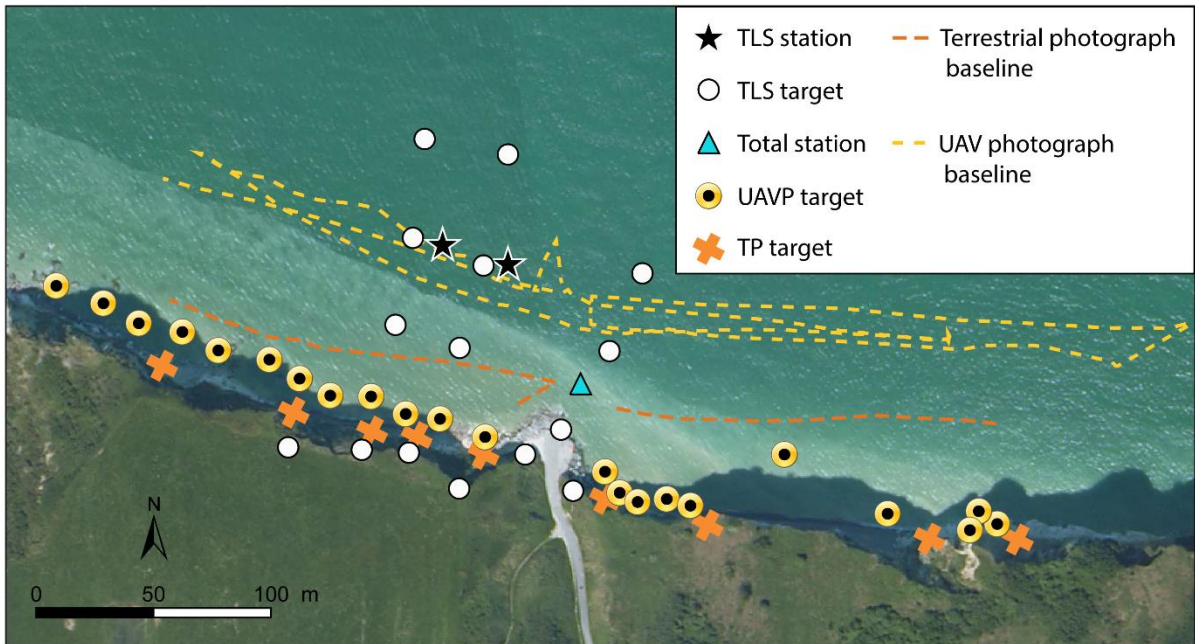
616

617 Figure 1. Presentation of the study area



618

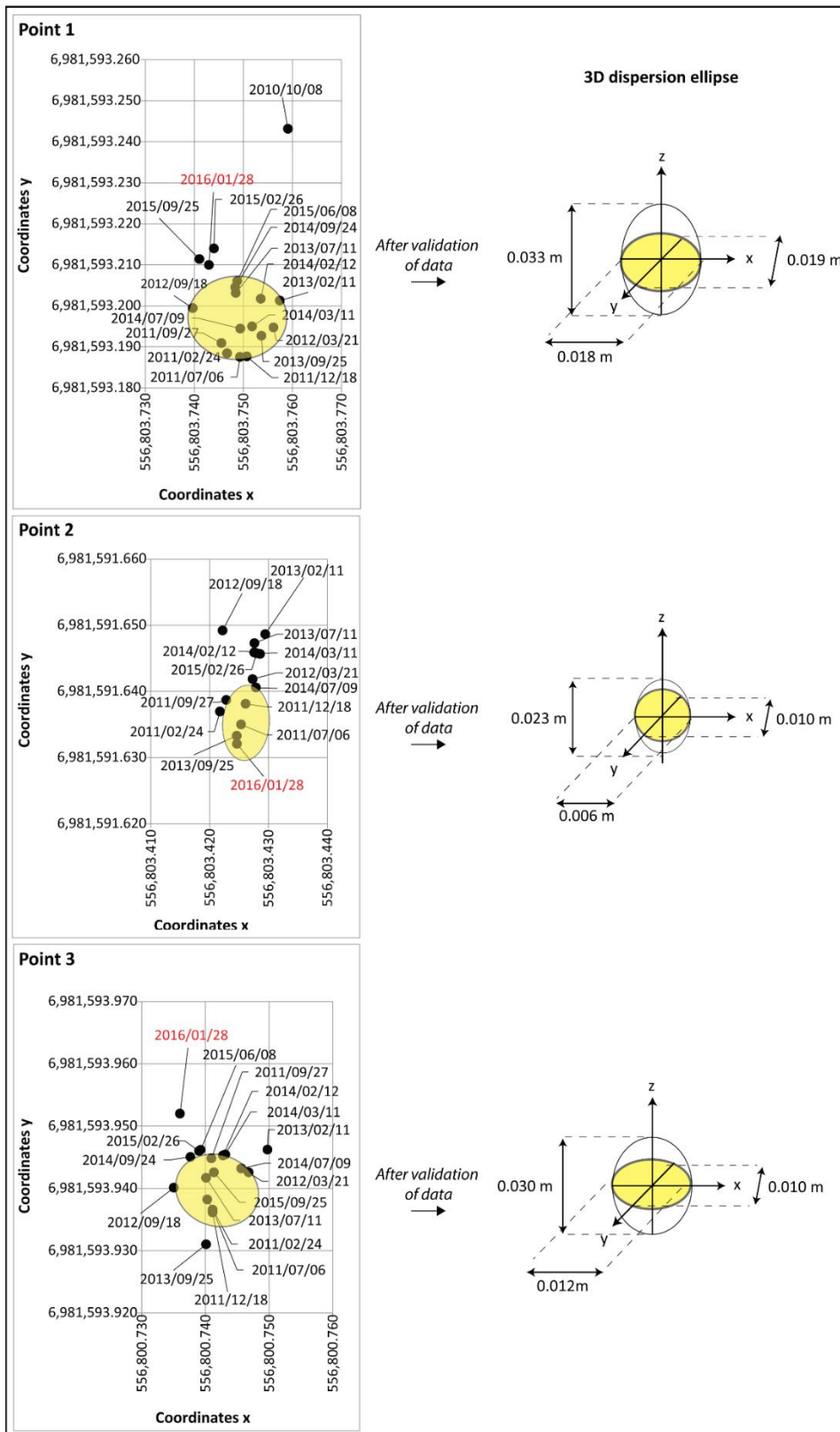
619 Figure 2. Panorama of Petit Ailly cliff face (Varengueville-sur-Mer) and instrumentation
 620 used for the survey (28 January 2016)



621

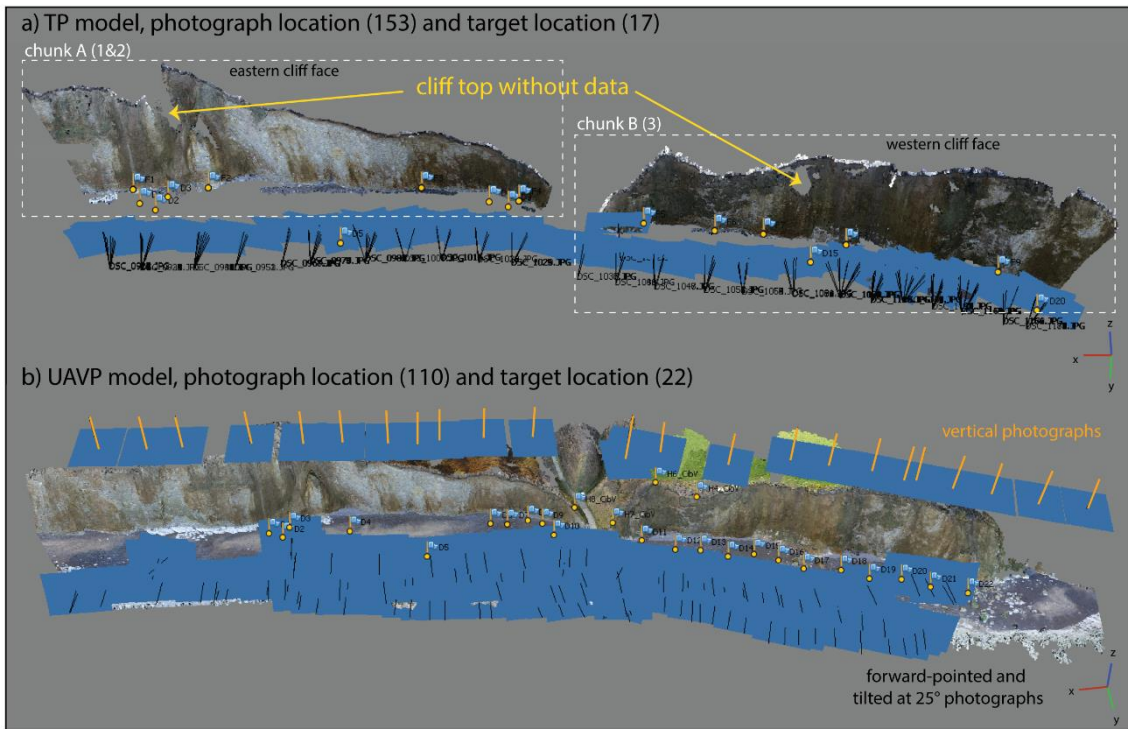
622 Figure 3. Location of the instruments, GCPs and protocol for the survey (28 January
 623 2016) (cliff-top view)

624



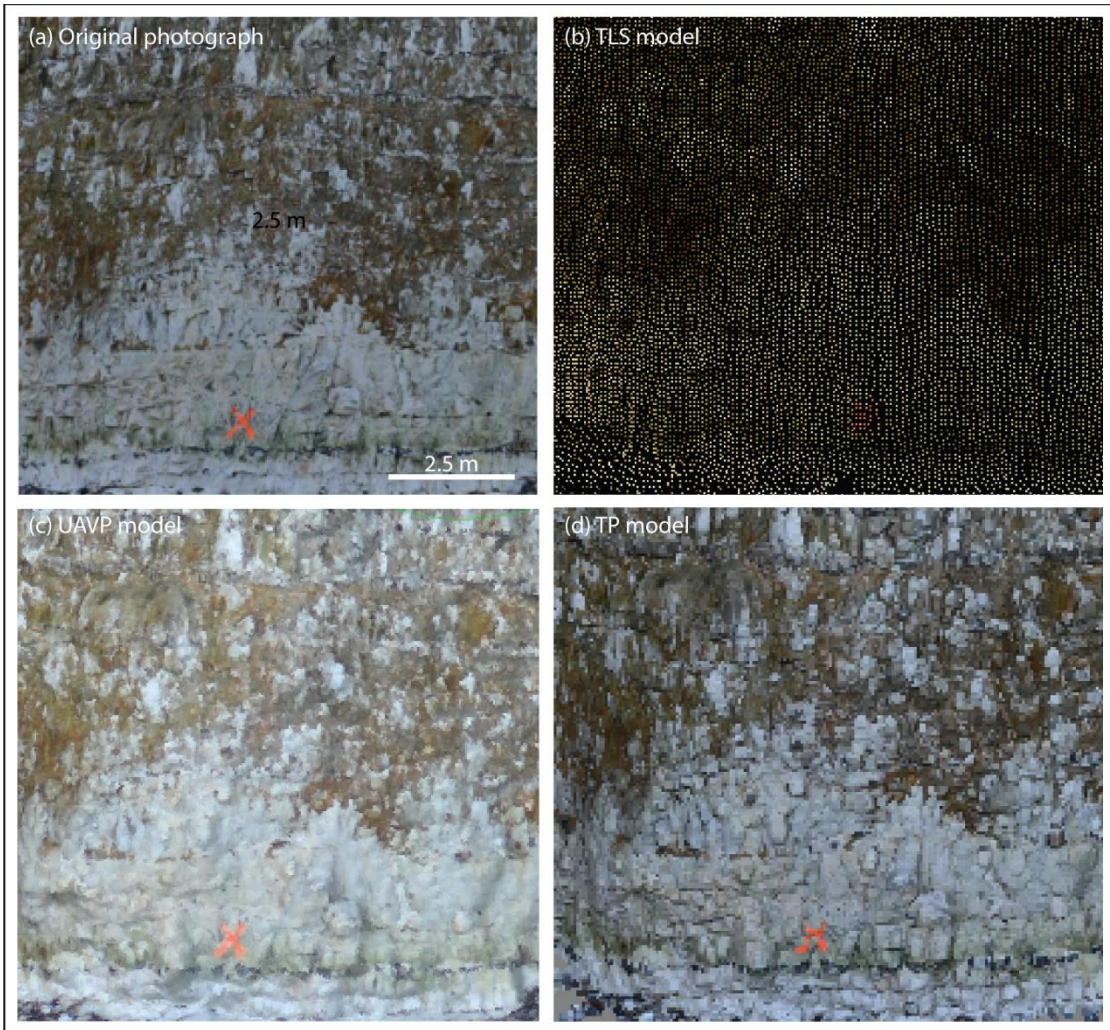
625

626 Figure 4. Maximum dispersion ellipses measured by the total station at surveyor nails
 627 for the long-term monitoring (the survey used in this paper is depicted in orange in the
 628 online edition)



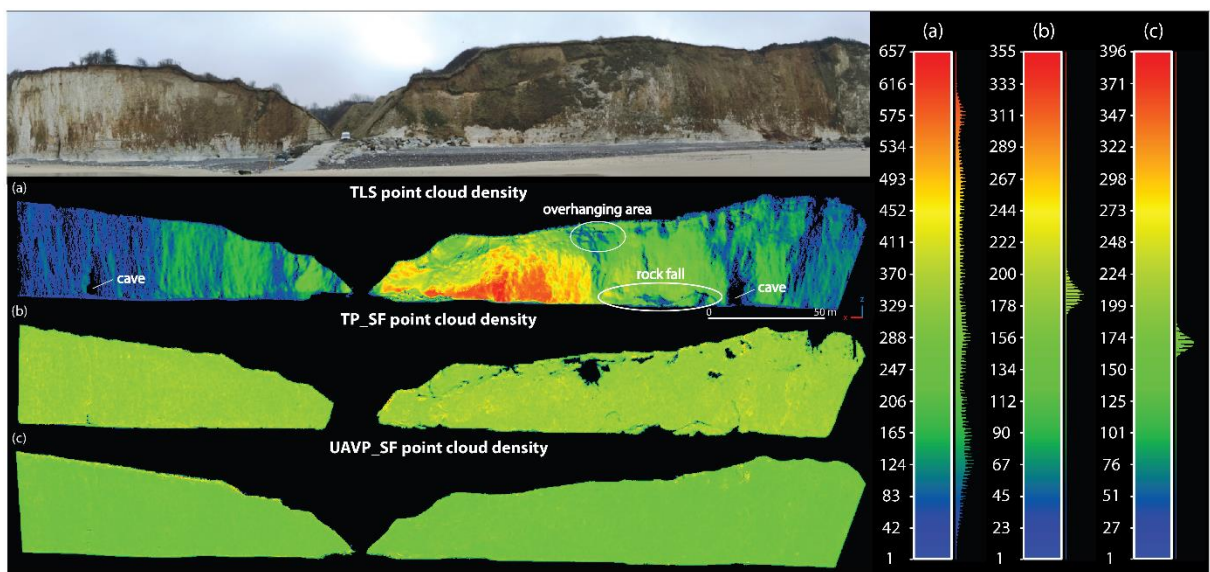
629

630 Figure 5. Location and overlap of photographs, location of GCPs, and TP and UAVP
 631 models



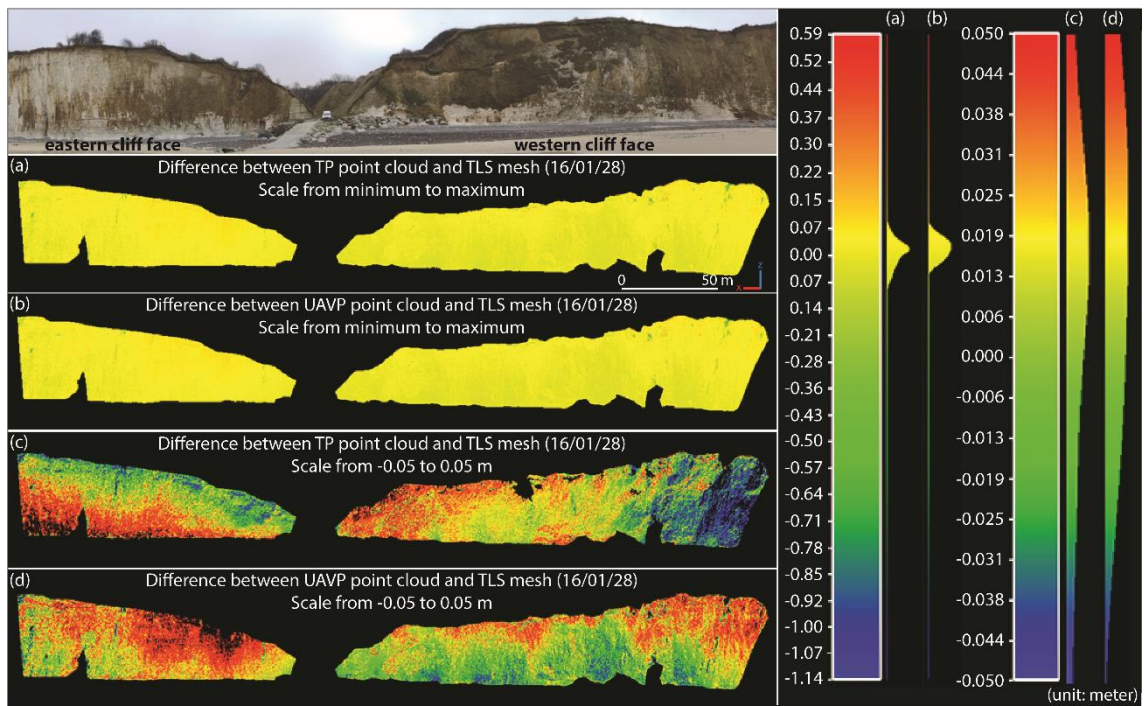
632

633 Figure 6. Cliff face zoom from (a) original photograph, (b) TLS model, (c) UAVP
 634 model and (d) TP model



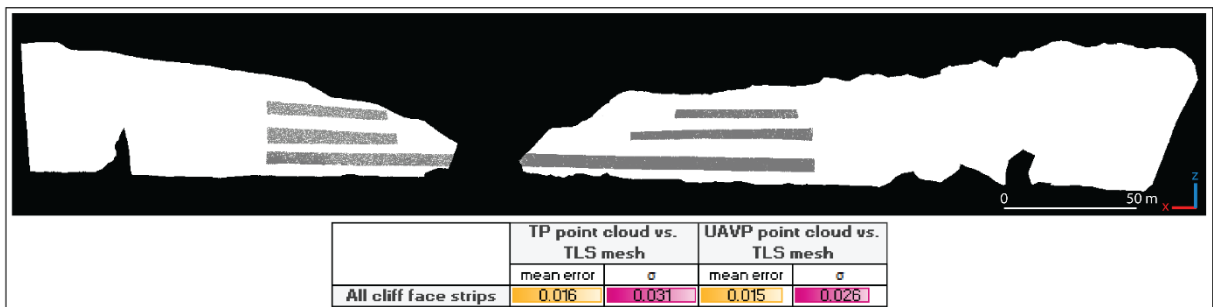
635

636 Figure 7. Density of point clouds per m² (TLS, TP, UAVP)



637

638 Figure 8. Distribution of difference between datasets over the cliff face



639

640 Figure 9. Comparison between all cliff-face strip error values and standard deviation

641

642

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647

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