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# 1 **Sedimentary Coastal cliffs of Normandy: modalities and quantification of retreat**

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## 14 **Abstract :**

16 The Normandy cliffs studied in this paper correspond to the north-western termination of the Paris  
17 sedimentary basin. The latter is characterized by the existence of more or less high, undulating and  
18 sometimes faulted plateaus, explaining the lithostratigraphic diversity of the outcrops, and the variety  
19 of types of cliff falls and gravitational landslides encountered. These plateaus are carved into cliffs  
20 with much faster retreat due to the outcropping of sedimentary formations (from the Jurassic to the  
21 Upper Cretaceous) favorable to weathering. Spatial and temporal variations of Norman sedimentary  
22 cliff retreat rates over multi-temporal data are examined. Data are derived from historical maps and air  
23 photographs but also from recent lasergrammetric and photogrammetric monitoring. These latter  
24 measures are on specific sites monitored at high frequency and resolution. The diachronic analysis of  
25 all these data gives retreat rates in line with the international literature, 0.2-0.3 m/yr. The spatial  
26 variations of the cliff retreat rates, at the Normandy scale, can be explained by geological structure,  
27 especially at the cliff foot, but also by the influence of cliff collapses or anthropogenic obstacles that  
28 disrupt the longshore drift (rates can be multiplied by 2). The contribution of the recent  
29 lasergrammetric and photogrammetric techniques shows along the Norman cliffs (1) the spatial  
30 distribution of the retreat or evolution rates on the cliff face. For chalk cliff of Seine Maritime, the  
31 ablation rate evaluated by TLS (Terrestrial Laser Scan) on active cliffs over a period of 7 years  
32 corroborates that established by photo-interpretation (observed over nearly 50 years), i.e. around 36  
33 cm/year for the cap d'Ailly and almost zero for the abandoned cliffs of Dieppe; scree movements  
34 (debris falls) represent 100% of the evolution of the abandoned cliff faces while they account for 2%  
35 of the total retreat of the active cliff of cap d'Ailly. About the rhythms, multi-temporal data shows that  
36 the temporalities evolution of cliff extends from 1 to 7 decades according to the lithology. The high  
37 resolution and frequency monitoring provide also some information about the factors responsible for  
38 triggering gravitational landslides (rockfall, slide, debris fall). For the cliff characterized by landslides  
39 (Villerville et Vaches Noires), which are under the dominating influence of the rainfall and the  
40 groundwater level evolution, the study proposed a regional warning, especially in cases in which the  
41 piezometer of the site exceed a depth of 11m (Groundwater Level) and the effective rain on a 4-  
42 months-period is over 250 mm. In this respect, and for chalk and limestone cliffs, the monitoring is  
43 inconclusive, because the origin of evolutions is more multifactorial.

## 44 **Introduction:**

45 Before the 1990s, the vast majority of coastal geomorphology work focused on accumulation coasts,  
46 due to the presence of many economic challenges threatened by rapid regressive changes, or  
47 potentially accelerated by contemporary mean sea level rise (Trenhaile, 2000; Woodroffe, 2002;  
48 Kennedy *et al.*, 2017). However, rocky and cliffy coasts are said to represent more than 75% of the  
49 world's coastline (Emery *and* Kuhn, 1982; Davis *and* Fitzgerald, 2003), and are now one of the few  
50 sources of sediment for beaches. It is only in the last two to three decades that studies on these  
51 retreating coasts have increased (Kennedy *et al.*, 2014; Kennedy *et al.*, 2017). This is probably due to  
52 the rising impact of their retreat on coastal activities and populations, and to the development of tools

53 and methods to understand the slow but abrupt dynamics of these complex rocky coastal systems  
54 (Sunamura, 1992; Paskoff, 1998; Bird, 2000; Brunnsden and Lee, 2004; Young *et al.*, 2009; Costa *et al.*,  
55 *et al.*, 2004; Costa *et al.*, 2004; Gomez-Puyol *et al.*, 2014; Letortu *et al.*, 2015b; Guiliano, 2015). The  
56 Norman morphostructural environment (between the Bay of Mont Saint Michel and the Tréport) is  
57 favorable to the development of retreating coasts, the evolution of which can be very important  
58 (Maquaire, 1990; Costa, 1997; Costa *et al.*, 2004; Lissak, 2012; Elineau, 2013; Lissak *et al.*, 2013;  
59 Letortu *et al.*, 2015b; Maquaire *et al.*, 2013; Medjkane *et al.*, 2018). To the extreme west of the study  
60 area (Cotentin) appears the Armorican Massif (Fig. 1) composed of ancient sedimentary, metamorphic  
61 and volcanic soils (crossed locally by granitic intrusions). Rocky coasts are made up with these  
62 Paleozoic materials (Dugué *et al.*, 1998) with very slow retreat. In the rest of the study area, to the  
63 north, the ancient Armorican lands are covered, sometimes in discordance, by the northwestern  
64 termination of the Paris sedimentary basin (Juignet, 1974; Lasseur, 2007; Le Cossec, 2010;  
65 Benabdellouahed *et al.*, 2014). The latter is characterized by the existence of more or less high,  
66 undulating and sometimes faulted plateaus, explaining the lithostratigraphic diversity of the outcrops,  
67 and the variety of types of gravitational landslides encountered. Thus, in contact with the  
68 epicontinental sea that is the Eastern and Central Channel, these plateaus are carved into cliffs with a  
69 much faster retreat due to the outcropping of sedimentary formations (from the Jurassic to the Upper  
70 Cretaceous) favorable to weathering. This article has a twofold objective: first, to provide, on a  
71 historical scale and using traditional photo-interpretation methods, the values of the retreat of Norman  
72 sedimentary cliffs. In a second step, and on specific sites monitored at high frequency and resolution  
73 (SNO-Dynalit and SNO-OMIV sites, photogrammetric and lasergrammetric monitoring), the objective  
74 is to provide initial results on some of the main issues that drive the research community working on  
75 cliff coasts, namely, the spatial distribution of the retreat or evolution rates on the cliff face, the  
76 evolution rhythms, and the factors responsible for triggering gravitational landslides (rockfall, slide,  
77 debris fall).

78

## 79 **1/ Study area**

80 The coastal cliffs studied in this paper exclude cliffs carved from Paleozoic rocks in the Cotentin  
81 region (from Saint Vaast la Hougue to Bay of Veys). The Norman cliffs studied therefore correspond  
82 to the north-western termination of the Paris sedimentary basin and have an average amplitude of  
83 about fifty meters, even if they can exceed 100 m in the Seine Maritime area. At the foot of the latter is  
84 a large shore platform (150 to 700 m wide), with a low slope (0.2 to 2%), sometimes covered with thin  
85 sandy veneers. In their upper part, the shore platforms are hidden by a flint gravel barrier in Seine-  
86 Maritime or resistant limestones and sands of multi-metric thickness in Calvados (Costa *et al.*, 2006).  
87 With regard to the morphostructural characteristics of the study area, we can observe (Fig. 1):

88 1- To the west of Calvados, between Grandcamp-Maisy and Saint-Côme de Fresné, lie the active cliffs  
89 of the Bessin plateau, which range in height from 10 to 75 m (section C-D, Fig. 1). These cliffs are  
90 composite in their topographical aspects and geological structures. The profiles are variable from one  
91 end to the other and in relation to the relative thicknesses between the limestones (Bajocian and  
92 Bathonian stages) and the marls of Port-en-Bessin (Bathonian stage). Three types of cliffs have been  
93 defined (Maquaire, 1990): a cliff with a soft marly pedestal topped by a limestone cornice, a cliff with  
94 a resistant pedestal in the marly limestone of the Lower Bathonian or the limestone of the Bajocian,  
95 and a simple subvertical cliff reinforced by the Bathonian limestone.

96 2- In the 'Caen Countryside', the similar system is reproduced between Saint-Aubin-sur-Mer and Lion-  
97 sur-Mer with a plateau at lower altitudes. Several small areas of low active cliffs (Bathonian  
98 limestone) do not exceed 10 m in height.

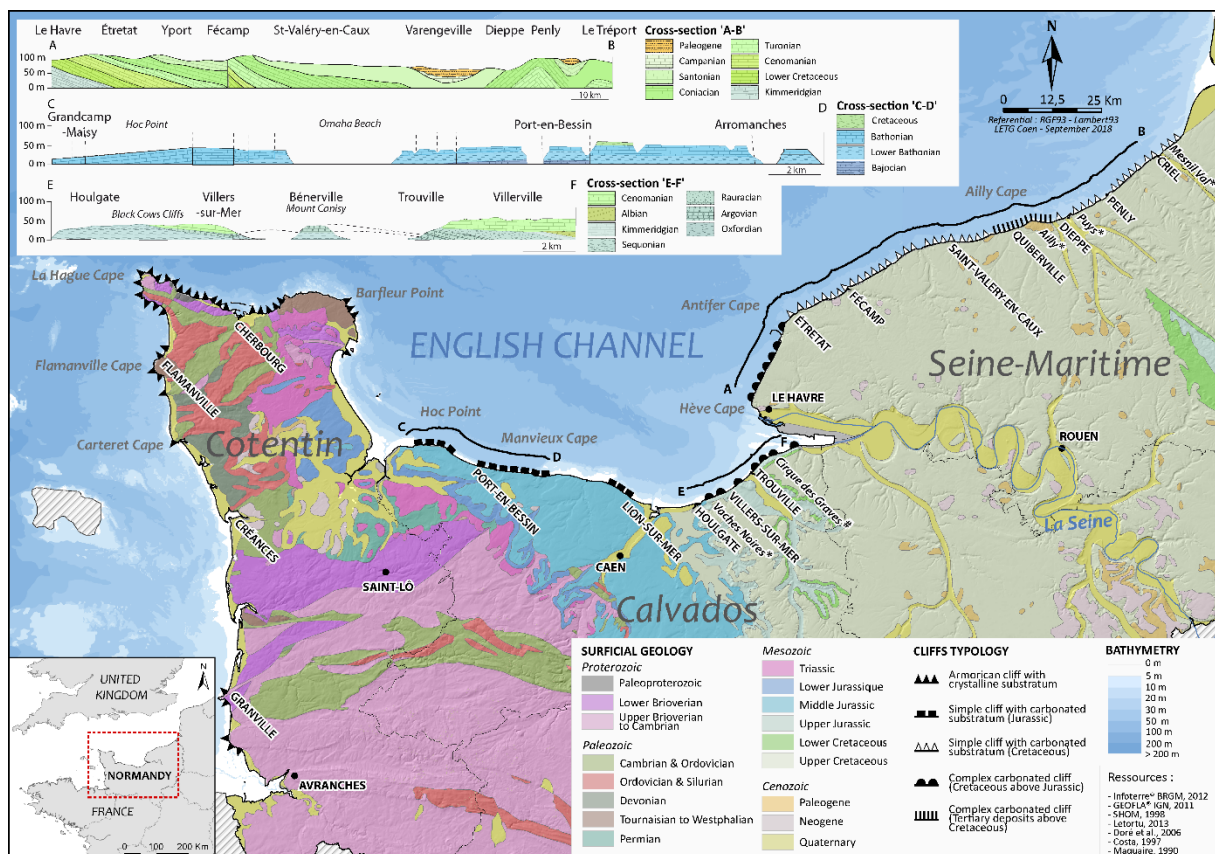
99 3- Along the plateau of the 'Pays d'Auge', the cliffs carved into the Jurassic and the Lower and Upper  
100 Cretaceous are discontinuous and looser (section E-F, fig. 1). The cliffs of the 'Vaches Noires', carved  
101 into the Oxfordian stage where some limestone beds are interstratified, are called mudflow cliffs,  
102 forming a landscape of badlands and pinnacles. In Benerville-sur-Mer, at the right of Mont Canisy  
103 (110 m), and especially between Trouville-sur-Mer and Honfleur, the cliffs reappear (section E-F, fig.  
104 1). Their foot is made of Jurassic age materials (limestone and marl) topped with Albian sand (Lower

105 Cretaceous) and Cenomanian chalk (Upper Cretaceous) suitable for deep-seated landslides (Maquaire,  
 106 1990; Lissak, 2012).

107 4- From Cap d'Antifer to Tréport, the cliffs are carved mainly into Upper Cretaceous chalk (from  
 108 Cenomanian to Campanian stages) whose facies are more or less rich in flint beds (section A-B, fig.  
 109 1). The local tectonic deformations of the Caux plateaus also explain the outcropping of some lower  
 110 Jurassic and Cretaceous strata (between Octeville-sur-Mer and Le Havre), or the conservation of sandy  
 111 and clay terrains of Tertiary age (Cap d'Ailly; Bignot, 1962). The different chalk layers (Pomerol *et*  
 112 *al.*, 1987; Mortimore *et al.*, 2004; Lasseur, 2007) show subtle variations in resistance, also found in the  
 113 cliff profile (Fig. 1). Thus, between Cap d'Antifer and Le Tréport, three types of cliffs have been  
 114 defined (Costa, 1997): simple vertical cliffs (main type) composed mainly of Coniacien-Santonian  
 115 chalk; cliffs with resistant pedestal, with a "basal" jump corresponding to the outcrop of the Turonian  
 116 stage or even the more resistant Cenomanian stage; and complex cliffs. For the latter, the Coniacien  
 117 and Santonian chalk (~ 30 m) are topped by clayey and sandy loose formations (~ 40 m), forming  
 118 three back cliffs (Cap d'Ailly).

119 Variations in resistance between the various outcrops (Juignet, 1974; Dugué, 1989; Juignet and  
 120 Breton, 1992; Laignel, 1997; Dugué *et al.*, 1998; Lasseur, 2007), visible in cliff profiles, reflect  
 121 various gravitational mechanisms (falls, slide, flow, etc.), but also different retreat rates and evolution  
 122 rhythms. The difficulty in quantifying cliff retreat lies in the slowness of the dynamics (a time taken to  
 123 prepare the rock material, often several decades before the rupture), the multiplicity and sometimes the  
 124 combination of marine and sub-aerial factors responsible for the dynamics, and the punctual  
 125 dimension of the evolution (spatially localized phenomenon).

126



127

128 Figure 1: Simplified geological map of the Normandy (from BRGM, French geological survey) and  
 129 litho-stratigraphic profiles of cliffs on the study site.

130 Normandy is located in the northwestern part of France, on both sides of the 50<sup>th</sup> northern parallel,  
 131 along the English Channel (epicontinental sea, 86 m deep on average). The environment is macrotidal

132 (Table 1) with a tidal range of 8 m (south) to 10 m (north). Waves (Table 2), which impact the cliff  
 133 foot during high tide, are limited but the wind sea can produce significant wave heights of up to 4 m at  
 134 Dieppe (annual return period).

Location	Barfleur	Le Havre	Dieppe	Le Tréport
<b>Higher Astronomic Tide (HAT) (IGN69)</b>	3.62 m	4.18 m	5.66 m	5.78
<b>Lower Astronomic Tide (LAT) (IGN69)</b>	- 2.98 m	- 4.08 m	- 4.52 m	- 4.43 m
<b>Higher level observed during storm (IGN69)</b>	4.02 m	/	5.95 m	/

135 Table 1: Tide level along the Normandy coast (Shom, 2007).

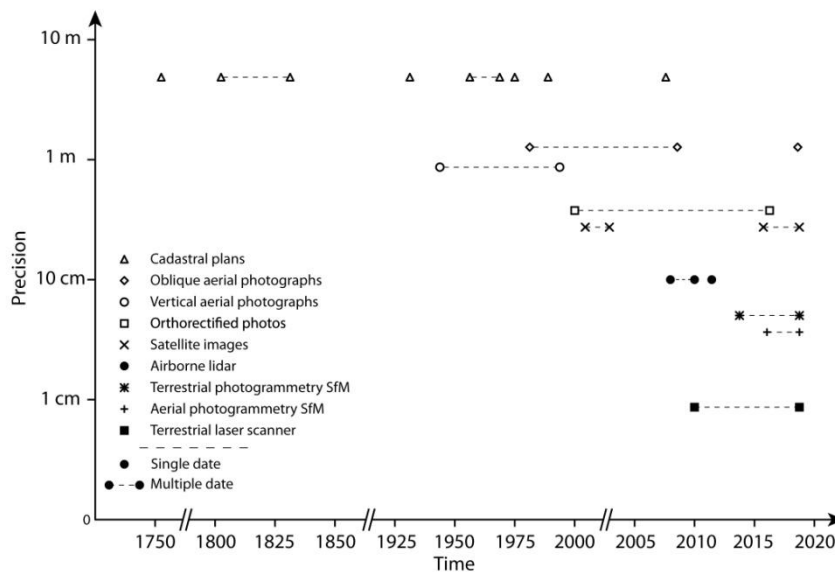
Location	Cherbourg	Le Havre	Antifer	Dieppe	Penly
<b>Annual height</b>	4.20 m	3.5 m	4.1 m	4.3 m	3.8 m
<b>Decennial height</b>	5.70 m	4.6 m	5.7 m	5.7 m	4.7 m

136 Table 2: Significant wave ( $H^{1/3}$ ) along the Normandy coast (in Augris *et al.*, 2004; Cerema, in press).

137 Normandy has a marine west coast climate. According to data from Météo-France (1971-2000),  
 138 average winter temperatures are positive but an average of 26 daily freeze/thaw cycles is recorded per  
 139 year (minimal temperature can reach  $-15^{\circ}\text{C}$ ). Rainfall is distributed over the year ( $\approx 800$  mm) although  
 140 fall and winter are the wettest seasons (51 mm in August and 94 mm in November). Daily rainfall can  
 141 exceed 77 mm in October.

## 142 2/ Methodology, material and documents

143 With regard to the objectives of this paper, the diachronic approach is central. Indeed, two main  
 144 techniques and documents are used (Fig. 2).



145  
 146 Figure 2: Techniques and documents used to study the evolution of Norman sedimentary coastal cliffs

### 147 2.1/ Quantification on historical scale and for all Norman sedimentary cliffs

148 This quantification (several decades) was carried out by classical photo-interpretation, then for the  
 149 Calvados, by comparison with ancient cartographic documents (cadastral register and "Terrier plan" of  
 150 the 19th century). The main documents used are vertical aerial photographs provided by the IGN  
 151 (National Geographic Institute), sometimes produced by photogrammetric method. The time interval  
 152 between the two series of aerial photographs is nearly 50 years (1947-2013) for the various territories  
 153 (Table 3). This diachronic approach is classic (May and Heeps, 1985; Moore, 2000; Moore and

154 Griggs, 2002; Lahousse and Pierre, 2002; Hénaff *et al.*, 2002; Costa *et al.*, 2004; Marques, 2006;  
155 Dornbusch *et al.*, 2008; Brooks and Spencer, 2010; Moses and Robinson, 2011; Letortu, 2013;  
156 Cerema, 2015). After georeferencing and rectification of the images at from 1:10,000 to 1:20,000 scale  
157 (Costa *et al.*, 2004; Letortu *et al.*, 2014; Lissak *et al.*, 2013; Maquaire *et al.*, 2013; Vioget, 2015;  
158 Roulland *et al.*, accepted), the digitization of the coastline was carried out (cliff top for the Seine  
159 Maritime, top and bottom for the Calvados cliffs). The margins of error of the results are not  
160 negligible (+/- 0.50 m to +/- 4 m). Associated with these aerial photographs, we benefited from  
161 airborne lidar data (RGE Alti- IGN) to provide a new layer of more accurate information (margin of  
162 error +/- 20 cm) that completes the analysis. Finally, for the cliffs of Calvados, old documents  
163 (cadastral registers) have been integrated. France has a single document, which is the cadastral map of  
164 all the municipalities. The first of these cadastral registers, called Napoleonic, was established in the  
165 19th century by order of Napoleon I. Carried out on a very large scale (from 1/1,000 to 1/2,500), this  
166 document has been updated to this day. The principle is attractive, but these documents exclusively  
167 express the limit of taxable parcels, which alone are perfectly mapped from one document to another.  
168 Consequently, the correct setting of these plots is logical, but it does not in any way ensure, given the  
169 danger of the measurement, the exact position of a very unstable steep slope of several tens of meters.  
170 Even if the margins of error around the position of the shoreline are large, the loss of perfectly located  
171 plots of land by erosion makes it possible to replace the cliff retreat rates obtained over a few decades  
172 in a wider time period. In addition, the multiplicity of aerial images used for different dates (Table 3)  
173 also makes it possible to provide initial information on the evolution rates of the studied cliffs.

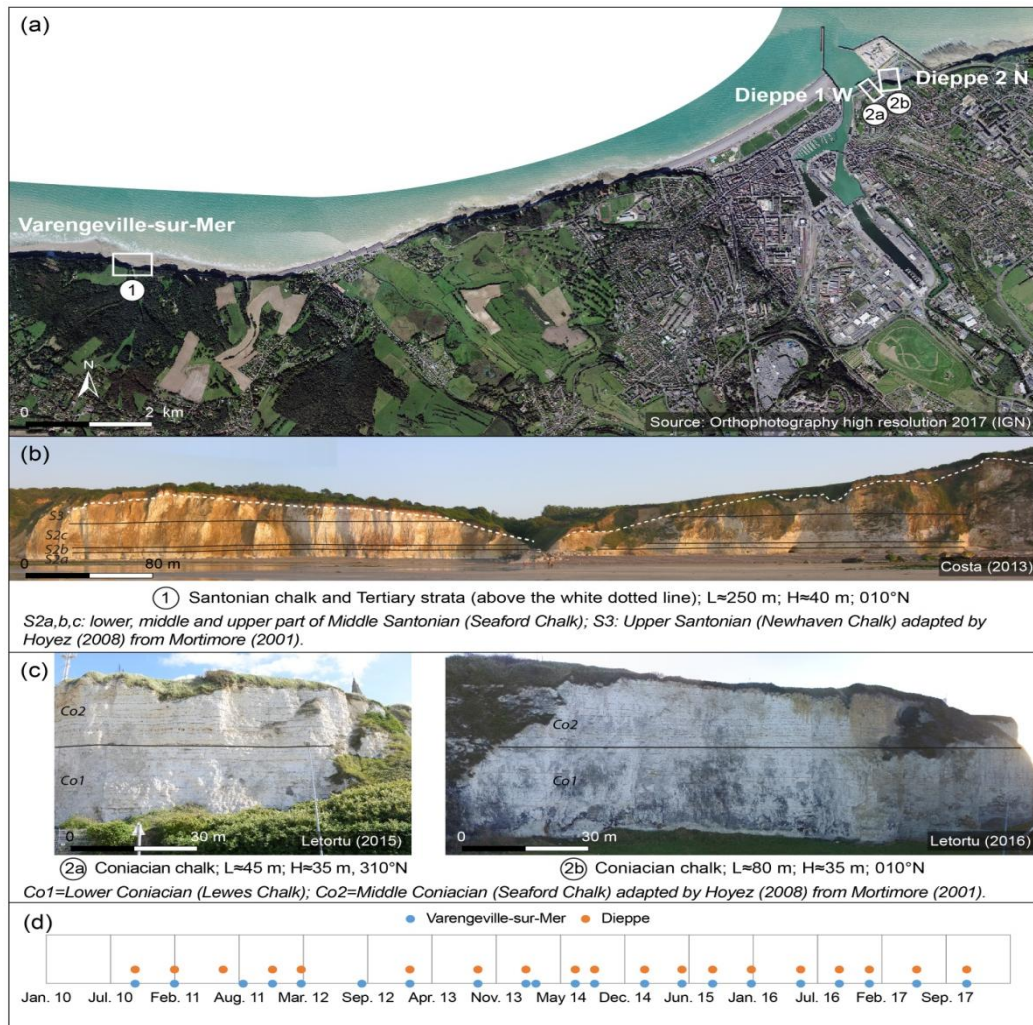
## 174 **2.2/ Quantification at high resolution and frequency diachronic monitoring**

175 In order to participate in the current debate on (1) the evolution of the cliff face, for which it is  
176 preferable, for analysis, to monitor the height or basal coastline (Lim *et al.*, 2005; Lim, 2014; Young *et al.*  
177 *et al.*, 2009; Dewez *et al.*, 2007; 2013; Michoud *et al.*, 2014; Letortu *et al.*, 2015b; Rosser *et al.*, 2013) (2)  
178 the rates of evolution (3) the processes responsible for the trigger of gravitational movements, a high  
179 resolution and frequency diachronic monitoring is carried out on some sites by lasergrammetric (TLS)  
180 and photogrammetric (SfM-MVS, *Structure-from-Motion - Multi-View-Stereo*) methods, completed on  
181 two sites by several continuous or permanent GPS stations. This work was undertaken within the  
182 framework of the SNO-Dynalit, but also SNO-OMIV.

183 Two sites are subject to these 3D monitoring in SNO Dynalit survey. These are the cap d'Ailly-Dieppe  
184 site (Seine Maritime), which has been performed since 2010 (surveys 3 to 4 times a year), and the  
185 Vaches Noires cliff near Villers-sur-Mer site since 2014 (surveys 3 to 4 times a year). On the third site  
186 of the Villerville slow-moving landslide, the monitoring system is based on twenty-four cemented  
187 benchmarks, three permanent GNSS receivers and several hydro-meteorological observation points  
188 (Lissak *et al.*, 2014).

189 **The first site is Cap d'Ailly-Dieppe** (Fig. 3a). From October 2010 (Fig. 3d), surveys using terrestrial  
190 laser scanning were carried out to monitor erosion on three chalk cliff faces with close lithological  
191 characteristics. The active cliff of Varengeville-sur-Mer is along the cap d'Ailly (6 km from Dieppe)  
192 on either side of the Petit Ailly dry valley (250 m long, 40 m high, facing 010°N, subvertical). The  
193 abandoned cliffs of Dieppe are located on the right bank of the Arques river mouth, behind an  
194 extension of the northeastern part of the harbor, land reclaimed from the sea. Dieppe 1 W (45 m long,  
195 35 m high, facing 310°N, subvertical) became abandoned during the nineteenth century whereas  
196 Dieppe 2 N (80 m long, 35 m high, facing 010°N, subvertical) became abandoned in the 1980s (Fig.  
197 3a and c). The western cliff is in front of the quay for the Newhaven–Dieppe ferry crossings. The cliff  
198 lithology in cap d'Ailly is made up with Santonian chalk, covered by a bed of clay and sand of  
199 Paleogene period (due to the syncline prone to strata preservation), which are very prone to erosion  
200 (Fig. 3b). The cliff section of Dieppe is made up of Coniacian chalk covered with residual flint  
201 formation (Fig. 3c). Even if each facies within a stage can have some subtle resistance contrasts, the  
202 Coniacian chalk is close to Santonian chalk (Laignel, 2003).  
203



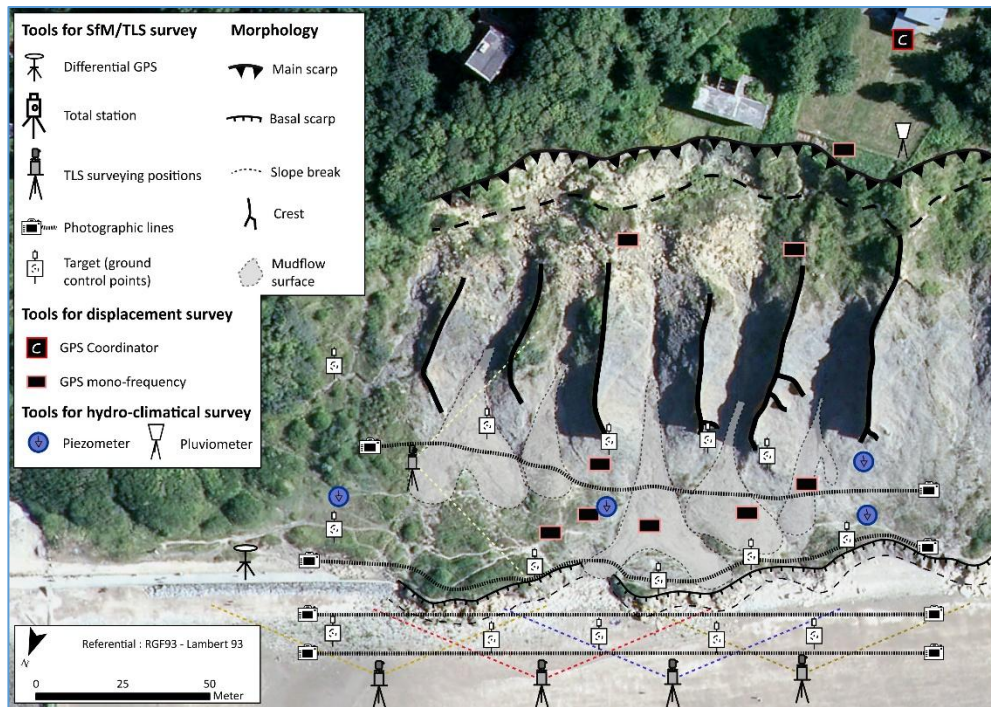


204  
205

206 Figure 3: (a) Location of the sites; (b) Main characteristics of cap d'Ailly/Varengeville-sur-Mer  
 207 site; (c) Main characteristics of Dieppe sites; (d) Terrestrial Laser Scanner (TLS) acquisition.

208

209 **The second site is Vaches-Noires coastal cliffs.** This site is located at the north-western part of the  
 210 Pays-d'Auge region between Houlgate and Villers-sur-Mer (Fig. 4), and is armed by Jurassic  
 211 limestone and clayed and marly formations. Their facies evolves under the action of continental and  
 212 marine subaerial processes through the accumulation of deposits resulting from rotational landslides  
 213 and/or mudflows at the base of the cliff which are then undermined by the sea (Maquaire *et al.*, 2013;  
 214 Medjkane *et al.*, 2018). Since September 2014, on a 200 meters coastline, cliff is monitored using 3D  
 215 models created by terrestrial laser scanner (3-4 surveys / year), terrestrial "Structure from Motion"  
 216 photogrammetry (7-8 surveys / year) and Unmanned Aerial Vehicle (UAV) photogrammetry (2-3  
 217 surveys / year). Nine single-frequency GPS have been installed on the site in order to continuously  
 218 monitor the surface displacements (landslides and mudflows). A rain gauge and four piezometers are  
 219 also installed on the site to have continuous rainfall values and oscillations of the water table.



220

221 Figure 4: Scheme of the measurement tools and equipment used for the monitoring of the “Vaches  
222 Noires” cliffs

223 The **SNO-OMIV** survey is focused on the **Villerville slope** site. This site is affected by a deep-seated  
224 rotational-translational complex landslide. It is monitored since the early 1980s, following the major  
225 event of 1982 (Maquaire, 1990). In order to measure the seasonal displacements affecting the landslide  
226 from upstream to downstream, 24 cemented landmarks were installed and their positions are regularly  
227 measured by GNSS. Since 2009, this equipment is completed by the installation of 3 GNSS receivers  
228 in the East part of the unstable area, which record their XYZ position every hour and provides a better  
229 knowledge of the evolution rhythms (velocity, distance, direction and thresholds) (Lissak, 2012;  
230 Lissak *et al.*, 2013). Groundwater fluctuations are observed across a network composed by a set of 20  
231 piezometers and inclinometers, mainly distributed on the eastern two thirds of the landslide, which is  
232 known as the most active area (Maquaire, 1990; Lissak, 2012; Lissak *et al.*, 2013). Among those  
233 devices, six are continuously tracked with multiparameter sensors (temperature and depth), the others  
234 are surveyed monthly with a contact gauge to highlight seasonal trends. Lastly, various hydro-  
235 meteorological parameters are registered by meteorological stations that records rainfall, temperature,  
236 solar radiation, wind speed and wind direction, nearby the unstable slopes at Villerville and on the  
237 plateau located at Saint-Gatien-des-Bois from 5 kilometres of the cliffs.

238 Along the **Bessin cliff**, on a local scale, four sites are surveyed by TLS and terrestrial photogrammetry  
239 SfM (4-5 times per year) since December 2017 in order to assess the rate of the retreat of the cliff base  
240 following the triggering factors. These sites are representative of the diversity of the landslide (falls,  
241 rotational and translational landslides ...) occurred in marly and limestone environments (Maquaire,  
242 1990; Vioget, 2015). In addition, on a regional scale, the evolution of Bessin cliffs is study by  
243 comparison of oblique aerial photographs taken since 1983 (thesis of Vincent Compain in progress).

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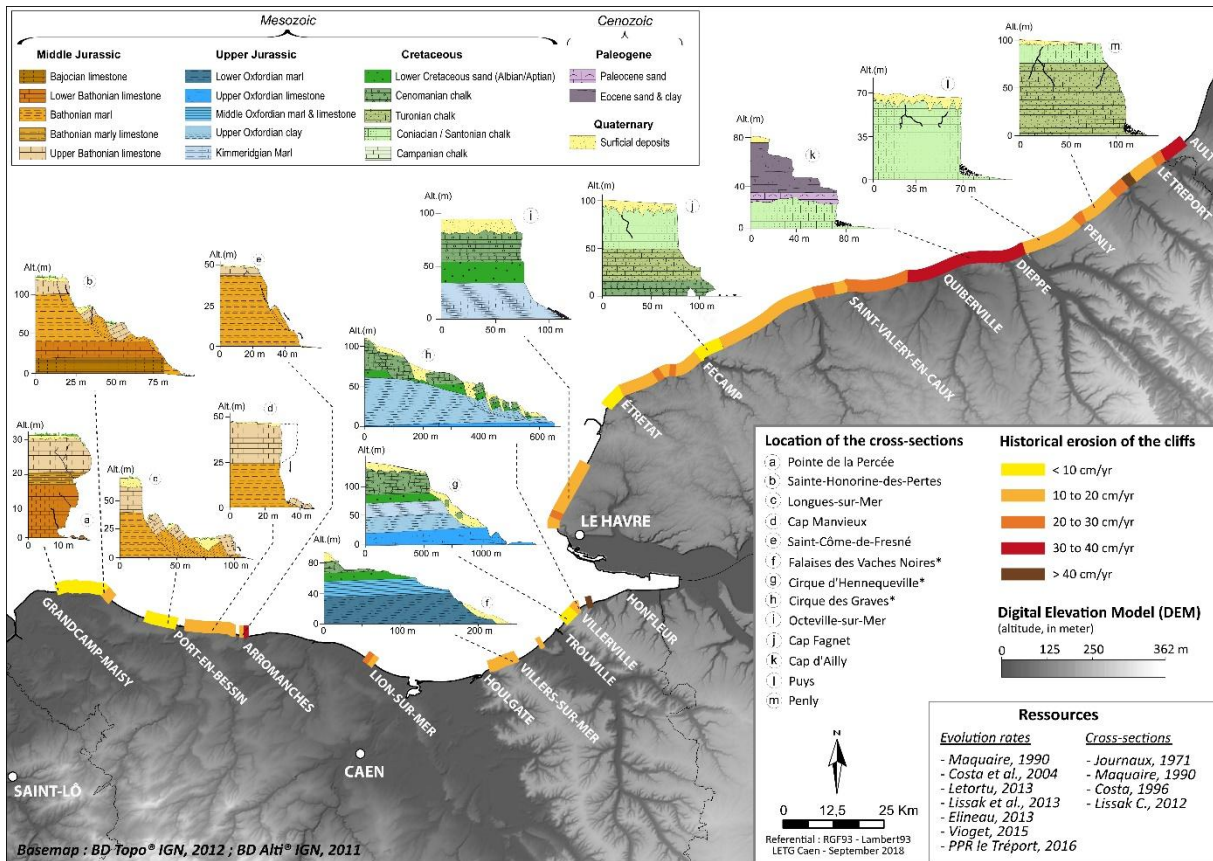
249 The TLS instrument used in this study is a RIEGL VZ-400 emitting a wavelength laser of 1,550 nm,  
250 which records unique echo digitization (RIEGL Laser Measurement Systems, 2014). The laser beam  
251 covers the environment with vertical scanning by an oscillating mirror and horizontal scanning by  
252 rotating the head. The point cloud is therefore centered on the position of the scanner. To have  
253 georeferenced data, the process of data acquisition requires additional equipment: target(s), a total  
254 station or a DGPS. The total station or the DGPS station is used to register the point cloud acquired in  
255 a relative coordinate system to an absolute coordinate system thanks to target(s) (RGF93/Lambert93,  
256 EPSG:2154). Data processing has 4 steps: (1) georeferencing and point cloud alignment; (2) manual  
257 point cloud filtering (vegetation, people, foreshore); (3) meshing using Delaunay triangulation and  
258 generation of a 3D Digital Elevation Model (DEM); (4) creating a DEM of Difference (DoD).  
259 Precision is the most important parameter in our monitoring, thus all the point clouds are fitted to a  
260 selected reference point cloud using best fit alignment algorithms (Cloudcompare® or 3DReshaper®).  
261 This adjustment reduces the error margin because it includes the TLS instrumental error (0.005 m at a  
262 range of 100 m, RIEGL Laser Measurement Systems, 2014) and the cloud adjustment error (fitting)  
263 only. To assess precision, fixed parts of the point cloud are compared using the usual data processing.  
264 The precision in planimetry is 0.03 m for cap d'Ailly and Dieppe 2 N, 0.02 m for Dieppe 1 W and  
265 Villers-sur-mer. The volume precision is  $\pm 156 \text{ m}^3$  in cap d'Ailly (surface of  $5,214 \text{ m}^2$ ),  $\pm 9 \text{ m}^3$  in  
266 Dieppe 1 W ( $434 \text{ m}^2$ ) and  $\pm 30 \text{ m}^3$  in Dieppe 2 N ( $1,018 \text{ m}^2$ ), and  $\pm 3 \text{ m}^3$  in Villers-sur-Mer ( $111 \text{ m}^2$ )  
267 (Medjkane *et al.*, 2018). These improved resolutions, particularly over the whole cliff face, and the  
268 higher frequency of acquisitions provide valuable information on ablation rates, spatial distribution,  
269 temporalities and the processes and factors responsible for triggering of gravitational movements.

270 The models obtained by SfM processing followed the method presented in Medjkane *et al.* (2018).  
271 The processing steps, carried out with Agisoft Photoscan, can be summarized as follows: (1) Image  
272 matching and orientation of cameras; (2) densification of the 3D point cloud; (3)  
273 triangulation/meshing of the point cloud; (4) texturing of the model; (5) creation of a DoD. The same  
274 targets used to georeference lasergrammetric models were used in photogrammetric models.  
275 Photographs were obtained with an advance grade camera to further improve model precision: Nikon  
276 D810 (36 million pixels, sensor size 36x24 mm) and a Sigma 35 mm fixed optics. Finally, to assess  
277 precision, the accuracy of control points on the model was compared with the precisely measured  
278 GCPs by calculating the RMSE (*Root Mean Square Error*, Eltner *et al.* 2016, Kaiser *et al.* 2014).  
279

## 280 **3/ Results**

### 281 **3.1/ Historical approach for all Norman sedimentary cliffs**

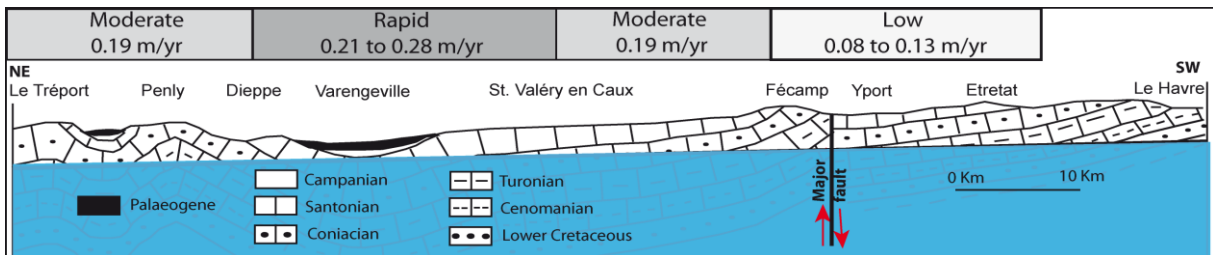
282 The study of the Norman sedimentary cliffs shows that their retreat is decimetric, from 0.1 to 0.5 m/yr  
283 during the last decades. These values are in line with the literature (Woodroff, 2002). The spatial  
284 variations of the cliff retreat rates, at the scale of Normandy, can be explained by geological structure  
285 from which the cliffs were formed) (Fig. 5). However, the differences are not excessive while various  
286 materials, of significantly different resistance, are exposed (limestones, chalks, marls, clays). The  
287 greatest variations of retreat appear for the cliffs of Seine Maritime which are nevertheless carved in  
288 materials, *a priori* more homogeneous, Cretaceous chinks.



289  
290 Figure 5: Synthesis of historical rates retreat of the Normandy sedimentary cliffs (in cm/year).

291 **Example of lithodependance: the chalk cliff of Seine Maritime**

292 Various authors have proposed cliff typologies that relate profile, resistance and disposition of rocks  
 293 (Guilcher, 1954; Trenhaile, 1987; Maquaire, 1990; Costa, 1997; Woodroffe, 2002; Senfaute et al,  
 294 2009; Dornbusch et al, 2008; Kennedy et al, 2014). These classifications sometimes make it possible  
 295 to deduce the effectiveness of the marine and continental processes involved (Emery and Kuhn, 1982;  
 296 Kuhn and Prüfer, 2014). Behind a lithological homogeneity that is only apparent, the variability of the  
 297 facies of the Seine Maritime chalk (Pomerol *et al.*, 1987; Mortimore *et al.*, 2004; Lasseur, 2007) very  
 298 clearly influences the modalities and evolution rates of the Seine-Maritime cliffs. Photogrammetry  
 299 analyses were carried out to quantify the retreat of chalk cliffs. The 1966 and 1995 vertical aerial  
 300 photographic surveys (1:10,000) from the French National Geographic Institute have been used (Costa  
 301 *et al.*, 2001; 2004). The mean retreat rate of the entire shoreline under study is approximately 6 m  
 302 between 1966 and 1995, which yields a rate of 0.21 m/yr. This average rate, however, masks a very  
 303 high spatial variability of cliff retreat (Fig. 6).



304  
305 Figure 6: Relationship between chalk rates cliff retreat and lithology (from Costa et al. 2001; 2004;  
 306 Letortu *et al.*, 2014).  
 307 In fact, the analysis allows three distinct areas to be distinguished: (i) an area of low retreat rate (0.8 to  
 308 0.13 m/yr) between Antifer and Fécamp; (ii) an area of moderate retreat rate (approximately 0.19

309 m/yr) between Fécamp and Saint-Valéry-en-Caux, and between Dieppe and Le Tréport; (iii) an area of  
310 rapid retreat (0.21 to 0.28 m/yr) between Saint-Valéry-en-Caux and Dieppe (Costa *et al.*, 2001; 2004;  
311 Letortu *et al.*, 2014).

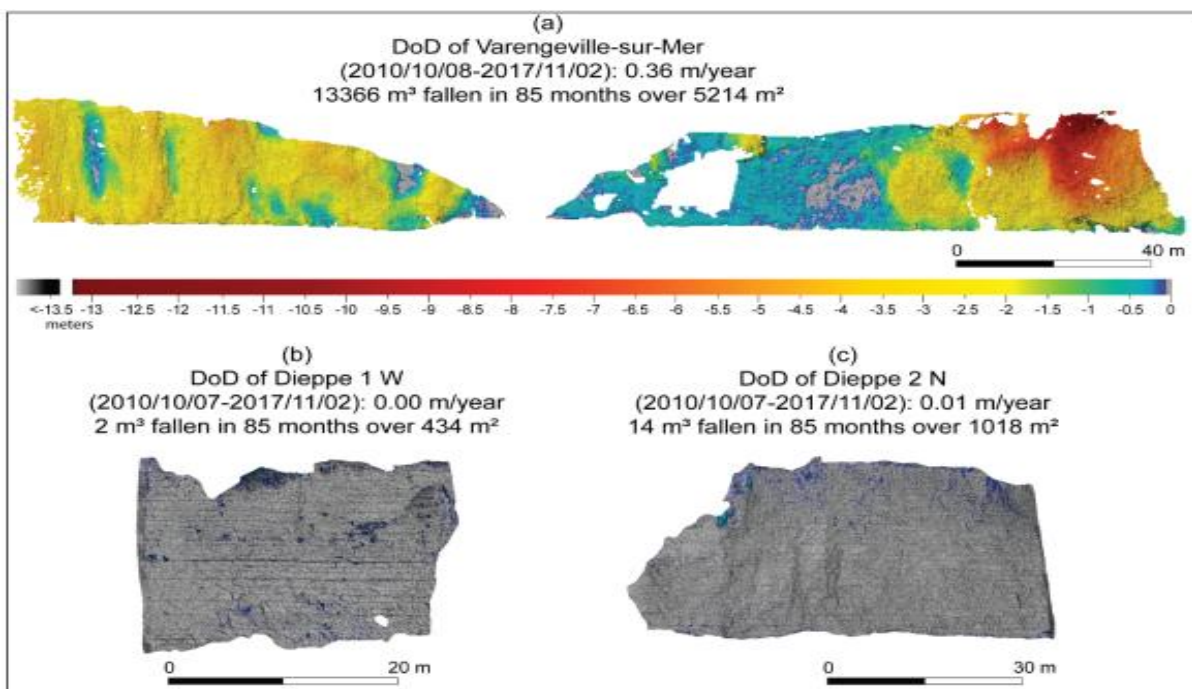
312

### 313 3.2/ Contributions of high resolution and frequency measurements

#### 314 Ablation rates and spatial distribution of the cliff face evolutions

315 For fast retreating cliffs, the emergence of techniques such as airborne or terrestrial lidars, terrestrial or  
316 UAV photogrammetry have made it possible to better estimate cliff retreat rates by integrating a  
317 fundamental dimension, the cliff face (Lim *et al.*, 2005; Rosser *et al.*, 2005; Young and Ashford, 2006;  
318 Costa *et al.*, 2001; 2004; Lahousse and Pierre, 2002; Dewez *et al.*, 2007; 2013; Young *et al.*, 2009;  
319 Lim *et al.*, 2010; Olsen *et al.*, 2011; Letortu *et al.*, 2015b; Michoud *et al.*, 2014; Kuhn and Prüfer,  
320 2014; Giuliano *et al.*, 2015; Rosser *et al.*, 2013).

321 This work (Fig. 7), carried out approximately every 3-5 months on active and abandoned chalk cliffs  
322 (cap d'Ailly and Dieppe, respectively), but with similar lithology, shows that over the period studied  
323 (2010-2017): (1) The ablation rate evaluated by TLS on active cliffs over a period of 7 years  
324 corroborates that established by photo-interpretation (observed over nearly 50 years), i.e. around 36  
325 cm/year for the cap d'Ailly and almost zero for the abandoned cliffs of Dieppe; (2) in 7 years, the  
326 entire front of the active cliff is affected by debris or mass movements; (3) scree movements (debris  
327 falls) represent 100% of the evolution of the abandoned cliff faces (for the moment!), while they  
328 represent 2% of the total retreat of the active cliff of cap d'Ailly. This quantification highlights the  
329 poor contribution of debris falls, and explains in a more detailed way the first assessments made on the  
330 same Norman chalk cliffs and East Sussex (Lageat *et al.*, 2006; May and Heeps, 1985); (4)  
331 Abandoned cliffs have evolved up to 36 times more slowly than active one, highlighting the  
332 importance of marine actions in the active cliff retreat (Letortu *et al.*, 2015b).



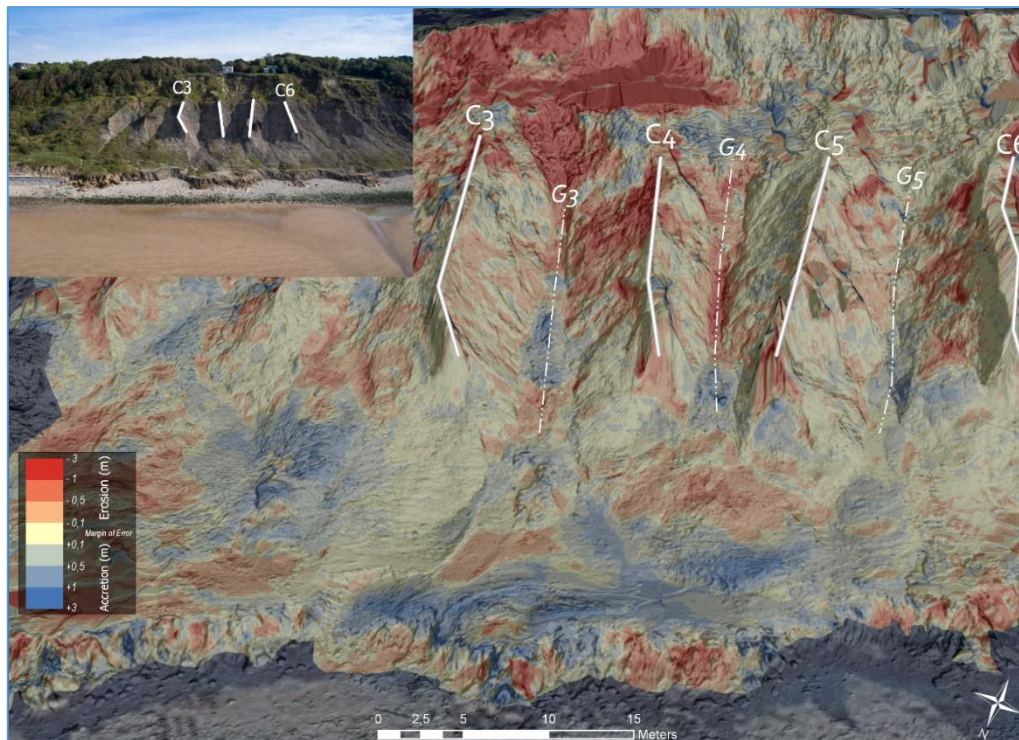
333

334 Figure 7: Erosion results of DoD over 7-years of monitoring of “cap d’Ailly/Varengueville-Dieppe”  
335 site.

336 For the “Vaches noires” cliffs, the TLS differential model (March 2015 and October 2017) clearly  
337 identifies erosion areas (red color) and accretion areas (blue color) (Fig. 8) at high spatial resolution.  
338 The main eroding areas are the upstream scarp, the flanks of the interfluvial ridges, and the basal scarp.



339 Those in accumulation are visible at the outlet of the gullies and very locally at the top of the basal  
 340 scarp. However, in detail, we note that the erosion and accumulation sectors follow one another  
 341 spatially in the gullies, at their outlet and at the level of the basal scarp. These values reveal the  
 342 seasonal activity of the cliffs of the “Vaches Noires” with a contribution of materials upstream of the  
 343 cliffs and the finest elements that will then be partially cleaned and swallowed by the sea. After these  
 344 observations, the high temporal frequency survey allowed to assess the different accumulated / eroded  
 345 volumes according to the processes and associated morphologies (ablation zone and accumulation  
 346 zone) between the different dates in order to better understand the seasonal temporality and the role  
 347 and the weight of each controlled factors (sea erosion and groundwater elevation) (Thomas Roulland  
 348 thesis in progress).

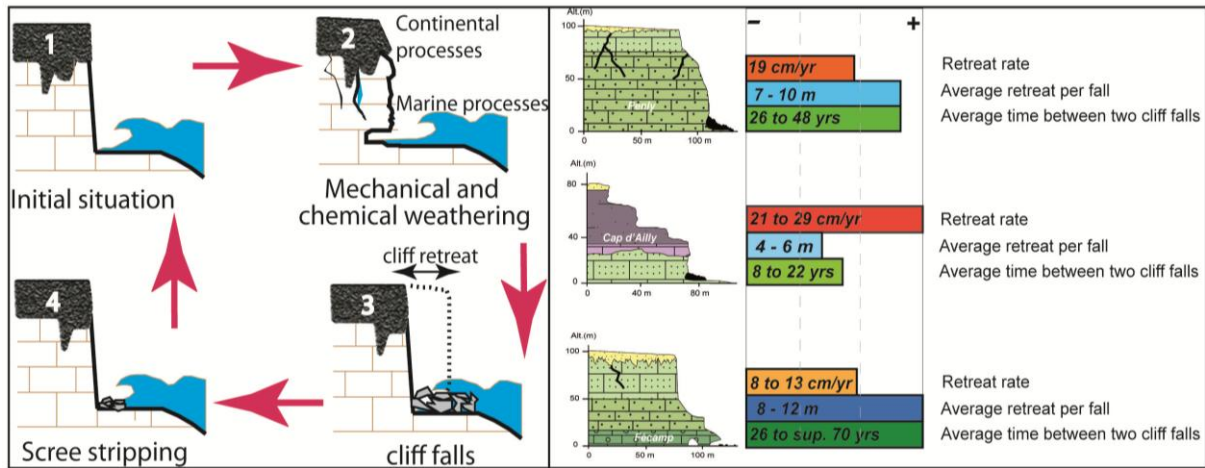


349  
 350 Figure 8: Erosion and accretion areas: TLS differential model of “Vaches noires” cliffs (March 2015 -  
 351 October 2017)

## 352 4/ Discussion

### 353 4.1/ Rhythms of evolutions

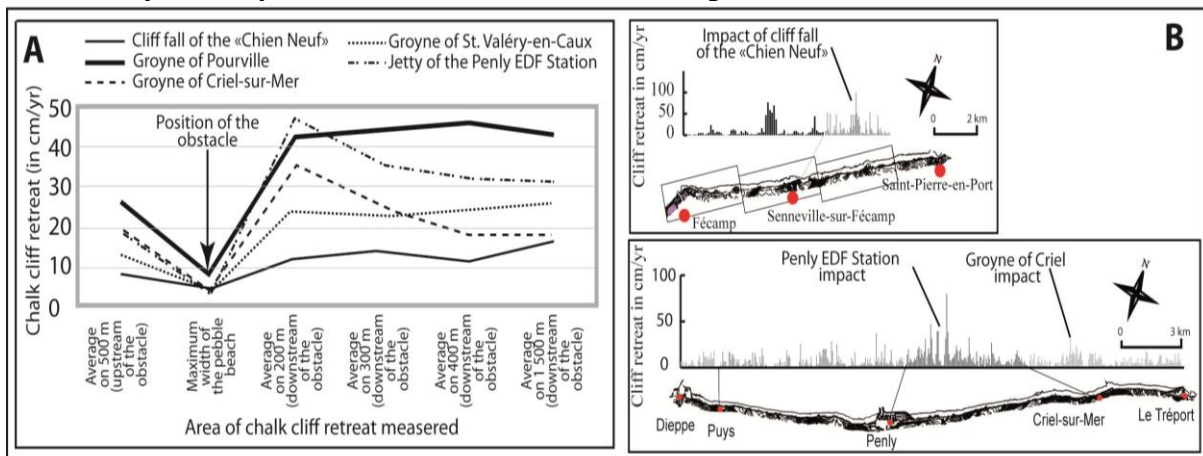
354 The identification of several sectors with distinctive retreat rates raises questions about the causes of  
 355 this spatial distribution of the cliff retreat rates (especially its relation to the outcropping of different  
 356 chalk strata), and more, the temporalities between two cliff collapses at the same location (Evrard et  
 357 Sinelle, 1980; Trenhaile, 1987; 2011; Sunamura, 1992; Prager *et al.*, 2008; Kennedy *et al.*, 2014). The  
 358 knowledge of the cliffs evolution rhythms is as fundamental as that of their rates, especially in the  
 359 context of the timing of the movement of properties and people threatened by the decline. As the  
 360 Figure 9 shows for the chalk cliffs of Seine Maritime, the sectors with “low” and “moderate” retreat,  
 361 are affected by infrequent but voluminous rockfalls (Costa 1997; Costa et al. 2003; 2004; Letortu  
 362 2013), and correspond to cliff foot cut into Turonian, Cenomanian, and even Coniacian outcrops  
 363 (Antifer/Fécamp ; Fécamp/Saint-Valéry-en-Caux ; Dieppe/Le Tréport). By contrast, the rapidly  
 364 retreating sectors, affected by frequent but less voluminous rockfalls, correspond to Santonian and  
 365 Campanian outcrops (Saint-Valéry-en-Caux/Dieppe).



366

367 Figure 9: Cliff retreat, average retreat per fall and average time between two cliff falls for cliffs chalk  
 368 of Seine Maritime.

369 Even within each of these coastal sections, important variations do exist. These sharp variations are  
 370 linked with the influence of cliff collapses or anthropogenic obstacles, such as harbour arms or major  
 371 groynes that disrupt the gravel transit from the south-west to the north-east. Then down current from  
 372 these obstacles, the cliff retreat can be multiplied by 2 (Costa *et al.*, 2006). These observations are  
 373 confirmed by the analysis of the retreat at 50 m intervals (Fig. 10).



374

375 Figure 10: Impact of major cliff falls or anthropogenic obstacles on chalk cliff retreat of Seine  
 376 Maritime (A), and some examples of measures at 50 m intervals (B).

377 For the **“Vaches Noires”** cliffs, by comparing old documents (terrier plan, land register map, aerial  
 378 photographs, postcard photography) and more contemporary data (orthophotographs, satellite images,  
 379 dGPS surveys, LIDAR survey) between 1759 and 2016 (257 years), the results show a marked decline  
 380 in the main scarp estimated at - 0.39 m/year, but also an average annual decline of - 0.27 m/year  
 381 between 1837 and 2016 (179 years). The secondary scarp declined more modestly by - 0.23 m/year  
 382 between 1759 and 2016 (257 years), then by - 0.48 m/year over the period 1837 and 2016 (179 years).  
 383 The basal scarp has a more contrasted evolution, with some sectors in erosion, others in progradation,  
 384 and some sectors without significant evolution (or included in the margins of error). The erosion  
 385 values are generally between - 0.02 m/year to - 0.15 m/year between the different periods. The  
 386 progradation values range from + 0.02 m/year to + 0.15 m/year, often included in front of the locality  
 387 "Hermitage". Comparison with the average evolution rates (in m/year) of other Normandy clay and  
 388 marl cliffs (ranging from -0.15 m/year to -0.30 m/year) showed that the foot of the basal scarp suffered  
 389 a slight overall decline. These studies showed that nuances needed to be made in the evaluation of  
 390 shorter time step velocities due to the reactivation and progression of major landslides on the foreshore  
 391 that alter the coastline. In the cliffs of the “Vaches Noires”, this is visible in the area known as  
 392 "l'Hermitage" where a large landslide occurred between 1837 and 1947, causing the main scarp to



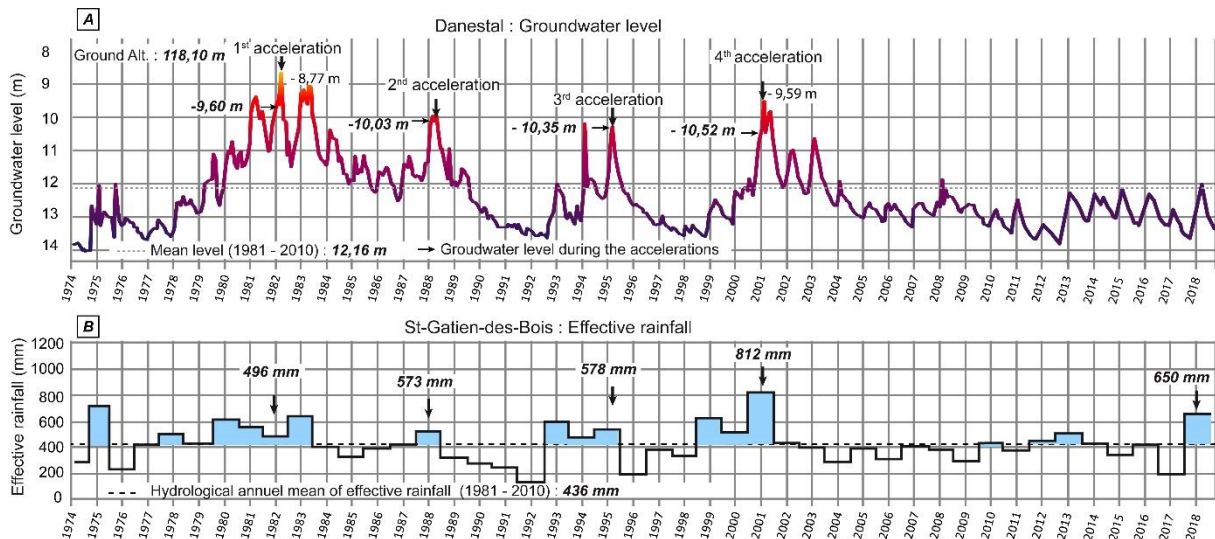
393 retreat by more than 120 m and the coastline to advance by more than 50 m (Maquaire *et al.*, 2013;  
 394 Roulland *et al.*, in press).

395 Thus, on sectors with cliffs evolving by landslides and mudflows, nuances in the evolutions must be  
 396 made according to the sectors and according to the periods considered. The evolution calculated over a  
 397 long period is probably more significant when taking into account the "cycle" of evolution of the cliff.  
 398 For marl cliffs of different configurations, evolution can occur within cycles of 30 to 40 years in  
 399 London clays (Hutchinson, 1973), or of a hundred years in the Gault clay cliffs of Dorset (Brunsden  
 400 and Jones, 1980) where the activation of summit flows depends largely on the retreat of the lower part  
 401 of the cliff (Pierre, 2005). Thus, for the "Vaches Noires" cliffs, the duration of the "cycle" to be taken  
 402 into account would be at least around 250 to 300 years to be able to set a long-term evolutionary trend  
 403 of decline.

404 **4.2/ Factors responsible for triggering gravitational landslides (rockfall, slide, debris fall) and**  
 405 **thresholds**

406 The cross-referencing of multi-date and multi-document data as well as that of some agents as erosion  
 407 processes can provide information about the factors responsible for triggering gravitational landslides.  
 408 At the **SNO-OMIV landslide of Villerville**, the link was clearly established between efficient rainfall,  
 409 groundwater level and displacements of the unstable slopes (Maquaire, 1990; Lissak *et al.*, 2009;  
 410 Lissak, 2012). Efficient rainfall increase the roof level of the groundwater until it exceed a threshold  
 411 rain quantity, considered in the literature as the main triggering factor of worldwide landslides  
 412 (Zezere, 2002; Zezere *et al.*, 2015; Guzzetti *et al.*, 2008; Peruccacci *et al.*, 2017). The link  
 413 intensity/duration has a particular impact on the overtaking of this threshold (Zezere *et al.*, 2015).

414 In order to highlight the relationship between rain, groundwater and displacement of the Villerville  
 415 deep-seated landslide, long-term chronicles of data should be used (Fig. 11). To this end, data from a  
 416 piezometer of the national network located in Danestal (in the hinterland, on the Pays d'Auge plateau)  
 417 were crossed-analysed with efficient rainfall data measured at the Météo-France weather station of  
 418 Saint-Gatien-des-Bois (located 5 km backwards the landslide). Then, those chronicles were linked to  
 419 the major events known which affected this great coastal landslide.

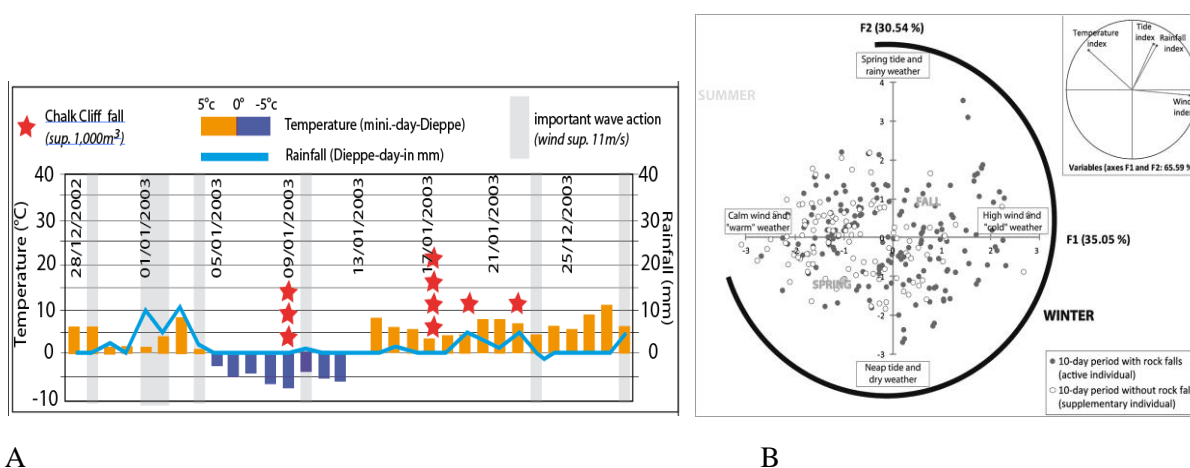


420  
 421 Figure 11: Evolution of the groundwater level of the Danestal well and of the effective annual rainfall  
 422 of the St-Gatien-des-Bois climatic station from 1974 to 2018

423 This correlation analysis, initially expressed by Lissak (2012), revealed a small-scale causal  
 424 relationship between the hinterland groundwater level and the four major accelerations observed on  
 425 the coast (Fig. 11). From this observation, a regional warning threshold have been proposed in cases in

426 which the piezometer of Danestal exceed a depth of 11m/GL and the effective rain on a 4-months-  
427 period is over 250 mm (Lissak *et al.*, 2013).

428 **For the chalk cliffs of Seine Maritime**, determination of the triggering factors of rock falls is more  
429 difficult. Based on a census of 331 chalk cliff rock falls collected weekly between 2002 and 2009 from  
430 Veules-les-Roses to Le Treport the relationship between dates of cliff rock falls and external factors  
431 commonly agreed as triggering (rainfall, temperature variations, tide and wind) is studied (Fig. 12).  
432 The combination of multivariate statistical and empirical analyses indicates (Letortu *et al.*, 2015a) that,  
433 (1) the high rainfall are an essential triggering factors and especially the most massive chalk rock falls  
434 (mostly larger than 10,000 m<sup>3</sup>) (confirmed studied of Pierre and Lahousse, 2006; Duperret *et al.*, 2002;  
435 2004; 2005), (2) but also the freeze/thaw cycles which are responsible for scree production phenomena  
436 (individual particles), (3) marine factors are not negligible but their influence is difficult to quantify  
437 because rock falls of small volumes may be quickly removed during a turbulent period. However, the  
438 contribution of each factor to triggering is difficult to determine because of combinations of factors  
439 (84 % of 331 cases), relays of processes and hysteresis phenomena. In view of these first results, it is  
440 still presumptuous to predict the location and time of triggering of rock falls. However, the statistical  
441 and naturalistic approaches adopted and the observations made in this study are from an original  
442 database, and constitute a real starting point for the prediction and prevention of the hazard of coastal  
443 chalk cliff rock falls.



444

445 A

B

446 Figure 12: Example of relationship between cliff falls inventoried and external factors shows  
447 combinations and relays of processes (A), and multivariate statistical analyses (PCA) of 331 chalk  
448 cliff rock falls (Letortu *et al.*, 2015a) of Seine Maritime (B).

## 449 Conclusion

450 The retreat rates of the sedimentary cliffs of Normandy are about 20-30 cm/year. These values are in  
451 line with what is generally observed for this type of geology (Woodroff, 2002; Dunrbush *et al.*, 2008;  
452 Mooses and Robinson, 2011; Kennedy *et al.*, 2017). Spatial disparities are due to lithological  
453 variations (outcrop less resistant at the foot of cliffs), but also and above all to the existence of  
454 obstacles to coastal drift (structures or cliff falls) which considerably and locally increase the retreat  
455 rates. These values are also comparable to what has been observed on the English coasts for similar  
456 materials (Dunrbush *et al.*, 2008) while the orientation towards swells is different. However, beyond  
457 the lithological variations there may be other factors that explain the spatial variation in retreat rates.  
458 Among these factors not exposed in this work are the width of the platform, the height of the cliff, the  
459 width of the beaches at the foot of the cliffs, the intensity of the fracturing of the rocks, the presence of  
460 more or less important groundwater...

461 This work also shows the interest of diachronic analysis using a multisource and multitemporal  
462 approach (comparison of historical documents of modest precision, but allowing observation over

463 large areas with high frequency and high resolution data, allowing the cliff face to be studied locally).  
464 This work provides information on the "periodicities" of the evolution of the various cliffs that are  
465 essential for the temporal management of the movement of goods and people.

466 The high frequency and high resolution monitoring carried out as part of SNO-Dynalit and SNO-  
467 OMIV greatly improves the knowledge of these sites. Even if the monitoring is carried out only in  
468 fairly small areas, it allows to finely spatialize the evolutions, especially on the cliff face. It makes it  
469 possible to distinguish between screes and mass movements, to quantify the production of debris  
470 brought to the sea. However, the development of these new techniques (laser and photogrammetry) is  
471 recent (a decade). The results therefore have a limited temporal representativeness. To be exhaustive,  
472 high-resolution data will have to be acquired over the entire cliff evolution periodicity ("evolution  
473 cycle"), which for some of them is at least two decades. Similarly, the frequency of surveys should be  
474 well above 3-4 per year to define the agents and processes responsible for weathering cliffs or  
475 triggering gravity movements. It is also for these reasons that it is very difficult to estimate the impact  
476 of climate change and sea level rise on cliff recession rates. Moreover, the extent of anthropization on  
477 coastal dynamics in recent decades masks the possible influence of these global changes.

478 This work also shows the importance of setting up observatories for long-term monitoring such as  
479 INSU's SNO-Dynalit and SNO-OMIV, or INEE's "workshop zones" ("Zones Ateliers" of National  
480 Institute on Ecology and Environment studies).

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487 Cot: flood and storm surge Risk and Hazard of coastal towns : quantitative and virtual reality approach  
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