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1 **Marine and Subaerial Controls of Coastal Chalk Cliff Erosion in Normandy (France)**  
2 **Based on a 7-year Laser Scanner Monitoring**

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12

13 Abstract:

14 Between October 2010 and November 2017, surveys using terrestrial laser scanning (TLS)  
15 were carried out every 4-5 months to monitor erosion on three chalk cliff faces with close  
16 structural characteristics in Normandy (the two Dieppe sites are abandoned cliffs while the  
17 Varengueville-sur-Mer site is an active one). The uniqueness of this paper is the comparison  
18 between these cliff sections and the significance of marine and/or subaerial controls in  
19 erosion. Beyond the quantification of annual retreat rates, which on the active cliff are  
20 currently 36 times greater than on the abandoned cliffs, this paper highlights the fundamental  
21 efficacy of marine controls in the current cliff erosion and the removal of falls (analyses of  
22 modalities of retreat and profile evolution according to a naturalistic approach). Subaerial  
23 processes appear to have a less erosive action than marine ones, because the studied  
24 abandoned cliffs show low erosion dynamics and have maintained a subvertical profile  
25 despite continentalization for between 30 to more than 120 years.

26

27 Keywords: Marine processes; Subaerial processes; Cliff erosion; Terrestrial laser scanning  
28 (TLS).

## 30 **1. Introduction**

31 The retreat rates, the modalities of erosion (frequency, intensity, and spatial distribution), and  
32 the cliff profile depend on the morpho-structural conditions and the efficacy of marine and  
33 subaerial agents and processes (Emery and Kuhn, 1982). Improving understanding of  
34 erosion is necessary because coastal cliff dynamics are inherently non-linear. Nothing  
35 happens for several years and suddenly a fall can occur and may cause fatalities and  
36 damage to infrastructure close to cliff line. One of the challenges in the research is to foresee  
37 coastal evolution to ensure the resiliency of coastal communities (e.g. Gilham et al., 2018).  
38 Research contributions into the dynamics of rocky coasts in recent years allow for a better  
39 understanding of retreat rates in a variety of locations worldwide (Brooks and Spencer, 2010;  
40 Bezore et al., 2016; Sajinkumar et al., 2017; Young, 2018), the identification of factors  
41 responsible for erosion (for a review, Kennedy et al., 2014a) and of some precursor signs  
42 before failure (Rosser et al., 2007), but knowledge of the respective contributions of  
43 triggering factors responsible for erosion are still difficult to determine (Costa, 2005; Naylor et  
44 al., 2010; Lim et al., 2011; Kuhn and Prüfer, 2014; Letortu et al., 2015a) even though some  
45 research has been successful in prioritizing factors (Bernatchez and Dubois, 2008;  
46 Bernatchez et al., 2011). In the northeastern part of Normandy (NW France), along the  
47 Channel, the plateaus of the Parisian Basin abruptly end in subvertical cliffs made up of  
48 Upper Cretaceous chalk with flint bands. The cliff line in Seine-Maritime had an average  
49 retreat rate of 0.15 m/year between 1966 and 2008 (Letortu et al., 2014) and has been  
50 increasingly monitored for a better understanding of erosion (e.g. Prêcheur, 1960; Evrard  
51 and Sinelle, 1987; Costa, 1997; Hénaff et al., 2002; Costa et al., 2004; Mortimore et al.,  
52 2004b; Regard et al., 2012; Rohmer and Dewez, 2013 ; Letortu et al., 2015b). On this chalky  
53 coast, there is a broad consensus on the role of lithological control and intense rainfall events  
54 as the main drivers of erosion. The trigger for falls often coincides with heavy winter rainfall  
55 (Duperrret et al., 2002; Letortu et al., 2015a) particularly during wet years that cause the  
56 water table to rise in the chalky massif (Lageat et al., 2006) or during heavy rainfall during

57 dry periods (Duperret et al., 2004). However, a significant erosion factor on both the cliff and  
58 shore platform is the role of freeze/thaw cycles (Moses et al., 2006; Dewez et al., 2015;  
59 Letortu et al., 2015a). Lageat et al. (2006) concluded that subaerial processes were the main  
60 processes responsible for the triggering of chalk cliff falls on the French Channel coast and  
61 that marine influence was limited to the removal of falls. This has been questioned in recent  
62 years because numerous researchers have highlighted the role of marine factors, both as an  
63 eroding agent and as a removal agent to reactivate erosion (Hénaff et al., 2002; Earlie et al.,  
64 2015; Letortu et al., 2015a; 2015b). To feed the debate, our previous research used  
65 statistical analyses (adjustment to power law scaling (Letortu et al., 2014) and multivariate  
66 analysis as PCA) and empirical analyses to identify the triggers of coastal chalk cliff failure  
67 based on an inventory of 331 rock falls collected weekly between 2002 and 2009 from  
68 Veules-les-Roses to Le Tréport (37.5 km, Seine-Maritime). The results highlighted that 'cold  
69 and dry weather', 'high rainfall and high wind' are the conditions most likely to trigger rock  
70 falls (Letortu et al., 2015a). To go one step further and identify the dominance of marine or  
71 subaerial forcing, the current research analyzes retreat rates, modalities of retreat  
72 (frequency, intensity, and spatial distribution) and cliff profile evolution based on a 7-year  
73 monitoring project using Terrestrial Laser Scanning (TLS) of three cliff faces with close  
74 structural characteristics (lithology, stratigraphy, and tectonics) but different exposures to  
75 marine processes (abandoned and active cliffs).

76

## 77 **2. Study area**

### 78 *2.1. Regional settings*

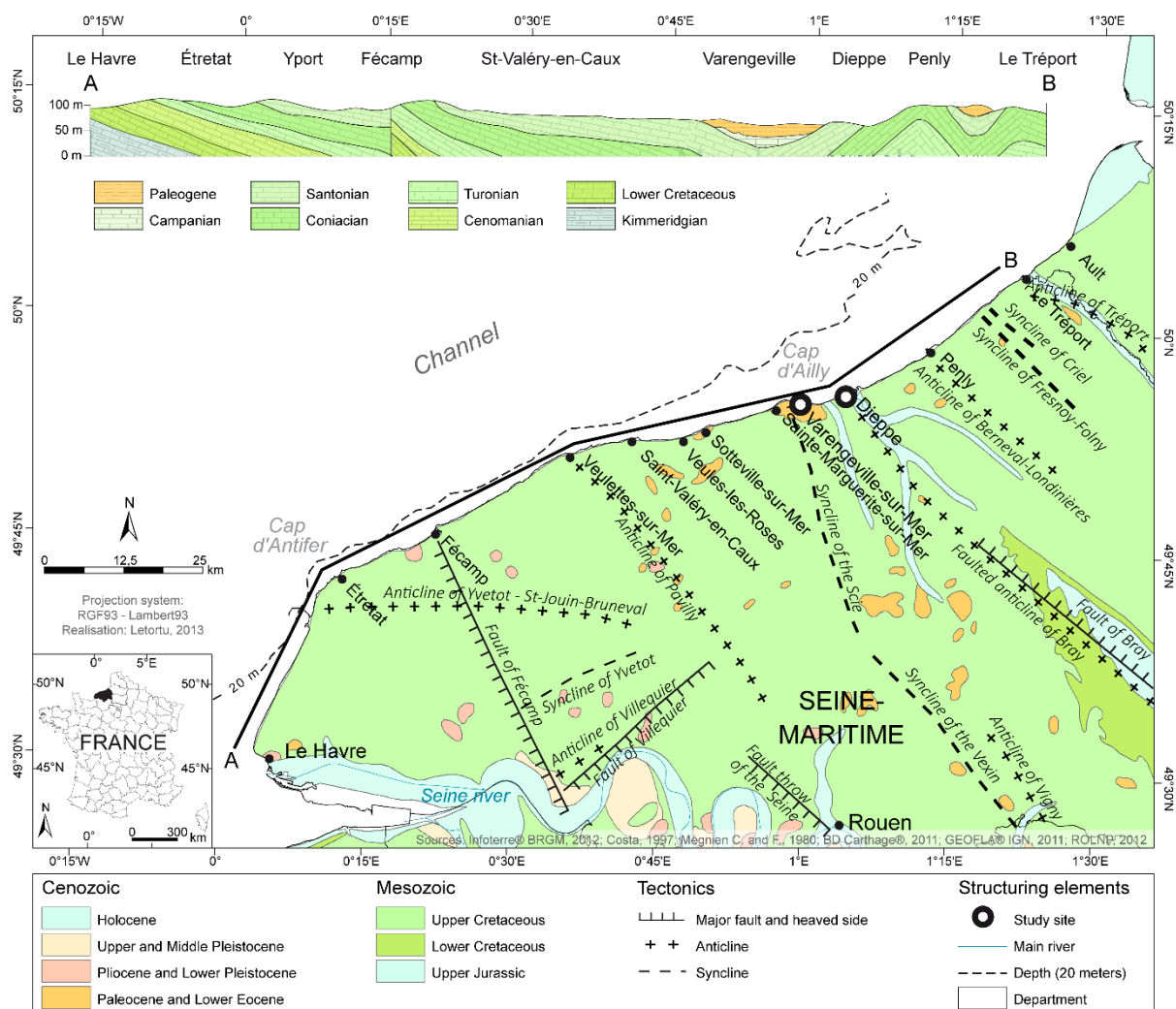
79 The study area is of three Norman cliff sections along the Channel (Seine-Maritime): one cliff  
80 face in Varengeville-sur-Mer and two others in Dieppe (Fig. 1). The climate is a marine  
81 temperate west coast climate with mild temperatures throughout the year (4.9°C in January  
82 and 16.9°C in August according to Météo-France (1971-2000)). Temperatures in winter are  
83 positive (the coldest month is January with 4.9°C) but freeze/thaw cycles can be numerous  
84 (an average of 26 daily freeze/thaw cycles per year) and frost can be intense (up to -15°C).

85 Rainfall occurs throughout the year (about 800 mm) but the wettest month is November, with  
86 93.8 mm, and the driest is August, with 50.6 mm. However, in August, thunderstorms may  
87 occur and lead to a maximum daily rainfall of 100.8 mm. Wind is frequent with a total of  
88 102.8 days per year with gusts greater than or equal to 16 m/s, especially in December and  
89 January. The average tidal range is 8 m and swell is limited. However, wave height due to  
90 wind sea can reach 4 m in Dieppe (annual return period) (Augris, 2004).

91 The topography of the Seine-Maritime is characterized by the Pays de Caux plateau  
92 (average altitude of 150 m) extending to the Channel, an Upper Cretaceous cliff line made up  
93 with chalk with flint bands, oriented SW/NE. This plateau is dissected by valleys and dry  
94 valleys. The valleys are quite wide (kilometer extent) and are former alluvial plains. This  
95 plateau presents different deformations with a succession of anticlines and synclines, in a  
96 NW/SE direction (Armorican direction), sometimes prolonged by flexures and faults (Cavelier  
97 et al., 1979; Mégnien and Mégnien, 1980; Cazes et al., 1985; Pomerol and Feugueur, 1986;  
98 Cavelier and Lorenz, 1987) (Fig. 1). A topographic saddle, which corresponds to the  
99 northwestern termination of the “Norman gutter” (the exhumed anticlinal inlier of the Pays de  
100 Bray, in the hinterland of Dieppe, constitutes a geographical entity that extends south to  
101 Picardy) follows the syncline of the Vexin and extends to that of the Scie.

102 Cliffs from cap d’Antifer to Le Tréport (100 km) have an average height of 60-70 m but the  
103 structural variations explain the variations of height (from 20 m to more than 100 m; Fig. 1) of  
104 chalk stage outcrop (from the oldest to the newest stages: Cenomanian, Turonian,  
105 Coniacian, Santonian and Campanian). The subtle resistance contrasts of chalk outcrop  
106 explain different profiles of the cliffs (Pomerol et al., 1987; Costa, 1997; Mortimore et al.,  
107 2004b) and mostly explain the high spatial variability of the retreat rates (from 0.09 to 0.23  
108 m/year ( $\pm 0.03$  m/an; 1966-1995-2008)) obtained by photo-interpretation (Costa et al., 2004;  
109 Letortu et al., 2014). The retreat rate is the highest where, above Santonian and Campanian  
110 chalk strata, the residual flint formation (Pomerol et al., 1987; Laignel, 1997; Costa et al.,  
111 2004) has been replaced by a bed of clay and sand sediments about 10-30 m thick from the

112 Paleogene period (Bignot, 1962). This bed is mainly along the cap d'Ailly (Sainte-Marguerite-  
 113 sur-Mer, Varengeville-sur-Mer), and Sotteville-sur-Mer (Fig. 1).  
 114 The pre-existing fracture network influences the rock mass strength and the mode of failure  
 115 (Middlemiss, 1983; Evrard and Sinelle, 1987; Duperret et al., 2004; Mortimore et al., 2004a).  
 116 The dominant fracture set collected on the cliff face and on the shore platform is N110-  
 117 N130E followed by N025E (Evrard and Sinelle, 1987; Genter et al., 2004; Costa et al.,  
 118 2006b). Genter et al. (2004) highlight the N110-130E fracture set is almost ubiquitous  
 119 throughout the Norman chalk coastline, made mainly of master-joints (large nearly vertical  
 120 fractures that cross the whole cliff with an apparent extension of tens to hundreds of metres)  
 121 and normal faults (typical apparent vertical offsets of cm to metre scale). Movements of  
 122 various magnitudes (from a few m<sup>3</sup> to hundreds of thousands of m<sup>3</sup>) are a ubiquitous  
 123 phenomenon along the Seine-Maritime coastline.



125 Fig. 1: Geological and structural framework in Seine-Maritime (Normandy) and the location of  
126 the studied sites. For interpretation of the references to color in this figure, the reader is  
127 referred to the web version of this article.

128

129 At the cliff foot, the shore platform has a fairly homogeneous appearance with a rocky  
130 surface and is slightly inclined towards the sea (from 0.2 % gradient at Le Tréport to 2 % at  
131 cap d'Antifer). Its width is between 100 and 750 m. In contact with the cliff foot and the shore  
132 platform, the average width of the gravel beach is about 15-20 m, with a thickness of 2-3 m.  
133 At the valley outlets, where they are supported by longitudinal sea defense structures (dikes  
134 and piers), their width may exceed 100 m and their thickness 11 m at the Dieppe jetty (Costa  
135 et al., 2006a).

136

## 137 *2.2. Site selection*

138 The active cliff at Varengeville-sur-Mer is along the cap d'Ailly (6 km from Dieppe) (Fig. 2a),  
139 on either side of the Petit Ailly dry valley. This cliff is 250 m long, 40 m high, facing 010°N,  
140 with a subvertical profile (from 70° to overhang). The historical annual retreat rate is of 0.38  
141 m/year (1966-2008 from Letortu et al., 2014).

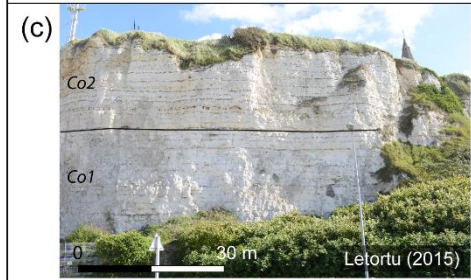
142 The abandoned cliffs at Dieppe are located on the right bank of the Arques river mouth,  
143 behind an extension of the northeastern part of the harbor, land reclaimed from the sea.  
144 Dieppe 1 W is 45 m long, 35 m high, facing 310°N, with a subvertical profile. This cliff, in front  
145 of the Newhaven–Dieppe ferry port, has a historical annual retreat rate of 0.04 m/year (1966-  
146 2008 from Letortu et al., 2014). Dieppe 2 N is 80 m long, 35 m high, facing 010°N, with a  
147 subvertical profile. The historical annual retreat rate of Dieppe 2 N is of 0.06 m/year (1966-  
148 2008 from Letortu et al., 2014). Dieppe 1 W became abandoned during the nineteenth  
149 century whereas Dieppe 2 N became abandoned in the 1980s (Fig. 2a).

150

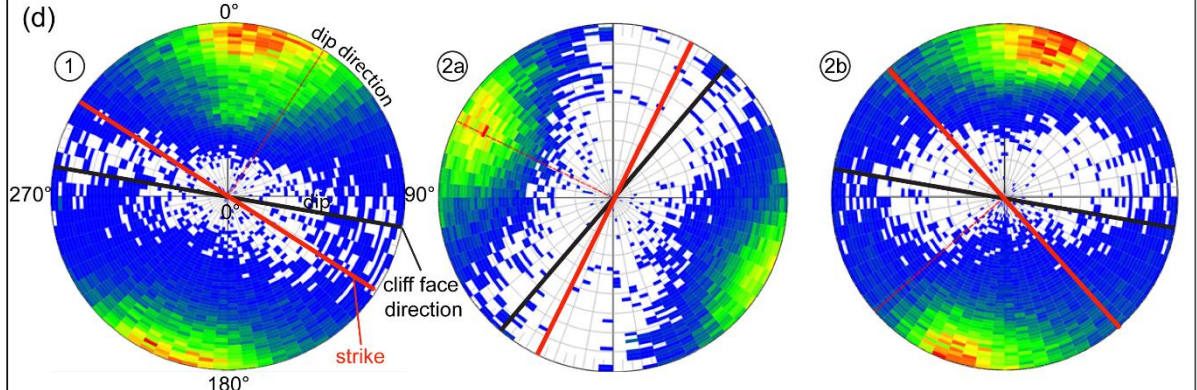




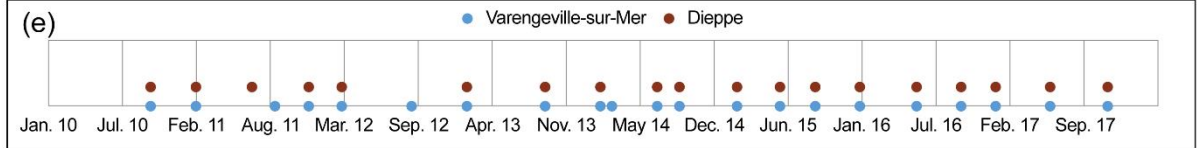
① Santonian chalk and Tertiary strata (above the white dotted line); L≈250 m; H≈40 m; 010°N  
 S2a,b,c: lower, middle and upper part of Middle Santonian (Seaford Chalk); S3: Upper Santonian (Newhaven Chalk) adapted by Hoyez (2008) from Mortimore (2001).



②a Coniacian chalk; L≈45 m; H≈35 m, 310°N  
 ②b Coniacian chalk; L≈80 m; H≈35 m; 010°N  
 Co1: Lower Coniacian (Lewes Chalk); Co2: Middle Coniacian (Seaford Chalk) adapted by Hoyez (2008) from Mortimore (2001).



Stereograms of facets extracted with FACETS in Cloudcompare® from the first 3D point cloud of each site (Dewez et al., 2016).





152 Fig. 2: (a) Location of the sites; (b) Main characteristics of Varengeville-sur-Mer site (Chalk  
 153 Formations are adapted by Hoyez (2008) from Mortimore (2001)); (c) Main characteristics of  
 154 Dieppe sites (Chalk Formations are adapted by Hoyez (2008) from Mortimore (2001)); (d)  
 155 Stereograms of each cliff section (planar facets with their strike, dip and dip direction) extracted  
 156 with FACETS in Cloudcompare® (Dewez et al., 2016); (e) Temporal distribution of the TLS  
 157 surveys.

158

159 The site at Varengeville-sur-Mer is on the Scie syncline (at 6 km west of the faulted Bray  
 160 anticline) and the sites of Dieppe are connected to the eastern part of Bray fault (Fig. 1). The  
 161 cliff lithology at Varengeville is made up of Santonian chalk, covered by a bed of clay and  
 162 sand of Paleogene period (due to the syncline prone strata preservation). Clay and sand are  
 163 very prone to erosion (Fig. 2b). The cliff section of Dieppe is made up of Coniacian chalk  
 164 covered with residual flint formation (Fig. 2c). Even if each facies within a stage has some  
 165 subtle resistance contrasts, the Coniacian chalk is close to the physical and lithological  
 166 characteristics of Santonian chalk (Laignel, 2003) (Table 1). However, Coniacian chalk is  
 167 less fine, rougher to the touch than Santonian, with conglomeratic, yellowish and hardened  
 168 chalk beds that are a little more numerous (Auffret and Bignot, 1978).

169

170 Table 1: Physical and lithological characteristics of the Coniacian and Santonian chalk  
 171 stages of the western part of the Parisian Basin (Laignel, 2003)

Stage	Facies	Porosity %	Permeability millidarcy	Density
Coniacian	white chalk (dominant facies)	22.6 - 38.3	1.1 - 2.6	1.6 - 1.7
	whitish chalk, slightly clayey (mainly at the base)			1.8 - 1.9
	nodular chalk (mainly at the base)			1.9 - 2.4
Santonian	white chalk	40.2 - 45.6	3.5 - 5.6	1.6 - 1.8
	nodular chalk (very rare)			1.9 - 2.2

172

173

174 In the studied sites, the regional set (N110-N130E) is apparent in the stereograms, with  
 175 master joints at Varengeville-sur-Mer and Dieppe 2 N (Fig. 2d). In Dieppe 1 W, the strike is  
 176 about N025E, which is the secondary fracture set observed by Genter et al. (2004). The

177 bedding dips are very low (0.5-1%) (Bignot, 1971). These fracture orientations and lithology  
178 result in falls with a dominant vertical failure type in the three sections. Infrequently, sliding  
179 failure type might occur in Varengueville-sur-Mer between Lower-Middle Santonian and Upper  
180 Santonian (Duperret et al., 2004).

181 In contact with the Bray faulted anticline (Fig. 1) the fracturing is high. Genter et al. (2004)  
182 measured, for the total of fracture types, a mean spacing between fractures of 5-10 m for the  
183 eastern part of Dieppe, against 15-20 m in Varengueville-sur-Mer. Fracturing difference may  
184 impact on rates and modalities of retreat due to "pre-cutting" of the cliff but, according to  
185 Duperret et al. (2004), the empirical relationship between numerous falls and intense  
186 fracturing is not systematic probably because the natural fracture properties and the  
187 interaction with other parameters may be more complex. Indeed, the higher value of  
188 fractures in Dieppe (5-10 m) than in Varengueville (15-20 m) does not lead to higher historical  
189 annual retreat rates. Besides, subtle differences in resistance between both stages cannot  
190 explain such contrasting regressive dynamics. This is explained by the efficacy (or inefficacy)  
191 of the external erosion forcing.

192 The studied cliff faces are characterized by: (1) Coniacian and Santonian chalk stages prone  
193 to erosion; (2) two contexts - Varengueville is an active cliff (marine and subaerial processes  
194 act together) and Dieppe is an abandoned cliff (action of subaerial processes only); (3) their  
195 proximity (distance of 6 km), assuming weather conditions are similar; (4) their verticality  
196 (from 75° to overhang), their height (35-40 m) and the linearity of the coastline; and (5) their  
197 spatial extent (from 45 m long in Dieppe to 250 m long in Varengueville-sur-Mer).

198

### 199 **3. Material and methods**

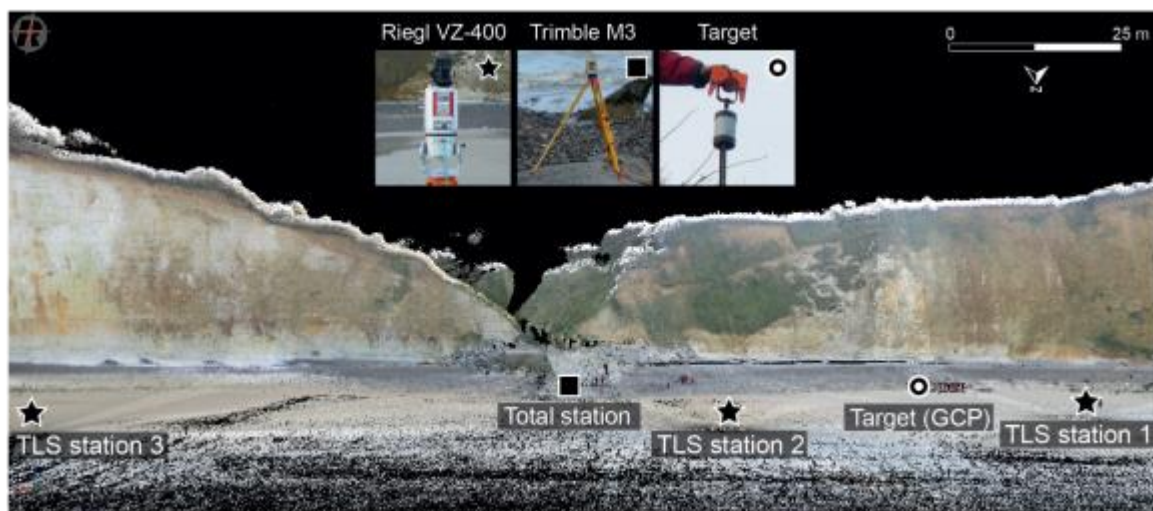
#### 200 *3.1. TLS surveys*

201 A terrestrial laser scanner is an optical active remote-sensing technology. The two-way time  
202 of flight of a laser pulse reflected by a point is used to measure the point position (range and  
203 angles) relative to the device. The laser beam covers the environment with vertical scanning  
204 by an oscillating mirror and horizontal scanning by rotating the head. This instrument is

205 widely used and numerous applications of the TLS technique on slope instabilities are given  
206 by the review of Abellán et al. (2014).

207 In Varengeville-sur-Mer, the two scanner stations are positioned on the foreshore at about 75  
208 m from the cliff face (Fig. 3). In Dieppe, the two scanner stations are precisely positioned on  
209 the ground at a horizontal distance of 33 m (Dieppe 1 W) and 37 m (Dieppe 2 N) from the  
210 subvertical cliff face respectively. The site configuration and the survey design (with one  
211 target and a Trimble M3 total station) reduce occlusion and poor incident angles and enable  
212 large spatial coverage with a very high resolution (median spacing from 0.02 m in Dieppe to  
213 0.05 m in Varengeville-sur-Mer). TLS survey is described in detail in Letortu et al. (2015b;  
214 2018).

215



216  
217 Fig. 3: Description of the instruments used for the cliff face erosion monitoring (survey of  
218 2017/11/02 in Varengeville-sur-Mer).

219

220 Since October 2010, 21 diachronic surveys have been performed in Varengeville-sur-Mer  
221 and 19 in each of Dieppe sites (every 4-5 months, 2h per site by 3 people; Fig. 2e).

222 Stabilization work on both cliff faces in Dieppe in February 2013 reduced the length of the  
223 studied areas due to rock protection meshes set up on the cliff face (from 45 m to 25 m-long  
224 for Dieppe 1 W, from 80 m to 45 m-long for Dieppe 2 N).

225

### 226 3.2. Data processing and error margin

227 Data processing has 4 steps: (1) georeferencing and point cloud alignment; (2) manual point  
228 cloud filtering (vegetation, people, foreshore); (3) meshing using Delaunay triangulation and  
229 generation of a 3D Digital Elevation Model (DEM); and (4) creating a DEM of Difference  
230 (DoD).

231 Precision is the most important parameter in our monitoring, thus all the point clouds are  
232 fitted to the 6 July 2011 reference point cloud using best fit alignment algorithms  
233 (Cloudcompare® or 3DReshaper®). This adjustment reduces the error margin because it  
234 includes the TLS instrumental error and the cloud adjustment error (fitting) only. To assess  
235 precision, fixed parts of the point cloud are compared using the usual data processing. The  
236 precision in planimetry is 0.03 m for Varengeville-sur-Mer and Dieppe 2 N and 0.02 m for  
237 Dieppe 1 W. The volume precision is  $\pm 156 \text{ m}^3$  in Varengeville-sur-Mer (surface of  $5214 \text{ m}^2$ ),  
238  $\pm 9 \text{ m}^3$  in Dieppe 1 W ( $434 \text{ m}^2$ ) and  $\pm 30 \text{ m}^3$  in Dieppe 2 N ( $1018 \text{ m}^2$ ).

239 Some disturbances occurred during data acquisition such as temporary ground vibrations  
240 due to the docking of a cross channel ferry (2011/07/06 and 2013/02/12 in Dieppe 1 W) or  
241 scanner sinking in wet sand (2011/02/24 and 2015/02/26 in Varengeville-sur-Mer). Thus,  
242 these four point clouds have artifacts and they are not used to quantify the rate of retreat, but  
243 are retained to study the spatial distribution of material departures (dates in gray in Fig. 6). In  
244 February 2013, stabilization work was carried out in Dieppe. These consisted of clearing  
245 hazardous parts of the cliff (human erosion in Fig. 5) and setting up safety nets. To monitor  
246 the natural evolution of the cliff, these human activities are not considered in the calculations.

247

### 248 3.3. Data analysis

249 This 3D dataset allows the analysis of different characteristics of the cliff face evolution such  
250 as the eroded surface and volume, calculations of retreat rates, the modalities of retreat and  
251 the profile evolution. Emery and Kuhn (1982) present the profile of active cliffs as an indicator  
252 of the power balance between the resistance and homogeneity of the material outcropping

253 on the cliff face and the combined aggressiveness of marine and subaerial agents (including  
254 ground water) associated with gravity. A steep slope at the foot of a cliff generally indicates  
255 dominance of marine erosion, while a gentle slope at the base means that subaerial erosion  
256 dominates. This classification has been included in numerous publications (e.g. Kuhn and  
257 Prüfer, 2014) and is used in this paper to identify, from a geomorphological point of view, the  
258 dominant forcing on erosion of the studied cliffs.

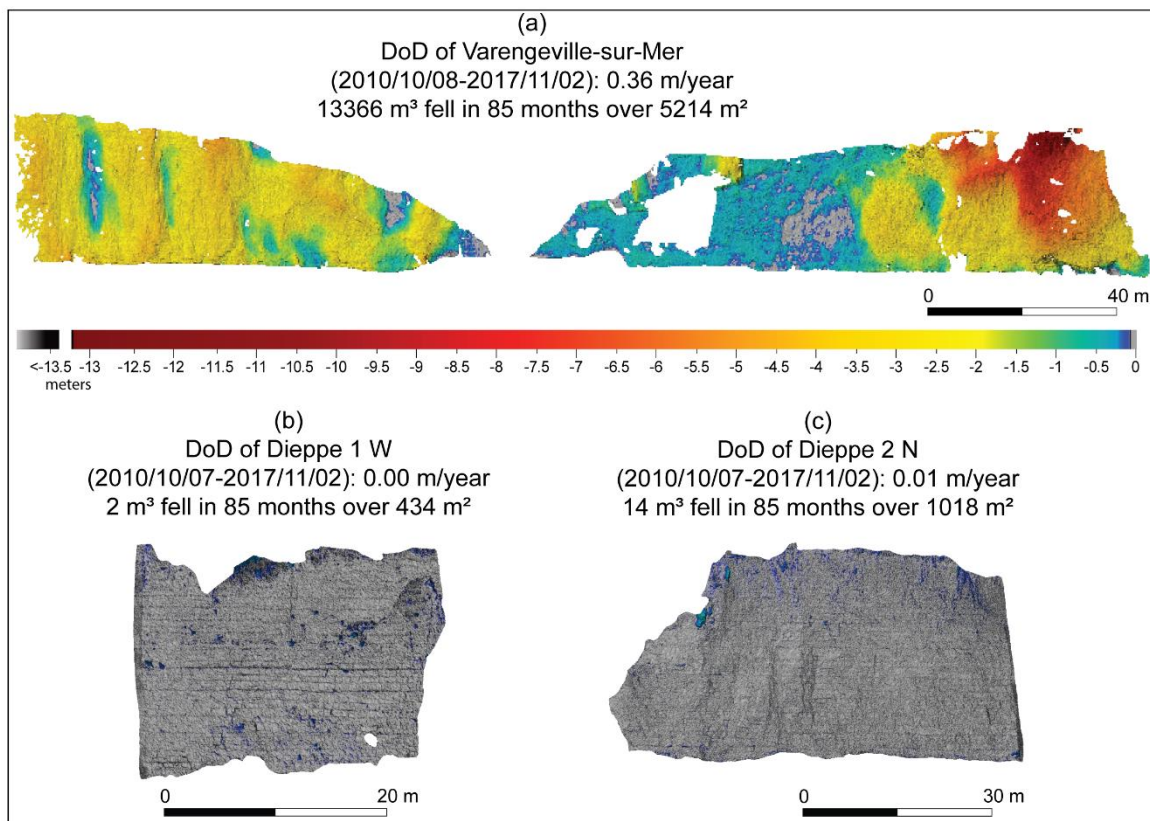
259

## 260 **4. Results**

### 261 *4.1. Annual retreat rates*

262 Unsurprisingly, the wave-battered cliff currently retreats faster than the abandoned ones but  
263 with a significant difference: 36 times faster than Dieppe 2 N. The annual retreat rate is 0.36  
264 m/year in Varengeville-sur-Mer ( $13366 \pm 156 \text{ m}^3$  fell in 85 months over  $5214 \text{ m}^2$ , thus an  
265 average fall volume of  $1887 \text{ m}^3/\text{year}$ ). It is 0.00 m/year in Dieppe 1 W ( $2 \text{ m}^3 \pm 9 \text{ m}^3$  fell in 85  
266 months over  $434 \text{ m}^2$ , thus an average fall volume of  $0.3 \text{ m}^3/\text{year}$ ) and 0.01 m/year in Dieppe  
267 2 N ( $14 \text{ m}^3 \pm 30 \text{ m}^3$  fell in 85 months over  $1018 \text{ m}^2$ , thus an average fall volume of  $2 \text{ m}^3/\text{year}$ )  
268 (Fig. 4). Despite the very high precision of the method presented in this study, this  
269 quantitative assessment may not be representative for the abandoned cliffs because erosion  
270 results are below the margin of error. However, these annual retreat rates on the cliff face  
271 observed by TLS over seven years are close to those observed by the cliff top photo-  
272 interpretation between 1966 and 2008 (Letortu et al., 2014) with 0.38 m/year in Varengeville  
273 and 0.04-0.06 m/year in Dieppe. Taking into account the error margin of  $\pm 0.03 \text{ m/year}$  of the  
274 photo-interpretation method, the 2010-2017 TLS results seem to be representative of the  
275 historical retreat rate values (42 years, 1966-2008).

276



277

278 Fig. 4: Erosion results of DoD over 7 years of monitoring at each of the sites. For interpretation  
279 of the references to color in this figure, the reader is referred to the web version of this article.

280

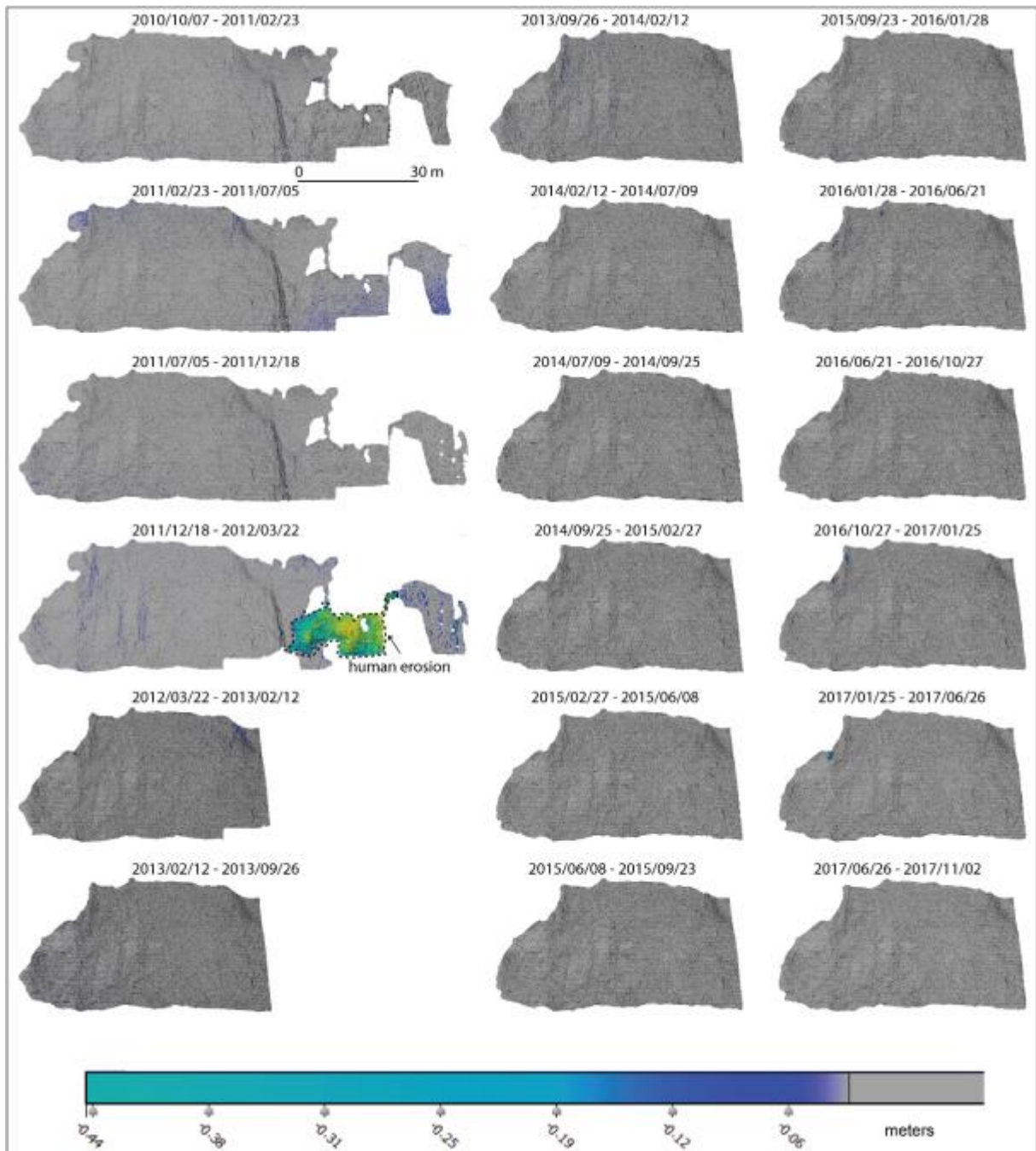
#### 281 4.2. Retreat modalities and the responsible forcing

282 Whereas erosion occurs almost everywhere on the cliff face in Varengeville-sur-Mer, erosion  
283 is rare and localized on the cliff face in Dieppe (Fig. 4). The patterns of erosion are different  
284 between sites. According to the classification of slope movements by Varnes in 1978 (which  
285 was updated by Dikau et al. (1996) and Hungr et al. (2014)), two terms can be used to  
286 describe movements of coherent rock in relation to fallen volume. Debris fall is used where  
287 tiny blocks or flakes (up to a decimeter) fall from across the cliff face, and rock fall is used to  
288 describe large-scale movements that fall from all or part of the cliff face.

289 The abandoned cliffs of Dieppe are only affected by debris falls (Fig. 5, dark blue) over the 7-  
290 year period. However, research in local newspapers between 1950 and 2010 reported that  
291 rock falls had already occurred on the studied abandoned cliffs. In March 2001, a rock fall  
292 was observed near Dieppe 1 W. We must bear in mind that these events have return periods



293 of several decades (Letortu et al., 2014). For the 7-year monitoring period, debris falls are  
294 mostly located at the cliff foot or at the cliff top (Fig. 5) and are responsible for the annual  
295 retreat rate of up to 0.01 m/year in Dieppe 2 N.  
296

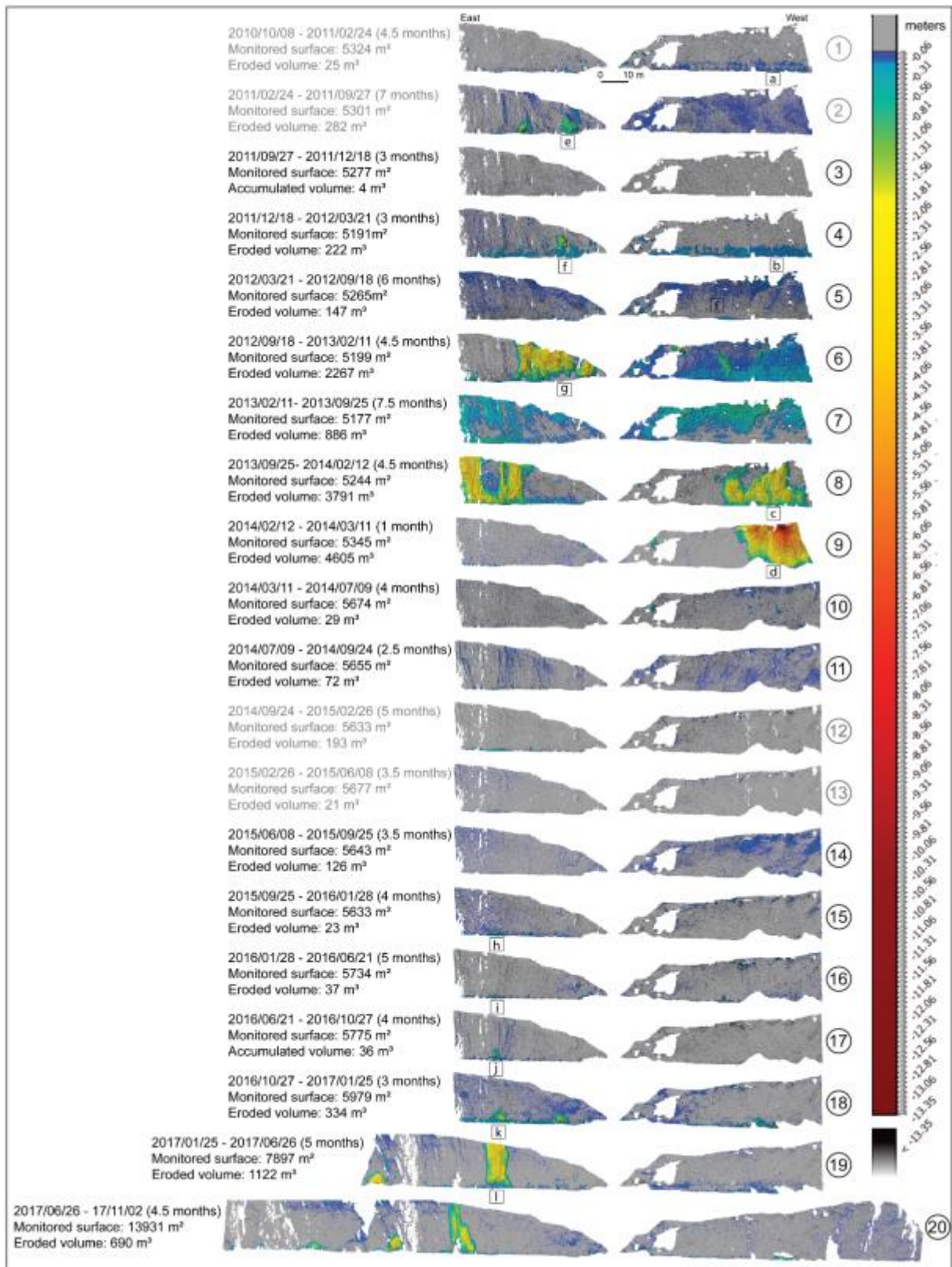


297  
298 Fig. 5: DoDs of the cliff face in Dieppe 2 N between 2010/10/07 and 2017/11/02. For  
299 interpretation of the references to color in this figure, the reader is referred to the web version  
300 of this article.

301

302 The active cliff in Varengeville-sur-Mer is affected by debris falls (Fig. 6, dark blue) and rock  
303 falls (Fig. 6, from light blue to dark red). The location of debris falls are variable: they are  
304 located at the cliff foot (DoD 1, 4), at the cliff top (DoD 5, 10), and mainly on the whole cliff  
305 face (DoD 2, 11, 14, 15, 16, 18, 19, 20).

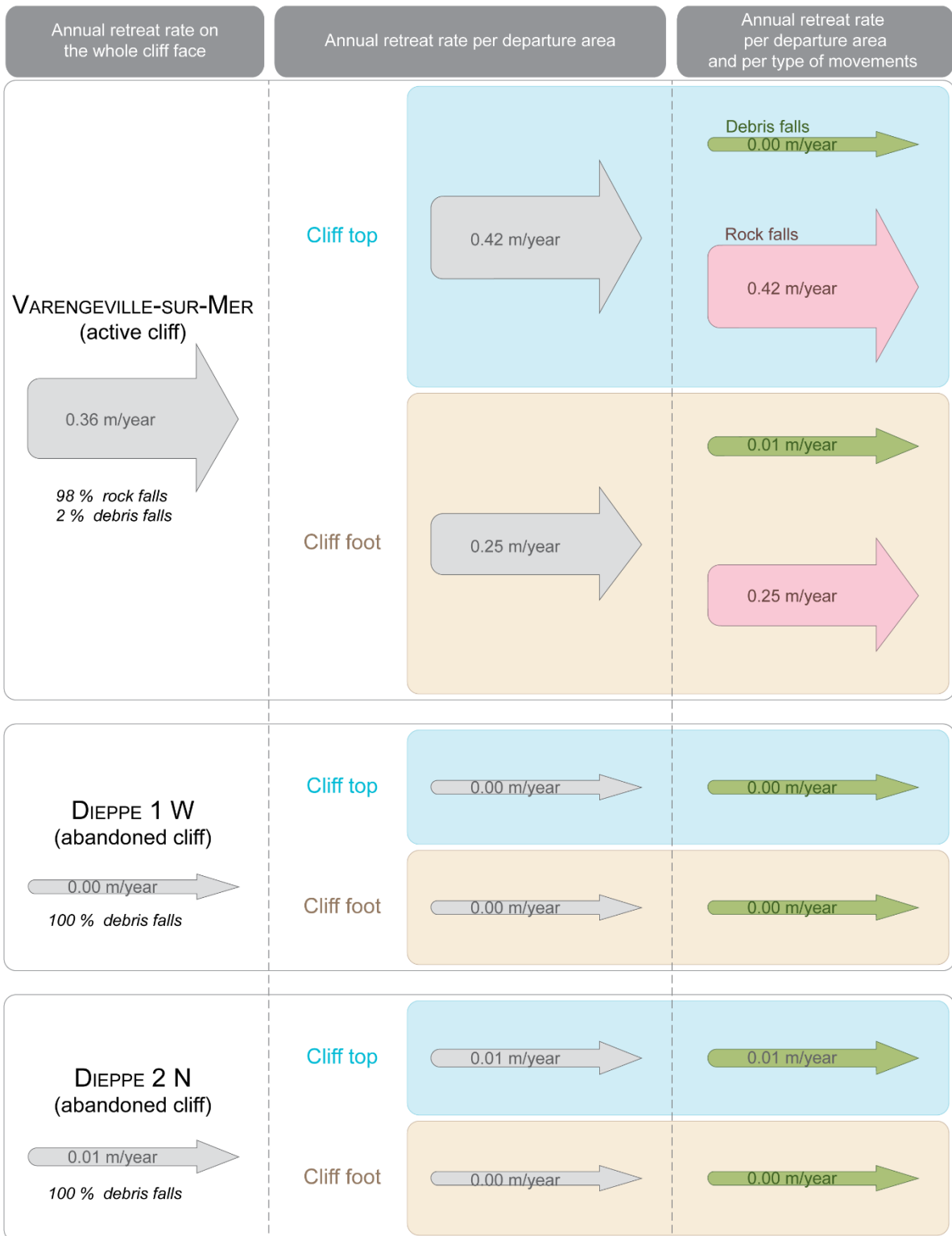
306



307  
 308 Fig. 6: DoDs of the cliff face in Varengeville-sur-Mer between 2010/10/08 and 2017/11/02 (gray  
 309 title and number when the DoD is affected by a high error margin). For interpretation of the  
 310 references to color in this figure, the reader is referred to the web version of this article.

312 In order to compare both environments (abandoned and active cliffs), we observe debris falls  
313 which are present in both contexts. In the context of the active cliff, debris falls are  
314 responsible for less than 2 % of the total erosion ( $218 \text{ m}^3$ ) measured over the period with  
315 retreat rates of 0.00-0.01 m/year (over 0.36 m/year). These retreat rates are consistent with  
316 the erosion observed on the abandoned cliffs where only debris falls are observed (Fig. 7).  
317 This value of 2 % is lower than those evoked in the literature (from 10 % (May and Heeps,  
318 1985; Hénaff et al., 2002) to 25 % (Letortu et al., 2015b)). This could be due to different  
319 monitoring time periods and the higher error margin of the previous methods of quantification  
320 (extrapolation from several debris falls observed in the field).

321



322

323 Fig. 7: Annual retreat rates in function of location (site and departure area) and type of  
 324 movements (debris and rock falls).

325

326 Because debris falls occur mainly at the cliff top of the abandoned cliff of Dieppe 2 N, the  
327 retreat rate by debris falls observed on the active cliff top could be due to the same forcing.  
328 The retreat rate appears negligible in Varengeville-sur-Mer (0.00 m/year), so subaerial  
329 forcing is probably low for the erosion by debris falls but they may participate in the erosion  
330 by rock falls.

331

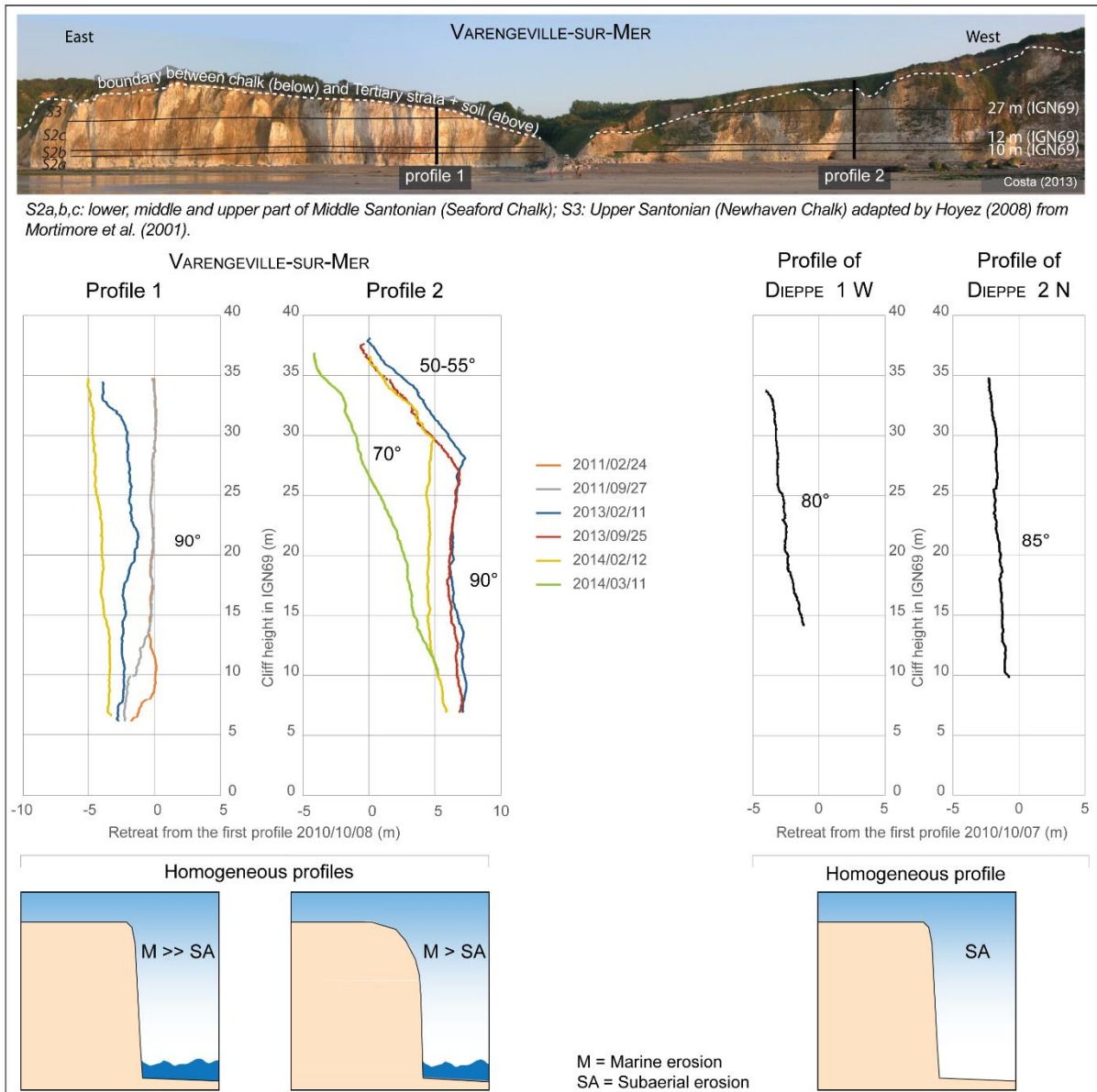
#### 332 *4.3. Profile analysis*

333 Applying the classification scheme of Emery and Kuhn (1982) to the investigated cliff  
334 sections, the abandoned cliffs present homogeneous profiles underlining the homogeneity of  
335 the rock (Coniacian chalk) (Fig. 8). The profiles are also steady and subvertical (80-85°)  
336 underlining the low aggressiveness of subaerial processes on these cliff faces. Indeed, the  
337 expected slope value for a continentalized profile is from 5 to 30° in temperate climates  
338 (Pinot, 1998) but the continentalization of between 30 to more than 120 years is short in  
339 terms of geomorphological time scales.

340 For the active cliff in Varengeville-sur-Mer (Santonian chalk), changes in the shape of the  
341 profiles are observed. These various spatial patterns may highlight differences in the spatial  
342 and temporal variability of marine and subaerial processes (Fig. 8).

343





344

345 Fig. 8: Main evolutions of the cliff profile in Varengeville-sur-Mer and Dieppe during 7 years  
 346 of monitoring. For interpretation of the references to color in this figure, the reader is referred  
 347 to the web version of this article.

348

349 On the eastern cliff face, profile 1 highlights the lithological homogeneity and the dominant  
 350 role of marine processes in erosion (Fig. 8):

- 351 • between 2011/02/24 and 2011/09/27: attack on the cliff foot probably due to marine  
 352 processes generating a notch (up to 2.28 m deep) and an overhang on the upper part  
 353 (110°);

- 354 • between 2012/09/18 and 2013/02/11: attack on the overhang (there is very little change  
355 at the foot) generating a subvertical profile;
- 356 • between 2013/09/25 and 2014/02/12: attack on the whole cliff face by a vertical failure  
357 type generating a vertical profile.

358 On the western cliff face, profile 2 highlights an erosion difference between the cliff foot and  
359 top which seems to be due to the combination of marine and subaerial agents and processes  
360 in the evolution of the profile (Fig. 8):

- 361 • between 2013/02/11 and 2013/09/25 : attack on the cliff top by subaerial processes  
362 (erosion up to 0.62 m) whereas the cliff foot seems less affected by marine processes  
363 (erosion up to 0.21 m);
- 364 • between 2013/09/25 and 2014/02/12: attack on the cliff foot probably due to marine  
365 processes (erosion up to 1.49 m) and a rock fall of the whole cliff face (vertical failure  
366 type) maintaining a vertical profile (erosion up to 2.08 m);
- 367 • between 2014/02/12 and 2014/03/11: attack at the top of the cliff due to subaerial forcing  
368 (erosion up to 5.82 m) generating a homogeneous profile but with a slope of 70°.

369 During the 7 years of monitoring, marine processes seem largely dominant in the active cliff  
370 context with regard to vertical profiles, because the latter are maintained by the undermining  
371 and removal role of marine agents. However, subaerial processes also contribute to the  
372 retreat.

373 Our erosion results have been linked to external factors to be more precise about the  
374 dominant forcing. Two “dead times” and two “high points” of erosion can be identified and  
375 have been linked to environmental conditions (Fig. 9):

- 376 • October 2010 to September 2012: A low erosion period occurred with a maximum retreat  
377 of 2.31 m and an average annual retreat rate of 0.07 m/year. This period of 23.5 months  
378 is characterized by calm wave conditions, a cold and humid fall in 2010 (17 daily  
379 freeze/thaw cycles in December), a mild and dry winter and spring in 2011, a wet  
380 summer in 2011 (+141 % rainfall in August in comparison with the 1971-2000 climate

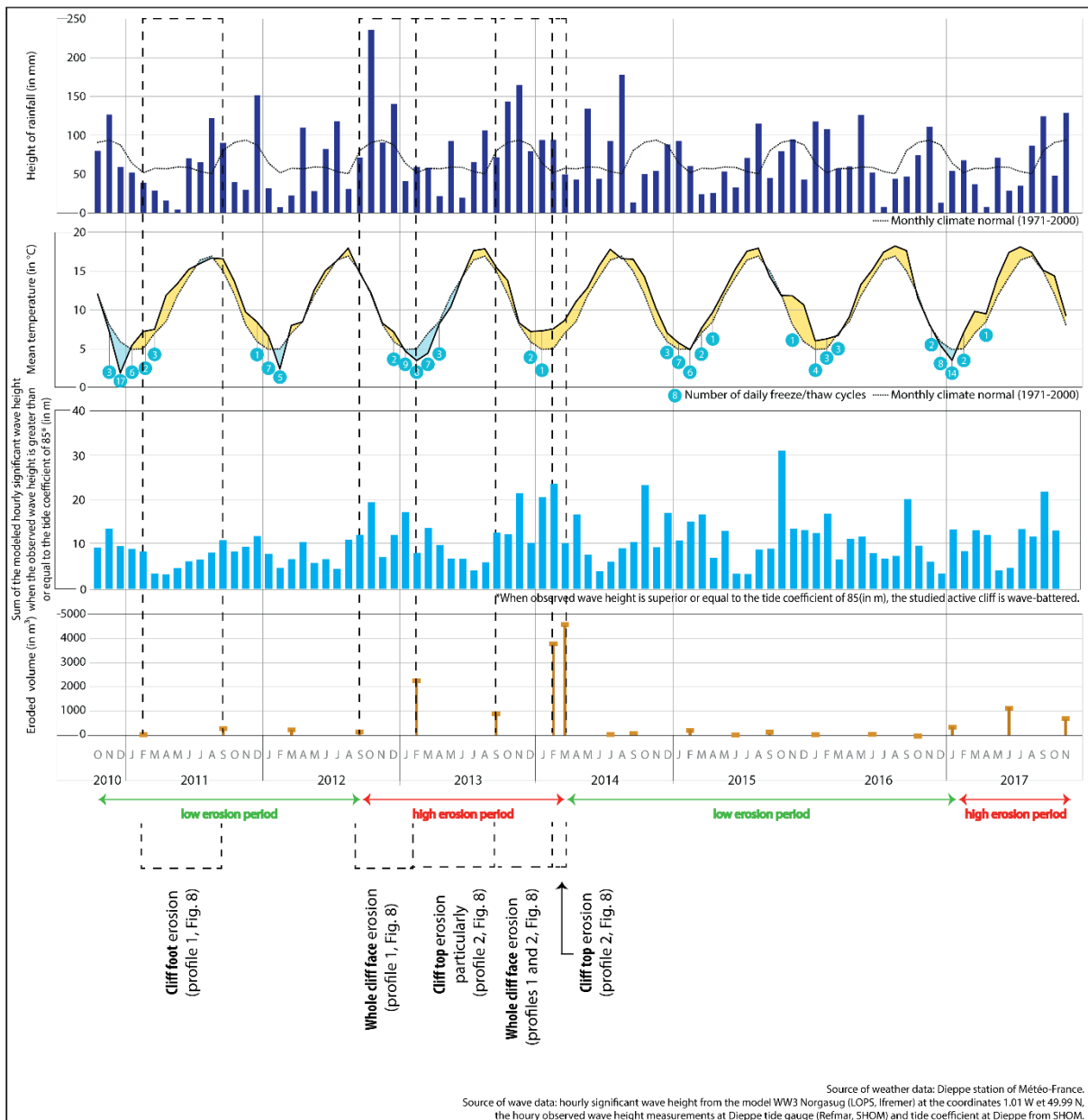
381 normal from Météo-France data), a mild and dry fall in 2011 and the winter of 2012, and  
382 a humid spring-summer in 2012.

383 • September 2012 to March 2014: A high erosion period (maximum retreat of 12.93 m and  
384 an average annual retreat rate of 1.51 m/year) occurred for 17.5 months and was  
385 characterized by high rainfall in October and December 2012, and with a cold winter (24  
386 daily freeze/thaw cycles); the spring of 2013 had a dry April and June (-62 % and -67 %  
387 rainfall in comparison with the climate normal, respectively) but summer months of July  
388 and August were warm and rainy (+23 % rainfall in July with thunderstorms, +110 % in  
389 August), the fall and winter of 2013-2014 were particularly mild (an average of +70 % of  
390 mean temperature for the three winter months) but characterized by violent storms and  
391 rainfall (+76 % in November) and with frequent storm wave conditions.

392 • March 2014 to January 2017: A low erosion period (maximum retreat of 2.73 m and an  
393 average annual retreat rate of 0.02 m/year) occurred for 31.5 months. This period is  
394 characterized by a drier and warmer spring in 2014 than the climate normal, a very rainy  
395 summer (+73 % and +251 % in July and August, respectively), a dry fall (-83 % in  
396 September, -45 % in October and -42 % in November) but with storm wave conditions in  
397 October, a mild and rainy winter in 2014-2015 (+55 % rainfall in January 2015), a dry  
398 spring in 2015 (-55 % rainfall in April), and a warm summer in 2015 characterized by a  
399 very rainy July and August (+126 % rainfall in August); the fall and winter of 2015-2016  
400 were mild (+72 % of mean temperature in November and 147 % in December, 177 % in  
401 January) and with storm wave conditions in October but the winter was rainy (+84 % in  
402 January, +108 % in February), the spring of 2016 was "classic", summer 2016 was warm  
403 (+15 % of mean temperature for the three summer months) and almost dry (-85 % in  
404 July 2016), followed by a "classic" October and November but a very dry December (-85  
405 % rainfall).

406 • January to November 2017: A high erosion period (maximum retreat of 6.21 m and an  
407 average annual retreat rate of 0.28 m/year) occurred with a mild (except January with 14  
408 freeze/thaw cycles), calm and dry winter (-15 % and -36 % rainfall in January and March

409 ; +40 % of mean temperature in February and March), the spring and summer of 2017  
 410 were quite warm and dry (-51 % rainfall and +25 % of mean temperature in June, -34 %  
 411 in July but +71 % in August) but the month of September had storm wave conditions and  
 412 the fall had warmer temperatures than the climate normal (+37 % of mean temperature  
 413 in October) and had variable rainfall (-47 % in October, +37 % in November).  
 414



415  
 416 Fig. 9: Evolution of climate (rainfall, temperature, number of freeze/thaw cycles from Météo-  
 417 France data) and wave conditions (sum of the modeled hourly significant wave height (in m)  
 418 when the hourly observed wave height is greater than or equal to the tide coefficient of 85)

419 around Dieppe (from WW3 Norgasug data (LOPS, IFREMER), and SHOM data) and the  
420 erosion in Varengeville-sur-Mer.

421

422 As per Letortu et al. (2015a), the whole cliff face erosion occurs particularly during high  
423 rainfall and high wave conditions over the 7-year monitoring period. However, the  
424 relationships are not systematic as in August and October 2014 when high rainfall and high  
425 wave conditions occurred respectively without significant erosion (Fig. 9). Due to the  
426 imprecise dating of falls (time frequency of 4-5 months), it is not possible to be more explicit  
427 about the main processes responsible for erosion. Moreover the determination has four main  
428 sources of difficulty:

- 429 • First, the non-linear evolution of the coastal environment limits direct cause and effect  
430 relationships. Thresholds, hysteresis, synergies/combinations, positive and negative  
431 feedbacks, and 'purge' effect (described in detail in Viles, 2012) all complicate the  
432 analysis of relationships. For example, the relative role of marine and subaerial  
433 processes in cliff erosion may change over time, because platforms gradually widen over  
434 long time periods, which affects the amount of wave energy delivered to the foot of the  
435 cliff (negative feedback);
- 436 • Secondly, the boundary conditions (sea level, climate, geology, tide and wind wave)  
437 modulate the domination of agents and processes over the evolution of the coast at a  
438 given place and time, requiring spatial and temporal scales to be jointed together. For  
439 example, the erosive power of the ocean will depend on the relative balance between  
440 tidal and wave climates (Kennedy et al., 2014b);
- 441 • Third, the cliff is also inherited past environmental changes (Trenhaile, 2002): in our  
442 understanding of current processes and their impacts, we must also integrate long-term  
443 rock degradation (Griggs and Trenhaile, 1994; Swenson et al., 2006; Joyal et al., 2016);
- 444 • Finally, studies often focus on the cliff face while the cliff belongs to a vast system  
445 including nearshore, platform, cliff and hinterland (Trenhaile, 1987). Studies that focus

446 on a single component are likely to provide only a partial view of the behavior of the  
447 entire slope (Lim, 2014).

448

#### 449 *4.4. Basal notch creating instability on the whole cliff face*

450 Figs. 6 and 8 show one of the retreat modalities previously described along the Seine-  
451 Maritime coastline (Costa et al., 2006a; Dewez et al., 2013; Letortu et al., 2015b): the  
452 creation of a basal notch (created by debris falls or rock falls) that, by overhanging, will  
453 gradually destabilize the whole cliff face and generate a rock fall from the whole cliff face.  
454 Three cases are observed during the seven years of monitoring on both sides in  
455 Varengeville-sur-Mer (Fig. 6, on the western part: a to d; on the eastern one: e to g, and h to  
456 l). For example, debris fall 'a' generates a maximal basal notch on the western side of 0.2 m,  
457 reactivated by debris fall 'b' (maximal notch of 0.25 m). A few months later, the created  
458 overhang is eroded by rock fall 'c' from the whole cliff face (1875 m<sup>3</sup>) which is reactivated a  
459 month later by rock fall 'd' (4616 m<sup>3</sup>).

460

## 461 **5. Discussion**

### 462 *5.1. Profile analysis*

463 The profile analysis as a proxy of the power balance between the resistance and  
464 homogeneity of the material outcropping on the cliff face and the combined aggressiveness  
465 of marine and/or subaerial forcing has several limitations. First, the profile evolution is often  
466 the result of multiple factors which interact in time and space which can make the definite  
467 interpretation of the responsible factor more complex. Second, the analysis can be  
468 complicated by local effects (as in profiles 1 and 2 in Varengeville). Third, "equifinality" can  
469 occur: the same profile can be obtained by different processes.

470

### 471 *5.2. Roles of structural variations and of the gravel barrier*

472 The Dieppe cliff profiles (1 W and 2 N) and profile 1 in Varengeville-sur-Mer are similar in  
473 their subverticality and their homogeneity. This highlights (1) the low efficacy of subaerial



474 forcing (or, for the active cliff, the very high efficacy of marine forcing) in cliff erosion, and (2)  
475 a close resistance between Santonian and Coniacian chalk stages with a common mode of  
476 failure: the vertical failure mode.

477 But at the Varengueville site, profiles 1 and 2 are different (Fig. 8). Marine forcing is  
478 predominant but the role of subaerial processes is much more visible in profile 2 with a more  
479 convex cliff top (softer slope). A hypothesis could be the greater thickness of the overlying  
480 Tertiary strata on the western part, which, due to the presence of perched groundwater  
481 (Bignot, 1971), would accelerate the retreat at the top of the cliff. However, cliff face retreat  
482 rates were calculated for each side of the dry valley: annual retreat rates are almost the  
483 same with 0.37 m/year for the western part and 0.35 m/year for the eastern part. Difference  
484 in thickness of Tertiary strata does not seem to influence retreat rates but it can influence the  
485 modality of retreat. Another hypothesis could be a difference in fracturing between the two  
486 sides of the dry valley, modifying drainage and infiltration. A more detailed analysis of the  
487 fracturing needs to be carried out. The last hypothesis could be the influence of the  
488 descending road to the sea which, acting as a groin, accumulates gravel on the front western  
489 part (up to 5 m thick) to the detriment of the immediate downdrift side (eastern part, up to 2.5  
490 m thick). The gravel barrier could cause negative feedback with increased wave protection at  
491 the cliff foot, leading to a likely decrease in the efficacy of marine processes on the western  
492 part of the cliff foot. In addition, profile 2 has no basal notch although this is the case on  
493 profile 1, highlighting the role of marine forcing on the eastern part. However, the amount and  
494 configuration of beach material can also create positive feedback with higher wave erosive  
495 efficacy by providing abrasive elements (Sunamura, 1992), as evoked in our previous paper  
496 in the study area (Letortu et al., 2015b) (Fig. 6, DoDs 1 and 4).

497

### 498 *5.3. Subaerial forcing inferior to marine forcing but non-negligible*

499 The subvertical profiles of the active cliff and the current annual retreat rate, 36 times higher  
500 when the cliff is wave-battered, highlight the supremacy of marine over subaerial controls in  
501 the erosion of chalk cliffs around Varengueville-sur-Mer between 2010 and 2017. However,

502 subaerial processes are present (the freeze/thaw action is visible in DoD 19 in Fig. 6 and is  
503 supported by Fig. 10, the runoff zones are visible at the cliff top in Figs. 5, 6), but they seem  
504 much less active than marine processes in destabilizing cliffs.

505



506

507 Fig. 10: Successive zooms of debris falls at the cliff foot of Varengeville-sur-Mer after  
508 freeze/thaw cycles (2017/01/25)

509

510 The slow continentalization of the abandoned cliffs in Dieppe may be explained by the low  
511 efficacy of subaerial processes in erosion but it is important to note that these morphological  
512 adjustments take time, and, local factors, notably hydrogeomorphological, could explain this  
513 slow evolution. The plateau here is characterized by a high fracturing of the chalky block  
514 (close to the Bray fault) where a karstic system may extend along pre-existing fracturing.

515 Dieppe 1 W and 2 N have a well-developed karstic network that was widened during the  
516 Second World War, before being roughly filled. Moreover, the plateau is also locally  
517 characterized by a slope and a dip towards the hinterland, lowering the chalk water table  
518 level at the foot of the cliff, and directing a large part of the surface flows towards the dry  
519 valley a few hundred meters behind the cliff (stereogram of Dieppe 2 N; Fig. 2d). The  
520 monitored chalk cliffs could be less saturated than elsewhere due to these local factors.  
521 The combined marine and subaerial processes alternate in time and space in the active cliff  
522 context. TLS monitoring has made it possible to visualize "erosion patterns" in Varengeville-  
523 sur-Mer which appear to be seasonal: between September and February, the cliff foot is  
524 often eroded partly by marine processes while between March and September, it is rather  
525 the cliff top that is eroded due to subaerial activity (Fig. 6). Moreover, erosion increased in  
526 Varengeville-sur-Mer during the winter of 2013-2014, when conditions were particularly  
527 stormy on the Atlantic and Channel coasts (Blaise et al., 2015; Earlie et al., 2015) (Fig. 9).  
528 Our results confirm that marine processes play the most important erosive role during the  
529 studied period, and also that of removing falls at the foot of the cliffs. Indeed, the roles of  
530 marine processes are visible following stormy periods with 1) the cliff foot bleached due to  
531 wave erosive action and 2) a milky sea due to the dissolution of chalk falls (Fig. 11).  
532



533  
534 Fig. 11: Marine action visible after a stormy period (December 2017-January 2018) in  
535 Varengeville-sur-Mer (a) with bleached cliff foot (b) and the removal of falls by dissolution  
536 into the sea.

537

538 The removal role can be estimated from the rock fall of 2014/02/15-16 observed on the  
539 western cliff face at Varengueville-sur-Mer and evacuated between 2016/10/28 and  
540 2017/01/25 (Fig. 6). The minimum monthly removal rate is  $53 \text{ m}^3$  per month. This removal  
541 rate seems low compared to the literature and our field observations beyond the studied  
542 sites. Hénaff et al. (2002) report removal volumes of around  $40 \text{ m}^3/\text{day}$ , or  $14500 \text{ m}^3/\text{year}$ . In  
543 Varengueville-sur-Mer, 2 km west of the area monitored by TLS, a rock fall of  $5700 \text{ m}^3$   
544 occurred at the end of May 2006 and disappeared six months later, in December 2006. The  
545 removal rate is close to that found by Hénaff et al. with an evacuated volume of  $30 \text{ m}^3/\text{day}$  for  
546 this rock fall (Fig. 12).

547



548

549 Fig. 12: Evolution of the cliff face in Varengueville-sur-Mer (2 km from the monitored site)  
550 between 2006/03/09 and 2006/12/19 with a rock fall of  $5700 \text{ m}^3$  in late May. In August, the  
551 rock fall is partially removed, and by December 2006 it has been completely removed.

552



553 Thus, a high spatial variability of removal rates is observed. Beyond the elapsed time interval  
554 between the two surveys, the removal rate is explained by a multitude of factors which  
555 influence the modalities and the efficacy of the removal (size of blocks and chalk types,  
556 kinematics of rock falls, volume of rock falls depending on the height of the cliffs and the  
557 fracturing of the chalk, volume of gravel barrier etc.).

558

## 559 **6. Conclusions**

560 Erosion of three chalk cliff faces in Normandy was monitored every 4-5 months since  
561 October 2010 using a terrestrial laser scanner. These cliff faces with close structural  
562 characteristics (including lithology with Upper Cretaceous chalk with flint bands of Coniacian  
563 and Santonian ages) are exposed differently to marine processes: the active Varengeville-  
564 sur-Mer cliff, affected by marine and subaerial processes, and the two abandoned Dieppe  
565 cliffs evolving under the action of subaerial processes only. The choice of sites and the high  
566 frequency, high resolution and centimeter precision monitoring ( $\pm 0.02$  to  $0.03$  m) make it  
567 possible to improve the understanding of 1) the cliff face retreat rates, 2) the modalities of  
568 cliff evolution, and 3) the efficacy of marine and subaerial controls in erosion of the studied  
569 cliff faces.

570 Over the 85 months between October 2010 and November 2017, our results highlight the  
571 predominance of marine processes in the retreat of the coastal chalk cliffs because: 1) the  
572 current annual retreat rate is 36 times higher in the active cliff context than in the abandoned  
573 cliff context; 2) the cliff profiles are subvertical due to the primacy of marine processes in the  
574 active cliff context and the low effectiveness of subaerial processes in the abandoned cliff  
575 context; and 3) the location of erosion highlights the great effectiveness of marine processes  
576 in destabilizing cliffs (from the generation of a basal notch through the overhang generating  
577 instability to the triggering of a rock fall of the whole cliff face) and in the removal of falls.

578 These results indicate that TLS data can be very useful in monitoring coastal cliff erosion and  
579 in contributing to the debate on the primacy of agents and processes responsible for erosion  
580 and the triggering of falls. Research perspectives using our database are numerous,

581 including the implementation of “rock fall” hazard warning systems. The various studies  
582 conducted in continental (Abellán et al., 2010; Royán et al., 2014; Kromer et al., 2017) and  
583 coastal areas (Rosser et al., 2007) focus on two types of precursory signs: the activity of falls  
584 before failure and deformations before failure. One of the important issues in forecasting  
585 systems lies in the coupling of spatial and temporal predictions, which are still rare in the  
586 scientific literature (e.g. Rosser et al., 2007; Arosio et al., 2009; Kromer et al., 2017) because  
587 of their great complexity (Abellán et al., 2014).

588 The current TLS monitoring must continue to improve temporal representativeness. Only  
589 reliable, homogeneous and sustainable monitoring will allow a better understanding of cliff  
590 evolution. The annual retreat rates will be refined in Dieppe by extending the monitoring time,  
591 which will allow the margin of error to be expanded. An increase in the temporal sampling of  
592 measurements would be desirable to refine knowledge on the contribution of marine and  
593 subaerial agents and processes responsible for triggering falls in Varengeville-sur-Mer. A  
594 high temporal sampling would also make it possible to develop the research axis on the  
595 precursory signs of failure. The great diversity of current monitoring instruments makes it  
596 possible to be more reactive (Letortu et al., 2018).

597 One of the limitations of our results is that they are difficult to transpose, as they are very  
598 dependent on the three studied sites. Other methods such as the mobile laser scanning  
599 (Michoud et al., 2014), make it possible to cover larger areas but their implementation costs  
600 and the necessary technical know-how are obstacles to their deployment. The spatial  
601 representativeness of the TLS monitoring we conducted has been widened in order to extend  
602 the scope of our results in various contexts. Since November 2017, TLS monitoring of the  
603 Sainte-Marguerite-sur-Mer cliff (6 km west from the TLS site in Varengeville-sur-Mer) has  
604 begun and it will be linked to a continuous cliff face multiparameter monitoring (temperatures,  
605 water table level, seismicity, rainfall, sea water level etc.) during the winter 2018-2019.

606

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617

## 618 **References**

- 619 Abellán, A., Calvet, J., Vilaplana, J.M., Blanchard, J., 2010. Detection and spatial prediction  
620 of rockfalls by means of terrestrial laser scanner monitoring. *Geomorphology* 119, 162–171.  
621 <https://doi.org/10.1016/j.geomorph.2010.03.016>
- 622 Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N.J., Lim, M., Lato, M.J., 2014. Terrestrial  
623 laser scanning of rock slope instabilities. *Earth Surf. Process. Landf.* 39, 80–97.  
624 <https://doi.org/10.1002/esp.3493>
- 625 Arosio, D., Longoni, L., Papini, M., Scaioni, M., Zanzi, L., Alba, M., 2009. Towards rockfall  
626 forecasting through observing deformations and listening to microseismic emissions. *Nat.*  
627 *Hazards Earth Syst. Sci.* 9, 1119–1131. <https://doi.org/10.5194/nhess-9-1119-2009>
- 628 Auffret, J.P., Bignot, G., 1978. Dieppe (est). Carte géologique à 1/50000.
- 629 Augris, C., 2004. Evolution morpho-sédimentaire du domaine littoral et marin de la Seine-  
630 Maritime. Ifremer.
- 631 Bernatchez, P., Dubois, J.M., 2008. Seasonal quantification of coastal processes and cliff  
632 erosion on fine sediment shorelines in a cold temperate climate, north shore of the St.  
633 Lawrence maritime estuary, Québec. *J. Coast. Res.* 24, 169–180. [https://doi.org/10.2112/04-](https://doi.org/10.2112/04-0419.1)  
634 [0419.1](https://doi.org/10.2112/04-0419.1)



635 Bernatchez, P., Jolivet, Y., Corriveau, M., 2011. Development of an automated method for  
636 continuous detection and quantification of cliff erosion events. *Earth Surf. Process. Landf.* 36,  
637 347–362. <https://doi.org/10.1002/esp.2045>

638 Bezore, R., Kennedy, D.M., Ierodionou, D., 2016. The drowned Apostles: the longevity of  
639 sea stacks over Eustatic cycles. *J. Coast. Res.* 75, 592–596. [https://doi.org/10.2112/SI75-](https://doi.org/10.2112/SI75-119.1)  
640 119.1

641 Bignot, G., 1971. Dieppe (ouest). Carte géologique à 1/50000.

642 Bignot, G., 1962. Etude sédimentologique et micropaléontologique de l'Eocène du Cap  
643 d'Ailly (près de Dieppe-Seine-Maritime). Paris.

644 Blaise, E., Suanez, S., Stéphan, P., Fichaut, B., David, L., Cuq, V., Autret, R., Houron, J.,  
645 Rouan, M., Floc'h, F., Arduin, F., Cancouët, R., Davidson, R., Costa, S., Delacourt, C.,  
646 2015. Bilan des tempêtes de l'hiver 2013-2014 sur la dynamique de recul du trait de côte en  
647 Bretagne. *Géomorphologie Relief Process. Environ.* 21, 267–292.  
648 <https://doi.org/10.4000/geomorphologie.11104>

649 Brooks, S.M., Spencer, T., 2010. Temporal and spatial variations in recession rates and  
650 sediment release from soft rock cliffs, Suffolk coast, UK. *Geomorphology* 124, 26–41.  
651 <https://doi.org/10.1016/j.geomorph.2010.08.005>

652 Cavelier, C., Lorenz, J., 1987. Aspect et évolution géologiques du Bassin de Paris,  
653 Association des Géologues du Bassin de Paris. ed.

654 Cavelier, C., Mégnien, C., Pomerol, C., Rat, P., 1979. Le Bassin de Paris. *Bull. Inf.*  
655 *Géologues Bassin Paris* 16, 2–52.

656 Cazes, M., Torreilles, G., Bois, C., Damotte, B., Galdeano, A., Hirn, A., Mascle, A., Matte, P.,  
657 Van Ngoc, P., Raoult, J.F., 1985. Structure de la croûte hercynienne du Nord de la France :  
658 premiers résultats du profil ECORS. *Bull. Société Géologique Fr.* 8, 925–641.  
659 <https://doi.org/https://doi.org/10.2113/gssgfbull.1.6.925>

660 Costa, S., 2005. Falaises à recul rapide et plages de galets: de la quantification des  
661 dynamiques d'un système complexe à la caractérisation des risques induits. *Habilit. À Dir.*  
662 *Rech. Univ. Bretagne Occident. Brest Tome 1*, 330.

663 Costa, S., 1997. Dynamique littorale et risques naturels : L'impact des aménagements, des  
664 variations du niveau marin et des modifications climatiques entre la baie de Seine et la baie  
665 de Somme (Haute-Normandie, Picardie; France). Paris 1.

666 Costa, S., Delahaye, D., Freiré-Díaz, S., Di Nocera, L., Davidson, R., Plessis, E., 2004.  
667 Quantification of the Normandy and Picardy chalk cliff retreat by photogrammetric analysis.  
668 Geol. Soc. Lond. Eng. Geol. Spec. Publ. 20, 139–148.

669 Costa, S., Lageat, Y., Hénaff, A., 2006a. The gravel beaches of north-west France and their  
670 contribution to the dynamic of the coastal cliff-shore platform system. Z. Geomorphol. 144,  
671 199–214.

672 Costa, S., Laignel, B., Hauchard, E., Delahaye, D., 2006b. Facteurs de répartition des  
673 entonnoirs de dissolution dans les craies du littoral du Nord-Ouest du Bassin de Paris. Z.  
674 Geomorphol. 50, 95–116.

675 Dewez, T.J.B., Girardeau-Montaut, D., Allanic, C., Rohmer, J., 2016. Facets : a  
676 Cloudcompare Plugin to Extract Geological Planes from Unstructured 3d Point Clouds.  
677 ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 41B5, 799–804.  
678 <https://doi.org/10.5194/isprs-archives-XLI-B5-799-2016>

679 Dewez, T.J.B., Regard, V., Duperret, A., Lasseur, E., 2015. Shore platform lowering due to  
680 frost shattering during the 2009 winter at Mesnil Val, English channel coast, NW France.  
681 Earth Surf. Process. Landf. 40, 1688–1700.

682 Dewez, T.J.B., Rohmer, J., Regard, V., Cnudde, C., 2013. Probabilistic coastal cliff collapse  
683 hazard from repeated terrestrial laser surveys: Case study from Mesnil Val (Normandy,  
684 northern France). J. Coast. Res. 702–707. <https://doi.org/10.2112/SI65-119>

685 Dikau, R., Brunsden, D., Schrott, L., Ibsen, M.L., 1996. Landslide Recognition: Identification,  
686 Movement and Causes. John Wiley & Sons, Chichester.

687 Duperret, A., Genter, A., Martinez, A., Mortimore, R.N., 2004. Coastal chalk cliff instability in  
688 NW France: role of lithology, fracture pattern and rainfall, in: Coastal Chalk Cliff Instability,  
689 Geological Society Engineering Geology Special Publication. Mortimore R.N. and Duperret  
690 A., London, pp. 33–55.

691 Duperret, A., Genter, A., Mortimore, R.N., Delacourt, B., De Pomerai, M.R., 2002. Coastal  
692 rock cliff erosion by collapse at Puys, France: The role of impervious marl seams within chalk  
693 of NW Europe. *J. Coast. Res.* 18, 52–61.

694 Earlie, C.S., Young, A.P., Masselink, G., Russell, P.E., 2015. Coastal cliff ground motions  
695 and response to extreme storm waves. *Geophys. Res. Lett.* 42, 847–854.  
696 <https://doi.org/10.1002/2014GL062534>

697 Emery, K.O., Kuhn, G.G., 1982. Sea cliffs: their processes, profiles, and classification. *Geol.*  
698 *Soc. Am. Bull.* 93, 644–654.

699 Evrard, H., Sinelle, C., 1987. La stabilité des falaises du Pays de Caux (Normandie), in:  
700 Actes Du Colloque “Mer et Littoral. Couple à Risque”, La Documentation Française, Paris.  
701 pp. 84–91.

702 Genter, A., Duperret, A., Martinez, A., Mortimore, R.N., Vila, J.-L., 2004. Multiscale fracture  
703 analysis along the French chalk coastline for investigating erosion by cliff collapse, in:  
704 Coastal Chalk Cliff Instability, Geological Society Engineering Geology Special Publication.  
705 Mortimore R.N. and Duperret A., pp. 57–74.

706 Gilham, J., Barlow, J., Moore, R., 2018. Marine control over negative power law scaling of  
707 mass wasting events in chalk sea cliffs with implications for future recession under the  
708 UKCP09 medium emission scenario. *Earth Surf. Process. Landf.* 43, 2136–2146.  
709 <https://doi.org/10.1002/esp.4379>

710 Griggs, G.B., Trenhaile, A.S., 1994. Coastal cliffs and platforms, in: Coastal Evolution. Carter  
711 R.W.G. and Woodroffe C.D., Cambridge, pp. 425–450.

712 Hénaff, A., Lageat, Y., Costa, S., Plessis, E., 2002. Le recul des falaises crayeuses du Pays  
713 de Caux: détermination des processus d'érosion et quantification des rythmes  
714 d'évolution/Retreat of chalk cliffs in the Pays de Caux: processes and rates. *Géomorphologie*  
715 *Relief Process. Environ.* 8, 107–118. <https://doi.org/10.3406/morfo.2002.1132>

716 Hoyez, B., 2008. Les Falaises du Pays de Caux: lithostratigraphie des craies turono-  
717 campaniennes. Publication Univ Rouen Havre.

718 Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an  
719 update. *Landslides* 11, 167–194. <https://doi.org/10.1007/s10346-013-0436-y>

720 Joyal, G., Lajeunesse, P., Morissette, A., Bernatchez, P., 2016. Influence of lithostratigraphy  
721 on the retreat of an unconsolidated sedimentary coastal cliff (St. Lawrence estuary, eastern  
722 Canada). *Earth Surf. Process. Landf.* 41, 1055–1072. <https://doi.org/10.1002/esp.3886>

723 Kennedy, D.M., Stephenson, W.J., Naylor, L.A., 2014a. Rock coast geomorphology: A global  
724 synthesis, Geological Society. ed. Kennedy D.M., Stephenson W.J. and Naylor L.A., London.

725 Kennedy, D.M., Stephenson, W.J., Naylor, L.A., 2014b. Introduction to the rock coasts of the  
726 world, in: *Rock Coast Geomorphology: A Global Synthesis*. Kennedy D.M., Stephenson W.J.  
727 and Naylor L.A., London, pp. 1–5.

728 Kromer, R.A., Rowe, E., Hutchinson, J., Lato, M., Abellán, A., 2017. Rockfall risk  
729 management using a pre-failure deformation database. *Landslides*.  
730 <https://doi.org/10.1007/s10346-017-0921-9>

731 Kuhn, D., Prüfer, S., 2014. Coastal cliff monitoring and analysis of mass wasting processes  
732 with the application of terrestrial laser scanning: A case study of Rügen, Germany.  
733 *Geomorphology* 213, 153–165. <https://doi.org/10.1016/j.geomorph.2014.01.005>

734 Lageat, Y., Hénaff, A., Costa, S., 2006. The retreat of the chalk cliffs of the Pays de Caux  
735 (France): erosion processes and patterns. *Z. Für Geomorphol.* 144, 183–197.

736 Laignel, B., 2003. Caractérisation et dynamique érosive de systèmes géomorphologiques  
737 continentaux sur substrat crayeux. Exemple de l'Ouest du Bassin de Paris dans le contexte  
738 nord-ouest européen.

739 Laignel, B., 1997. Les altérites à silex de l'ouest du Bassin de Paris: caractérisation  
740 lithologique, genèse et utilisation potentielle comme granulats (PhD Thesis). Rouen.

741 Letortu, P., Costa, S., Bensaid, A., Cador, J.-M., Quénot, H., 2014. Vitesses et modalités de  
742 recul des falaises crayeuses de Haute-Normandie (France): méthodologie et variabilité du  
743 recul. *Geomorphol. Relief Process. Environ.* 20, 133–144.  
744 <https://doi.org/10.4000/geomorphologie.10872>

745 Letortu, P., Costa, S., Cador, J.-M., Coinaud, C., Cantat, O., 2015a. Statistical and empirical  
746 analyses of the triggers of coastal chalk cliff failure. *Earth Surf. Process. Landf.* 40, 1371–  
747 1386. <https://doi.org/10.1002/esp.3741>

748 Letortu, P., Costa, S., Maquaire, O., Delacourt, C., Augereau, E., Davidson, R., Suanez, S.,  
749 Nabucet, J., 2015b. Retreat rates, modalities and agents responsible for erosion along the  
750 coastal chalk cliffs of Upper Normandy: The contribution of terrestrial laser scanning.  
751 *Geomorphology* 245, 3–14. <https://doi.org/10.1016/j.geomorph.2015.05.007>

752 Letortu, P., Jaud, M., Grandjean, P., Ammann, J., Costa, S., Maquaire, O., Davidson, R., Le  
753 Dantec, N., Delacourt, C., 2018. Examining high-resolution survey methods for monitoring  
754 cliff erosion at an operational scale. *GIScience Remote Sens.* 55, 457–476.  
755 <https://doi.org/10.1080/15481603.2017.1408931>

756 Lim, M., 2014. The rock coast of the British Isles: cliffs, in: *Rock Coast Geomorphology: A*  
757 *Global Synthesis*. Kennedy D.M., Stephenson W.J. and Naylor L.A., London, pp. 19–38.

758 Lim, M., Rosser, N.J., Petley, D.N., Keen, M., 2011. Quantifying the controls and influence of  
759 tide and wave impacts on coastal rock cliff erosion. *J. Coast. Res.* 27, 46–56.  
760 <https://doi.org/10.2112/JCOASTRES-D-09-00061.1>

761 May, V.J., Heeps, C., 1985. The nature and rates of change on chalk coastlines. *Z. Für*  
762 *Geomorphol.* 57, 81–94.

763 Mégnien, C., Mégnien, F., 1980. *Synthèse géologique du Bassin de Paris, Mémoire du*  
764 *Bureau des Recherches Géologiques et Minières*. ed.

765 Michoud, C., Carrea, D., Costa, S., Derron, M.H., Jaboyedoff, M., Delacourt, C., Maquaire,  
766 O., Letortu, P., Davidson, R., 2014. Landslide detection and monitoring capability of boat-  
767 based mobile laser scanning along Dieppe coastal cliffs, Normandy. *Landslides* 12, 403–418.  
768 <https://doi.org/10.1007/s10346-014-0542-5>

769 Middlemiss, F.A., 1983. Instability of Chalk cliffs between the South Foreland and  
770 Kingsdown, Kent, in relation to geological structure. *Proc. Geol. Assoc.* 94, 115–122.

771 Mortimore, R.N., 2001. ROCC project, Report on mapping of the chalk Channel coast of  
772 France from Port du Havre-Antifer to Ault. BRGM.

773 Mortimore, R.N., Lawrence, J., Pope, D., Duperret, A., Genter, A., 2004a. Coastal cliff  
774 geohazards in weak rock: the UK Chalk cliffs of Sussex, in: Coastal Chalk Cliff Instability,  
775 Geological Society Engineering Geology Special Publication. Mortimore R.N. and Duperret  
776 A., London, pp. 3–31.

777 Mortimore, R.N., Stone, K.J., Lawrence, J., Duperret, A., 2004b. Chalk physical properties  
778 and cliff instability, in: Coastal Chalk Cliff Instability, Geological Society Engineering Geology  
779 Special Publication. pp. 75–88.

780 Moses, C.A., Robinson, D.A., Williams, R.B.G., Marques, F.M.S.F., 2006. Predicting rates of  
781 shore platform downwearing from rock geotechnical properties and laboratory simulation of  
782 weathering and erosion processes. *Z. Geomorphol. Suppl.* 144, 19–37.

783 Naylor, L.A., Stephenson, W.J., Trenhaile, A.S., 2010. Rock coast geomorphology: Recent  
784 advances and future research directions. *Geomorphology* 114, 3–11.  
785 <https://doi.org/10.1016/j.geomorph.2009.02.004>

786 Pomerol, B., Bailey, H.W., Monciardini, C., Mortimore, R.N., 1987. Lithostratigraphy and  
787 biostratigraphy of the Lewes and Seaford chalks: A link across the Anglo-Paris Basin at the  
788 Turonian-Senonian boundary. *Cretac. Res.* 8, 289–304.

789 Pomerol, C., Feugueur, L., 1986. *Histoire géologique du Bassin de Paris, Mémoires du*  
790 *Muséum national d'histoire naturelle.* ed.

791 Prêcheur, C., 1960. *Le littoral de la Manche, de Sainte-Adresse à Ault: étude morphologique.*  
792 Poitiers: SFIL.

793 Regard, V., Dewez, T., Bourlès, D.L., Anderson, R.S., Duperret, A., Costa, S., Leanni, L.,  
794 Lasseur, E., Pedoja, K., Maillet, G.M., 2012. Late Holocene seacliff retreat recorded by 10Be  
795 profiles across a coastal platform: Theory and example from the English Channel. *Quat.*  
796 *Geochronol.* 11, 87–97. <https://doi.org/10.1016/j.quageo.2012.02.027>

797 Rohmer, J., Dewez, T., 2013. On the deviation of extreme sea-cliff instabilities from the  
798 power-law frequency-volume distribution: Practical implications for coastal management. *J.*  
799 *Coast. Res.* 1698–1703. <https://doi.org/10.2112/SI65-287>

800 Rosser, N., Lim, M., Petley, D., Dunning, S., Allison, R., 2007. Patterns of precursory rockfall  
801 prior to slope failure. *J. Geophys. Res. Earth Surf.* 112.  
802 <https://doi.org/10.1029/2006JF000642>

803 Royán, M.J., Abellán, A., Jaboyedoff, M., Vilaplana, J.M., Calvet, J., 2014. Spatio-temporal  
804 analysis of rockfall pre-failure deformation using Terrestrial LiDAR. *Landslides* 11, 697–709.  
805 <https://doi.org/10.1007/s10346-013-0442-0>

806 Sajinkumar, K.S., Kannan, J.P., Indu, G.K., Muraleedharan, C., Rani, V.R., 2017. A  
807 composite fall-slippage model for cliff recession in the sedimentary coastal cliffs. *Geosci.*  
808 *Front.* 8, 903–914. <https://doi.org/10.1016/j.gsf.2016.08.006>

809 Sunamura, T., 1992. *Geomorphology of Rocky Coasts*. John Wiley & Sons.

810 Swenson, M.J., Wu, C.H., Edil, T.B., Mickelson, D.M., 2006. Bluff recession rates and wave  
811 impact along the Wisconsin coast of Lake Superior. *J. Gt. Lakes Res.* 32, 512–530.  
812 [https://doi.org/10.3394/0380-1330\(2006\)32\[512:BRAWI\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2006)32[512:BRAWI]2.0.CO;2)

813 Trenhaile, A.S., 2002. Rock coasts, with particular emphasis on shore platforms.  
814 *Geomorphology* 48, 7–22. [https://doi.org/10.1016/S0169-555X\(02\)00173-3](https://doi.org/10.1016/S0169-555X(02)00173-3)

815 Trenhaile, A.S., 1987. *The geomorphology of rock coasts*. Oxford University Press,  
816 Incorporated.

817 Varnes, D.J., 1978. Slope movement types and processes, in: *Landslides: Analysis and*  
818 *Control*. Washington, pp. 11–33.

819 Viles, H.A., 2012. Linking weathering and rock slope instability: non-linear perspectives.  
820 *Earth Surf. Process. Landf.* 38, 62–70. <https://doi.org/10.1002/esp.3294>

821 Young, A.P., 2018. Decadal-scale coastal cliff retreat in southern and central California.  
822 *Geomorphology* 300, 164–175. <https://doi.org/10.1016/j.geomorph.2017.10.010>

823