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1 **Statistical and empirical analyses of the triggers of coastal chalk cliff failure**

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13

14 **ABSTRACT:**

15 The triggering factors of rock falls remain unknown due to a lack of exhaustive,
16 regular and accurate surveys. Based on an inventory of 331 rock falls collected
17 weekly between 2002 and 2009 from Veules-les-Roses to Le Treport (Upper
18 Normandy), the relationships between coastal chalk cliff rock falls (dates and
19 geomorphological features) and external factors commonly agreed as triggering
20 (rainfall, temperature variations, tide and wind) are studied. The combination of
21 multivariate statistical and empirical analyses indicates that (1) “cold and dry
22 weather” and “high rainfall and high wind” are the conditions most likely to trigger
23 rock falls, (2) the main triggering factors of rock falls are effective rainfall (for rock
24 falls mostly between 200 and 1,400 m³ or larger than 10,000 m³ and coming from the
25 whole cliff face), freeze/thaw cycles (especially for rock falls smaller than 200 m³ and

26 coming from the foot and top of the cliff face) and marine roughness (rock falls mainly
27 smaller than 200 m³ and coming from the cliff foot). However, the contribution of each
28 factor to triggering is difficult to determine because of combinations of factors (85 %
29 of 331 cases), relays of processes and hysteresis phenomena. In view of these first
30 results, it is still presumptuous to predict the location and time of triggering of rock
31 falls. However, the statistical and naturalistic approaches adopted and the
32 observations made in this study are from an original database, and constitute a real
33 starting point for the prediction and prevention of the hazard of coastal chalk cliff rock
34 falls in Upper Normandy.

35

36 **KEYWORDS:** coastal chalk cliff rock falls, triggering factors, statistical analyses,
37 empirical analysis, Upper Normandy

38

39 **Introduction**

40 Except for a consensus about the influence of structural features, external triggering
41 factors of rock falls are still under scientific debate. In this paper, the term “rock fall” is
42 used to describe movements of coherent rock (Varnes, 1978).

43 Many studies emphasize the importance of sub-aerial actions over marine actions
44 (Brossard and Duperret, 2004; Pierre and Lahousse, 2006), which are assumed to be
45 just a transport agent. The role of rainfall through surface runoff, infiltration, and water
46 table levels may reduce the stability of cliffs (Sunamura, 1992; Duperret et al., 2002;
47 Hénaff et al., 2002a; Young et al., 2009). Because of the porosity of coastal chalk
48 cliffs, they are particularly sensitive to processes induced by water (Hutchinson,
49 1972; May and Heeps, 1985; Duperret et al., 2002, 2004; Lahousse and Pierre,
50 2003; Pierre and Lahousse, 2006). Freezing action is also mentioned. Many

51 geomorphological studies have focused mainly on the freezing process (Robinson
52 and Jerwood, 1987) whereas thermoclasty has been less studied (Hall, 1999). This
53 freezing process has been extensively studied and sometimes quantified, especially
54 in periglacial environments, and may be conducive to triggering rock falls (Fournier
55 and Allard, 1992; Bernatchez and Dubois, 2008). The porosity of chalk leads to a
56 high sensitivity to temperature variations, with freezing often being considered a
57 triggering factor. For the coastal chalk cliffs studied, the porosity ranges between
58 32 % and 46 % from the Turonian to Campanian stages (Duperret et al., 2005). The
59 characteristics (including its porosity range) and salt content (Robinson and Jerwood,
60 1987; Jerwood et al., 1990a, 1990b) of chalk identify it as a “frost-shattered” rock. It is
61 the number of freeze/thaw cycles that is important rather than the intensity of freezing
62 (Letavernier, 1984). Cryoclastism can be quite remarkable in terms of debris
63 production: during the thaw of 31/12/1995, the volume of debris was estimated at 900
64 m³ for a cliff face surface of 44,000 m² (Costa, 1997).

65 Some authors consider that marine actions are too often overlooked and emphasize
66 the prevalence of these actions in cliff retreat (Hoek and Bray, 1977; McGreal, 1979;
67 Sunamura, 1982, 1992; Trenhaile, 1987; Trenhaile and Kanyaya, 2007). Their role as
68 a factor in erosion is widely recognized (King, 1972; Emery and Kuhn, 1982;
69 Sunamura, 1982; Trenhaile, 1987; Stephenson, 2000; Woodroffe, 2002; Costa et al.,
70 2006a; Lee, 2008; Castedo et al., 2012). The potential of wave action to destabilize
71 cliffs has been demonstrated by modeling (Emery and Kuhn, 1982; Sunamura, 1982;
72 Trenhaile 2009, 2010) and in the field by microseismic sensors (Adams et al., 2002;
73 Senfaute et al., 2009; Young et al., 2012) or with high resolution laser tools to view
74 the effects of undercutting and extraction (Dewez et al., 2013). Moreover, waves may
75 use gravels and boulders as projectiles to increase their attack power, causing

76 undercutting (Robinson, 1977; Costa et al., 2006b). On rocky chalk coasts, wave
77 action has been increasingly studied as a triggering factor of rock falls (Brossard and
78 Duperret, 2004; Costa, 2005; Costa et al., 2006a and b; Dornbusch et al., 2008).
79 Although Brossard and Duperret (2004) stated that the impact frequency of waves
80 without projectiles seems to be too low to trigger large rock falls, it appears that the
81 triggering of rock falls related to marine actions often occurs during paroxysmal storm
82 conditions.

83 In the recent scientific literature, the triggering of rock falls seems increasingly the
84 result of a combination of factors, as the coastal environment is a complex system.
85 However, this may reflect the difficulty of identifying the contribution of each factor,
86 which results from a lack of precise dating of rock falls over long periods, a lack of
87 high frequency data about the factors involved in the triggering and the diversity of
88 scales at which the data are recorded (Genter et al., 2004; Naylor et al., 2010).
89 Moreover, the results are often valid only for the study sites because of specific
90 contexts of morphostructural features and local meteorological and marine
91 conditions.

92 Collaboration between the LETG-Caen Geophen laboratory and the non-profit
93 organization ESTRAN led to the creation of a weekly inventory of rock falls between
94 2002 and 2009 from Veules-les-Roses to Le Treport (37.5 km). Using this original
95 database of 331 events over 7 years, the objective of this work is to participate in the
96 debate about the triggering factors of rock falls with two main research questions:

- 97 1) which marine and meteorological conditions are conducive to rock falls?
- 98 2) what is/are the triggering factor(s) of rock falls?

99 To answer these questions, this paper describes the application of two methods:
100 statistical analyses to identify the meteorological and marine conditions conducive to

101 rock falls and an empirical analysis to give a hierarchy of factors leading to the
102 triggering of rock falls. For each type of analysis, geomorphological features of rock
103 falls (fallen volume and the part of the cliff face area affected by the rock fall) are
104 integrated in our analyses to improve understanding of the relationships between
105 triggering factors and the types of movements generated. In fact, this work aims to
106 determine whether triggering factors generate various types of movements. If this is
107 not the case, the geomorphological characterization of rock falls per triggering factor
108 will improve the prediction of this hazard.

109

110 **Climate and rock fall database along the studied coastline**

111 In north-west France, the Upper Normandy coast (N 50°0'0", E 1°0'0") is located
112 along the English Channel (Figure 1). The environment is macrotidal with an average
113 tidal range of 8 m. Swell is limited but the wind sea can reach a significant wave
114 height of 4 m in Dieppe (annual return period) (Augris et al., 2004). Upper Normandy
115 presents a marine temperate west coast climate. Winter temperatures are positive
116 but an average of 26 daily freeze/thaw cycles is recorded per year (minimal
117 temperature can reach -15°C). Rainfall is distributed over the year (≈800 mm)
118 although fall and winter are the wettest seasons (min: 51 mm in August and max: 94
119 mm in November). Daily rainfall can reach 77 mm in October (Meteo-France, 1971-
120 2000) (Table I).

121 Located at the northwestern end of the sedimentary Paris Basin, Upper Normandy
122 coastal chalk cliffs consist of Upper Cretaceous chalk (from the Cenomanian to
123 Campanian stages) (Figure 1). These cliffs recede with an average retreat rate of
124 0.15 m/y but with a high spatial variability (0.23 m/y between Saint-Valery-en-Caux
125 and Dieppe (Costa et al., 2004, 2006b; Letortu et al., 2014a)). These values are not

126 representative of rock dynamics because, in reality, retreat occurs in jerks (rock falls).
127 These rock falls, currently unpredictable, threaten urbanization settled too close to
128 the coastline (Figure 2).

129 From 2002 to 2009, the non-profit organization ESTRAN monitored the cliff face
130 evolution between Veules-les-Roses and Le Treport (37.5 km) to provide an
131 inventory of rock falls .These cliffs are made of Turonian to Campanian chalk (Figure
132 1). For each of the 331 rock falls inventoried, photographs and measurements were
133 taken and recorded on an index card with information about the location, length,
134 height, width, and date of the rock fall (if the latter was unknown, the date of
135 observation was used) (Figure 3A). The rock falls have a variable distribution in time
136 and location (Figures 3B and 3C) (Letortu et al., 2014b). However, they occur
137 especially along the Cap d'Ailly (Varengeville/Sainte-Marguerite-sur-Mer; 53 % of
138 total fallen volume; 75 % of total number of rock falls) and in winter (53 % of total
139 fallen volume; 41 % of total number of rock falls).

140 Geomorphological features were added to this database (Table II). Using
141 photographs, it was possible to observe the departure area of material on the cliff
142 face (10 rock falls have an unknown departure area due to the lack of photographs).
143 The cliff face was divided into 3 parts (foot/middle/top and combinations): 32 % of
144 rock falls occur at the foot, < 1 % in the middle part, 6 % at the top, 42 % include the
145 whole cliff face and 20 % the foot and middle part of the cliff face.

146 This spatial distribution is important because it may give some clues about the
147 triggering factor. For example, a rock fall with a cliff top departure is more probably
148 due to sub-aerial agents than marine agents.

149 From rock fall measurements made by ESTRAN, the volume was calculated (rock fall
150 shape as a straight prism with a rectangular base; overall bulking factor of 33 %

151 (Hénaff et al., 2002b)). Twelve rock falls have an unknown volume due to the lack of
152 measurements. The fallen volume ranges from 1 m³ to 236,000 m³ but almost 40 %
153 of rock falls are smaller than 200 m³ (Figure 4A). The biggest example (236,000 m³
154 according to ESTRAN field measurements) occurred on the night of 13th to 14th March
155 2008 in Dieppe.

156 Due to the statistical range of the fallen volumes, and in order to perform statistical
157 and empirical analyses, the population was divided into different classes, determined
158 from the volume frequency histogram between 2002 and 2009 (method of observed
159 thresholds). Four classes appeared (Figure 4B):

160 - rock falls with a volume less than 200 m³ (126 rock falls, 39 %). Some may have
161 been evacuated in a few days (according to Hénaff et al. (2002b): about 40 m³ per
162 day are removed by marine actions along the Upper Normandy coast) and have left
163 few traces for the weekly inventory of the ESTRAN organization. Thus, the analysis
164 and results of these small volumes should be treated with caution;

165 - rock falls with a volume between 200 and 1,400 m³ (100 rock falls visible from one
166 week to another, 31 %). These mainly concern only one part of the cliff (foot, middle,
167 top);

168 - rock falls with a volume between 1,400 and 10,000 m³ (77 rock falls, 24 %). These
169 usually affect one part of the cliff face and sometimes the whole section;

170 - rock falls with a volume greater than 10,000 m³ (16 cases, 5 %). These movements
171 mainly affect the whole cliff face (15 cases, only 1 case from the cliff top).

172 The originality of the database lies in (1) the length of the observation period (7
173 years) and the coastline monitored (37.5 km), which enable statistical analyses of
174 331 rock falls, (2) the high periodicity of the readings (every week), (3) the precise
175 date of the discrete retreat events (from the 10-day period to the day), (4) the

176 horizontal point of view, which is the best one to follow all cliff changes (Young et al.,
177 2009), especially small ones, (5) the measurements and photographs of the rock
178 falls, which enable geomorphological characterization of the movements (volume,
179 departure area of the rock fall). This database can thus contribute to the current
180 debate about triggering factors of coastal chalk cliff rock falls.

181

182 **Methods**

183 The rock fall database offers great potential for statistical analyses due to the size of
184 the population (331 individuals), its accuracy and reliability. Rock falls (number or
185 fallen volume per decade) correspond to Y (dependent variables to explain) while the
186 independent variables X (assumed explanatory) are meteorological and marine
187 conditions (external factors influencing the occurrence of rock falls). This work is
188 based solely on the analysis of external factors (marine and continental factors), the
189 only homogeneously quantifiable elements across the sector considered. Obviously,
190 internal factors are also fundamental, but these data (fracturing, karstification,
191 lithostratigraphy) along 37.5 km of coastline are heterogeneous, at different scales,
192 and not always available (Laignel, 2003; Duperret et al., 2004; Mortimore et al., 2004;
193 Costa et al., 2006a; Hoyez, 2008).

194 To choose external variables, many data are available (Meteo-France, SHOM
195 (French Naval Hydrographic and Oceanographic Service)) but variables must:
196 - have a meaning in terms of agents and processes potentially conducive to
197 triggering (thermal variations such as freeze/thaw cycles, hydroclasty, marine
198 roughness);

199 - be non-redundant (determined by a correlation matrix carried out with all factors) in
200 order not to alter statistical analyses (e.g. two variables about rainfall against one for
201 wind give a higher statistical weight for rainfall);
202 - be the most discriminating variable per type of factor (rainfall, temperature, wind,
203 tide). This is observable by the variable contributions from Principal Component
204 Analysis (PCA) performed with all meteorological and marine data (minimum
205 temperatures, maximum temperatures, sum of rainfall, sum of effective rainfall,
206 maximum tide coefficient, and mean tide coefficient).
207 After being selected, the meteorological and marine variables were used for
208 analyses. Some of these are more relevant with the mean value (or sum) or, in
209 contrast, with the extreme value:
210 1) MinTmin (temperature index): minimum daily temperature during a 10-day period
211 (°C) in Dieppe. We are interested in minimum temperatures because it is possible to
212 take into account freeze/thaw periods for a frost-shattered material such as chalk;
213 2) MReff (rainfall index): mean of daily effective rainfall over a 10-day period (mm) in
214 Dieppe. The mean of rainfall that actually affects the cliff is interesting because it
215 informs about runoff and infiltration (with widening of fissures), and thus about aquifer
216 recharge with delay. For these reasons, effective rainfall is chosen (equal to the
217 difference between total rainfall and actual evapotranspiration) and is calculated from
218 the hydric balance. The mean of effective rainfall gives the same information as the
219 sum of effective rainfall because the latter is divided by the ten days of the 10-day
220 period;
221 3) MaxWFmax (wind index): maximum of daily wind force over a 10-day period (m/s)
222 in Dieppe. Wind provides interesting data because it has an influence on swell and

223 thus on marine actions that affect the cliff foot. The maximum wind gives a good
224 indication of swell (linked to wind force);
225 4) MCoef (tide index): mean of tide coefficient over a 10-day period in Dieppe. Tide
226 has an influence on cliff stability. Combined with wind, it gives information about
227 marine roughness and thus instability at the cliff foot. Clearly, the tide coefficient
228 mean over a 10-day period might appear unrepresentative. However, 1) this period is
229 chosen to be consistent with the other factors; 2) despite this time gap, many rock
230 falls are distinguished by spring or neap tides.

231 The time scale chosen is the mobile 10-day period for three reasons:

- 232 - the frequency of the inventory is weekly, so ten days include this time lag between
233 two surveys;
- 234 - generally, ten days before a rock fall are often necessary to identify the triggering
235 factor because it may be due to a cumulative effect (e.g. rainfall reaching a threshold
236 with few but continuous rainfalls over many days);
- 237 - the period of 10 days is often used in meteorological data (e.g. evapotranspiration)
238 because it enables the inertia of the system to be taken into account.

239 The fixed 10-day period scale (used in many meteorological studies) was not used
240 because it is unsuited to the problem. For example, a rock fall identified on the first
241 day of the month is for the 10-day period of 1 to 10, while the conditions responsible
242 for triggering correspond to the previous fixed 10-day period. Thus, the time scale
243 used is a mobile 10-day period (with the day of the date of the rock fall and the
244 previous nine days) for each variable.

245

246 Preparatory analyses: descriptive and bivariate statistics

247 First, the descriptive statistics (quartiles and median) of “factor” and “rock fall”
248 variables (number and fallen volume) were calculated in order to determine some
249 mathematical properties of the data that can influence the choice of analyses to use:
250 asymmetry distributions, outliers, and non-linear relationships between variables.
251 Thus, one of the conditions necessary for the application of linear regression models
252 and appropriate tests (distribution of residuals according to a law close to a centered
253 normal distribution) was checked graphically (Figure 5).
254 The “factor” variables are generally well distributed on either side of the mean, except
255 those indicators describing the intensity of effective rainfall. This shows a skewed
256 distribution, characterized by an over-representation of high outliers.
257 The dependent variable “number of rock falls” is strongly influenced by the presence
258 of 10-day periods with a high number of rock falls (15-20). It therefore highlights an
259 asymmetric distribution, characterized by a large number of outliers whatever the
260 observation scale. For the fallen volume, the median seems much more suited to the
261 application of linear models. These parameters were included in the linear bivariate
262 regression models.
263 Secondly, we fitted simple bivariate linear regression models describing the evolution
264 of variables to explain Y (number and volume of rock falls) as a function of the
265 potential explanatory variables X (external factors), taken one by one. The purpose of
266 this regression is (Cornillon and Matzner-Lober, 2011):
267 - to fit a model to explain Y in terms of X;
268 - to predict the Y values for new values of X.
269 It could be interesting to observe the relationships between, for example, minimum
270 temperatures and median volume of rock falls over a 10-day period (Figure 6). For
271 each tested relationship, bivariate methods did not appear appropriate because

272 trigger origins seem complex, with many factors involved. Therefore, other methods
273 need to be used. To identify marine and meteorological conditions conducive or not
274 to rock falls, multivariate analyses are relevant. To identify the triggering factor(s) of
275 rock falls, multivariate analyses cannot define a hierarchy in a combination of agents;
276 this requires an empirical analysis.

277

278 Multivariate statistical analyses

279 In order to answer our first question about marine and meteorological conditions
280 conducive to rock falls, multivariate analyses were performed with the four selected
281 external factors on two populations:

282 - a first population with 159 10-day periods with rock falls (331) and 109 10-day
283 periods without rock falls was chosen to identify which external factor(s) can
284 discriminate a 10-day period with and without any events. In other words, this is to
285 understand the combination of agents and processes likely or not to trigger rock falls;
286 - a second population with only 10-day periods (159) with rock falls (331) in order to
287 study precisely the rock falls and their characteristics as a function of the marine and
288 meteorological conditions identified as conducive to rock falls. In other words,
289 because there are only 10-day periods with rock falls, it is possible to identify
290 relationships between combinations of factors and characteristics of rock falls
291 (volume and area of departure).

292 In detail, the multivariate method used was divided into 3 steps from the rock fall
293 inventory (Figure 7):

294 1) a PCA was performed to visualize the relationships between the variables and the
295 existence of groups of individuals and groups of variables. This structure highlights
296 the agents *a priori* most relevant to sum up meteorological and marine conditions that

297 characterize individuals (10-day periods). It is also possible to observe the seasonal
298 distribution of variables and individuals;
299 2) the second step was a Hierarchical Cluster Analysis (HCA). Using the previous
300 results of the PCA, the variables of individuals (10-day periods) are their PCA
301 coordinates on the first three axes. This step differentiates individuals (10-day
302 periods) as a function of their meteorological and marine agents and thus creates a
303 typology (types of meteorological and marine conditions leading to rock falls). This
304 typology is then used to describe the mean characteristics of meteorological and
305 marine conditions leading to rock falls (average analysis);
306 3) lastly, the third step was the integration of the geomorphological component of
307 rock falls (volume and departure area) within the 10-day periods. It was performed by
308 the χ^2 test (independence test, p-value coupled with α level of 5 %¹) to check whether
309 certain types of meteorological and marine conditions preferentially generate many
310 rock falls. By integrating the type to each rock fall (and no longer to 10-day periods),
311 it is possible to know whether certain conditions trigger specific classes of rock fall
312 volume ($V < 200 \text{ m}^3$, $200 \text{ m}^3 \leq V \leq 1,400 \text{ m}^3$, $1,400 \text{ m}^3 < V \leq 10,000 \text{ m}^3$, $V > 10,000$
313 m^3) and/or a specific departure area (cliff foot, middle part of the cliff, cliff top, whole
314 cliff face).

315

316 Empirical analysis

317 This exploratory statistical approach (PCA, HCA and χ^2 test) provided major
318 elements of knowledge by identifying the meteorological and marine conditions
319 conducive to rock falls but it was impossible to determine the triggering factors.
320 Indeed, in multivariate analyses, each “factor” variable is represented by a single

¹ The risk of error is 5 % (α).

321 value that summarizes its behavior over the 10-day period. Thus, the detail of the
322 factor's behavior on each day of the 10 days, which often informs about the triggering
323 factor of the rock fall, remains hidden. To provide this information and answer our
324 second question, we performed an empirical analysis (or human-supervised analysis)
325 on 10-day periods with rock falls (159 cases).

326 In many fields, such as environmental studies, the use of empirical statements is
327 common and recognized (e.g. in the courts). Empirical methods and the experience
328 of practitioners often yield excellent results in the studies of fluvial geomorphology,
329 ecology, hydrology, and natural hazards. We believe that when statistical studies
330 reach their limits (often due to the nature of the data and the assumptions they
331 imply), experience, observation, common sense and intuition remain valid
332 assessment instruments. Moreover, many statistical methods and spatial analyses
333 need to be human-supervised.

334 This empirical analysis (a subjective method of ranking variables) was based on the
335 study of the daily values of sub-aerial and marine factors for each rock fall during 10-
336 day periods in order to identify the triggering factor (most active in frequency or
337 intensity) (Figure 8). After this human-supervised analysis, it was possible to identify
338 rock fall characteristics (volume, departure area) preferentially induced by respective
339 factors.

340

341 **Results**

342 Multivariate statistical analyses

343 *PCA, HCA and χ^2 test for 10-day periods with and without rock falls (first population)*

344 The first analysis focuses on the structure of meteorological and marine conditions

345 (with the four variables mentioned above) over 10-day periods with rock falls (active

346 individuals in PCA) and without rock falls (supplementary individuals in PCA) (a total
347 of 268 10-day periods) (Figure 9).

348 For this population, axes F1 and F2 of the PCA represent 66 % of the total inertia
349 (and 86 % with F3). The highest variable contribution on F1 (35 % of the total
350 information) is the wind (52 % contribution), which opposes temperatures
351 (contribution up to 30 %). Thus, the first axis characterizes wind and temperatures,
352 where negative values represent calm wind and “warm” weather and the inverse for
353 positive values. On the F2 axis (31 % of the total inertia), the tidal coefficient and
354 effective rainfall are the most influential (37 % and 35 %, respectively) and evolve in
355 the same direction. Thus, positive values of the F2 axis mean spring tide and rainy
356 weather (Figure 9). On the F3 axis (21 %), the tidal coefficient and rainfall are located
357 in opposite directions. Due to this distribution on the PCA, the diversity between 10-
358 day periods seems to be explained; first, by wind and temperature and secondly, by
359 rainfall and tidal coefficient.

360 Furthermore, the distribution of 10-day periods with rock falls is on either side of the
361 variables. Therefore, the triggering of rock falls seems to be more the result of a
362 combination of marine and sub-aerial factors than a single factor and occurs in many
363 combinations (Figure 9). Regarding the temporal distribution between 10-day periods
364 with and without rock falls, seasonality appears. Unsurprisingly, winter (rainy and
365 “cold” weather) is the most favorable season for 10-day periods with rock falls while
366 summer (low wind and “warm” temperatures) is the most favorable season for those
367 without rock falls (Figure 9). Another result provided by the PCA is that “wind” and
368 “temperature” factors differentiate 10-day periods with and without rock falls the most.

369 The HCA and average analyses (histograms in Figure 10) provide a typology of four
370 classes of meteorological and marine conditions characterizing 10-day periods (in
371 descending order of the number of rock falls) (Figure 10):

372 1) Type A is characterized by “cold” (temperature mean under 0°C (histogram at the
373 top of Figure 10) thus including freeze/thaw cycles) and dry weather (147 rock falls,
374 45 % within 100 10-day periods);

375 2) Type B is characterized by “warm” weather and calm wind (64 rock falls or 19 %
376 within 75 10-day periods);

377 3) Type C is characterized by high rainfall and high wind (generating swell) (63 rock
378 falls, 19 % within 38 10-day periods);

379 4) Type D is characterized by spring tide and “warm” weather (the remaining 17 %
380 within 55 10-day periods).

381 Lastly, the χ^2 test shows a statistically significant link between types of conditions and
382 10-day periods with and without rock falls (observed distance (13.0) higher than the
383 critical level (7.8) with a p-value of 0.005, so less than α):

384 - Type C “high rainfall and high wind” (generating swell) has an over-representation
385 of 10-day periods with rock falls (79 % of 10-day periods have rock falls, 21 % of the
386 remaining 10-day periods do not have rock falls);

387 - Type B “warm weather and calm wind” (corresponding to summer weather) has an
388 over-representation of 10-day periods without rock falls (52 %), so these are
389 conditions conducive to cliff stability.

390 To go further in the analysis, a second χ^2 test was performed to measure
391 independence between the number of rock falls (0, 1, 2 and more) and types of
392 meteorological and marine conditions. There is a statistically significant link between

393 these variables (observed distance (18.3) higher than the critical level (12.6) with a p-
394 value of 0.006, so less than α):

395 - Type C “high rainfall and high wind” has an over-representation of 10-day periods
396 with a minimum of 2 rock falls (47 %, against 21 % for 0 rock fall and 32 % for 1 rock
397 fall) whereas these are under-represented in Type B “warm weather and calm wind”
398 (19 %).

399 To summarize, in the four types of meteorological and marine conditions identified as
400 responsible (or not) for triggering rock falls, Type C (“high rainfall and high wind”) is
401 the best rock fall trigger over a 10-day period, especially in frequency (2 rock falls or
402 more) whereas Type B, characterized by “warm weather and calm wind”, is the least
403 favorable for the occurrence of rock falls (but they might occur).

404

405 *PCA, HCA and χ^2 test for 10-day periods only with rock falls (second population)*

406 For this second population (159 10-day periods), relationships between the variables
407 and the existence of groups of variables are the same as the previous PCA (because
408 10-day periods without rock falls in the PCA were supplementary individuals).

409 HCA identifies four types of meteorological and marine conditions for 10-day periods.

410 It is interesting to note that, although “warm weather and calm wind” are identified

411 with the first population as conditions not conducive to rock falls, a group of

412 individuals (10-day periods with rock falls) is always present around these variables

413 (in fourth position, with 56 rock falls within 33 10-day periods) (Figure 11). Thus, rock

414 falls are possible in these summer conditions, when people may stay all day on the

415 beach, near the cliff foot. A χ^2 test was performed on rock falls (no longer 10-day

416 periods) to highlight whether some conditions trigger specific types of rock fall

417 (volume and departure area). The results are as follows (in descending order of
418 number of rock falls, Figure 11):

419 1) Type 1 conditions are “cold” (with a mean temperature histogram under 0°C, so
420 numerous freeze/thaw cycles) and dry weather (147 rock falls, 44 % within 65 10-day
421 periods). For these conditions, the χ^2 test highlights that rock falls with volumes less
422 than 200 m³ are over-represented whereas rock falls with volumes greater than
423 10,000 m³ are under-represented (49 % for $V < 200 \text{ m}^3$, against 27 % for $200 \text{ m}^3 \leq V$
424 $\leq 1,400 \text{ m}^3$, 21 % for $1,400 \text{ m}^3 < V \leq 10,000 \text{ m}^3$, 2 % for $V > 10,000 \text{ m}^3$ and 1 % for
425 unknown volume);

426 2) Type 2, characterized by high rainfall and high wind (70 rock falls or 21 % within
427 31 10-day periods), has an over-representation of rock falls with a departure area of
428 the whole cliff face (56 % of cases, against 21 % for cliff foot, 13 % for foot and
429 middle part of the cliff, 3 % for middle part of the cliff and 7 % for cliff top). This type
430 of conditions has a high proportion of rock falls greater than 10,000 m³ with 9 % of
431 cases (whereas these massive rock falls represent only 5 % of the total number of
432 rock falls in the ESTRAN inventory);

433 3) Type 3 is characterized by a spring tide and “warm” weather (57 rock falls, or 17 %
434 within 30 10-day periods). This type has an over-representation of rock falls with a
435 fallen volume between 1,400 and 10,000 m³ (35 % of cases, against 32 % for $V <$
436 200 m^3 , 24 % for $200 \text{ m}^3 \leq V \leq 1,400 \text{ m}^3$, 9 % for $V > 10,000 \text{ m}^3$);

437 4) Type 4, the rarest, is characterized by “warm” weather and calm wind conditions
438 (the remaining 17 % within 33 10-day periods). This type has an over-representation
439 of (1) cliff foot rock falls (45 % of cases, against 28 % for the whole cliff face, 23 % for
440 foot and middle part of the cliff, 2 % for cliff top and 2 % for unknown volume), and (2)
441 rock fall volume between 200 and 1,400 m³ (45 % of cases, against 29 % for $V < 200$

442 m³, 20 % for 1,400 m³ < V ≤ 10,000 m³, 3 % V > 10,000 m³ and 3 % for unknown
443 volume).

444 Therefore, from this second population, we have complementary information about
445 conditions likely to trigger rock falls. “Cold (freezing) and dry weather” conditions
446 (Type 1) generate many rock falls, usually small in volume (less than 200 m³) without
447 a specific departure area. In contrast, “high wind and high rainfall” conditions (Type 2)
448 are more conducive to massive rock falls (more than 10,000 m³) from the whole cliff
449 face. “Warm weather and calm wind” (Type 4) generate rock falls of modest size (200
450 to 1,400 m³) mainly coming from the cliff foot. More surprisingly, “spring tide and
451 warm weather” conditions (Type 3) seem to be responsible for large rock falls (from
452 1,400 to 10,000 m³).

453

454 Empirical analysis

455 The empirical analysis confirms and adds to the multivariate analyses. With this
456 subjective method of variable ranking, triggering factors are identified:

457 1) effective rainfall seems to be involved in 56 % of the number of rock falls and 72 %
458 of the total fallen volume. Of these 185 rock falls probably due to rainfall, 79 cases
459 come from the whole cliff face (43 %) and 34 % are between 200 and 1,400 m³. As a
460 proportion of the 331 rock falls in the inventory, the characteristics of the 185 rock
461 falls triggered by rainfall are mostly: (1) between 200 and 1,400 m³ or over 10,000 m³
462 (64 % and 56 % of the ESTRAN database, respectively), (2) from the whole cliff face
463 (59 %) (Figure 12);

464 2) freeze/thaw cycles seem to be involved in 19 % of the number of rock falls and
465 10 % of the fallen volume. These rock falls are mostly from the whole cliff face (22
466 cases, 34 %) or the cliff foot (16 cases, 25 %) and smaller than 200 m³ (45 %).

467 However, as a proportion of the 331 rock falls in the database, the characteristics of
468 rock falls triggered by freeze/thaw cycles are mainly: (1) smaller than 200 m³ (23 %
469 of the inventory), (2) from the cliff top (50 %) or cliff foot (16 %) (area where chalk is
470 preferentially saturated in water by runoff or infiltration) (Figure 12);
471 3) the next factor is marine roughness, a combination of spring tide (coefficient more
472 than or equal to 85²) and high wind (more than 8 m/s) that generates marine actions
473 at the cliff foot, with 15 % of the number of rock falls and 9 % of the fallen volume.
474 These rock falls are mostly from the whole cliff face (20 cases, 31 %) or
475 unsurprisingly from cliff foot (17 cases, 27 %) and smaller than 200 m³ (42 %). As a
476 proportion of the 331 rock falls in the inventory, the characteristics of rock falls
477 triggered by marine roughness are mainly: (1) smaller than 200 m³ (17 %), (2) from
478 the foot/middle part of the cliff (20 %) or the foot cliff (17 %) (Figure 12). This factor
479 needs complementary studies, as its influence is difficult to quantify due to rock falls
480 of small volume being quickly removed during a turbulent marine period (and that
481 could be missed by the ESTRAN organization).
482 Nevertheless, these identified triggering factors rarely act alone. Only 49 rock falls
483 (15 %) seem to be triggered by a single factor. These few cases occurred with only
484 one predominant parameter (while other marine and sub-aerial factors were of low
485 frequency or intensity). The vast majority of rock falls is due to a combination of the
486 triggering factors mentioned above (very common in mid-latitudes). This is the case
487 during unsettled weather (rainfall, marine roughness), which occurs approximately
488 2/3 of the year along the Normandy coast (sometimes with freeze/thaw cycles).
489 Consequently, it is more appropriate to identify three types of weather leading to the
490 triggering of rock falls: periods of high effective rainfall over a 10-day period, periods

² With this value of 85, we are sure that the tide affects the foot of the cliff along the coastline studied.

491 of freeze/thaw cycles, types of weather characterized by atmospheric disturbance
492 involving heavy rainfall and high wind (thus high waves).

493

494 **Discussion**

495 The ESTRAN database is unique and significant because of the weekly frequency of
496 surveys (which track small and large rock falls), the precise dating of rock falls, the
497 length of the coastline surveyed (37.5 km) and the duration of 7 years. There are
498 other inventories of this coastal section (e.g. Duperret et al., 2004; Dewez et al.,
499 2013) but a comparison of results is difficult. Their spatial and temporal
500 representativeness are limited. For example, the inventory of Dewez et al. (2013)
501 was carried out on 750 m and for 2.5 years. Dating of rock falls remains limited: of
502 the order of the month to the season for Duperret et al. (2004). However, the types of
503 favorable conditions for triggering rock falls can sometimes tend towards the same
504 conclusions for massive rock falls, which are often linked to specific meteorological
505 conditions. For example, Duperret et al. (2004) show two types of triggering
506 meteorological conditions: heavy rainfall and sudden rainfall during dry periods.
507 However, these authors point out that their results are questionable because of the
508 small number of cases (55 including only 4 precisely dated).

509 This participation in the scientific debate about determining the factors and processes
510 likely to trigger rock falls is based on an exploratory statistical approach and an
511 empirical analysis. These two methods are complementary. Whereas the statistical
512 one provides the types of combination of meteorological and marine factors
513 conducive or not to rock falls, the empirical one determines the triggering factor for
514 each rock fall. Each of these approaches gives information about the modalities of
515 retreat (rock fall departure area and volume). The statistical analyses underline that

516 “cold and dry weather” and “high rainfall and high wind” are the best conditions for
517 triggering rock falls. The empirical analysis identifies effective rainfall as the most
518 important triggering factor. It seems to generate the majority of both rock falls (56 %) and fallen volume (72 %). It is followed by freeze/thaw cycles and marine roughness.
519 However, this subjective ranking of the triggering factors should be weighted in terms
520 of the frequency of their occurrence per year. Whereas rainfall occurs about 130 days
521 a year, freeze/thaw cycles are much less frequent: about 26 times a year over the
522 seven years observed (with 183 registered cases). Based on these results,
523 freeze/thaw cycles seem to be more “efficient” than rainfall, because when they
524 occur, rock falls are nearly always observed.

526 Contrary to what is often stated in the scientific literature, marine roughness does not
527 appear to be only a transport and debris removal agent. This is the third factor
528 explaining the triggering of rock falls. Unsurprisingly, marine roughness seems
529 particularly effective at the cliff base, involving rock falls of small volume (but can
530 cause mass movements affecting the whole cliff face). This result is consistent with
531 fine quantitative results obtained by terrestrial laser surveys carried out along this
532 coastline (Letortu et al., in press, accepted).

533 However, in many cases, the triggering of rock falls seems to be the result of a
534 combination of factors. The most common combination (56 rock falls out of 331) is
535 marine roughness (linked to wind speed and during spring high tide) and high
536 effective rainfall (instantaneous or cumulative). This corresponds to the very common
537 types of disturbed weather in mid-latitudes, which dominate for approximately 2/3 of
538 the year. Low pressure with two fronts crosses the English Channel and generates
539 high rainfall in Normandy and a marine roughness conducive to triggering rock falls. If
540 this type of weather is followed by a period of freeze/thaw cycles, cliff weathering and

541 cliff retreat will reach their peak. However, is this due to the inaccuracy of the rock fall
542 dating (often around a 10-day period)? To go beyond this limit, we collected 74
543 correctly-dated rock falls from the local press and carried out the statistical and
544 empirical analyses. Even if rock fall is dated to the day, the process of identifying the
545 triggering factor(s) remains complex. High rainfall plays a role but is also combined
546 with the other factors.

547 This work confirms that identifying triggering factors is complex because the evolution
548 of environments is not linear and not limited to direct causal relationships. The
549 “purge” effect, relays or combinations of processes and/or hysteresis phenomena
550 (which we tried to integrate by using a mobile 10-day period) complicate the analysis
551 of relationships. In addition, cliffs inherit past environmental changes (Trenhaile,
552 2002) i.e. they are influenced by the size and location of previous rock falls (the
553 “purge” effect). The purge effect means that a cliff face has been recently affected by
554 a fall, called here a “purge”. The cliff face is “new”, so it must not be affected by
555 another fall soon because it has to be “prepared” by preparatory processes for a
556 certain time to be ready to fall. So, cliff retreat is a process with a “memory” (Lee et
557 al., 2001). Whatever our understanding of current processes and their impacts, the
558 evolution of the cliff is partially based on the long-term degradation of the rock
559 (Griggs and Trenhaile, 1994; Swenson et al., 2006; Lim et al., 2011).

560 Moreover, the dichotomy between weathering factors and triggering ones is not
561 always obvious. This determination is complex because the relationships between
562 the factors are non-linear. Several reasons may explain this:

563 1) the transition state between weathering and triggering factors can be inappropriate
564 for common statistical methods (e.g. the presence of discretized data). It could be

565 more relevant to study these factors using fuzzy logic. This is why we tried to
566 incorporate temporal flexibility by working over mobile 10-day periods;

567 2) the triggering factor may be random. If the material is ready to fall, any factors,
568 whatever their intensity, are likely to generate a rock fall;

569 3) conversely, the factors identified as triggering (under certain conditions) may occur
570 without generating any departures of material due to a previous “purge” effect. The
571 material expected to fall is already on the ground. In other words, factors that can be
572 triggering are repeated but with no rock falls. They participate, like others, in lowering
573 the stability margin of the cliff to a critical value. In this case, the agents and
574 processes are just preparatory.

575 There is also the question of the time required to determine the triggering factors. Is
576 the 10-day period sufficient? Should the analysis period be increased when
577 meteorological and marine conditions are not dynamic in the 9 days preceding the
578 rock fall? This is the case of the collapse of 08/26/2001 (correctly-dated rock fall from
579 the local press) where no increase in the intensity or frequency of triggering agents
580 occurred (*a priori*) during the 10-day period, while on 08/02/2001 rainfall greater than
581 26 mm was recorded. Are these phenomena related? Are there other explanatory
582 factors (e.g. micro-earthquakes), processes such as hydroclasty, or decaying? Are
583 there hysteresis phenomena over intervals of several weeks? Lengthening the
584 observation period of agents and processes responsible for triggering rock falls would
585 make determining the contribution of each factor more complex, because of their
586 multiple occurrences over this longer time period.

587 This statistical approach and the empirical one are based on the analysis of external
588 conditions, but it is also essential to take internal factors into account (rock
589 mechanics, micro- and macro-cracking). Whereas, at first sight, the Upper Normandy

590 coastal chalk cliffs appear homogeneous in lithology, on a fine scale there are many
591 differences (Mortimore et al., 2004; Lasseur, 2007). These limitations of this work
592 must be taken into account in future developments to improve our results. For
593 example, it would be interesting to focus on a type of chalk lithology (e.g. Santonian
594 stage) with a specific departure area of rock falls. This will become possible when the
595 database has been enriched with new inventory years. Furthermore, data of
596 meteorological and marine parameters need to be on a finer temporal and spatial
597 scale. Thus, determining the agents and processes responsible for triggering rock
598 falls remains difficult due to the limited number of cases observed (especially
599 precisely dated) and a lack of knowledge of the internal parameters in chalk cliffs and
600 of meteorological and marine parameters on fine temporal and spatial scales.

601

602 **Conclusions**

603 The originality of this paper is the analysis of a large inventory of 331 rock falls (date,
604 geomorphological features) in Upper Normandy using multivariate statistical analyses
605 (PCA, HCA) and empirical analysis. The results, deduced directly from these
606 analyses, highlight innovative information about the conditions leading to rock falls
607 and triggering factors:

- 608 1) the frequency of rock falls is linked to meteorological and marine conditions:
609 unsurprisingly, high rainfall and high wind (winter weather with marine roughness) are
610 the most favorable conditions for 10-day periods with many rock falls (2 or more)
611 while warm weather and calm wind (summer weather) are the most favorable
612 conditions for 10-day periods without rock falls (but rock falls might occur).
- 613 2) the volume of rock falls depends on triggering factors: freeze/thaw cycles are
614 mainly responsible for debris falls (volume less than 200 m³) whereas high rainfall

615 triggers preferentially more massive rock falls (between 200 and 1,400 m³ or more
616 than 10,000 m³). Marine roughness seems to trigger rock falls of small volume (less
617 than 200 m³) in particular.

618 3) the cliff face location of rock falls is due to triggering factors: high rainfall mainly
619 triggers rock falls coming from the whole cliff face while freeze/thaw cycles trigger
620 rock falls coming from the top and foot of the cliff face. Unsurprisingly, marine
621 roughness seems particularly effective at the cliff base.

622 Some difficulties remain in quantifying the proportion of marine and sub-aerial factors
623 because of problems of combinations of factors (very common in mid-latitudes) or the
624 relay of factors (85 % of 331 cases) and probably hysteresis phenomena. In view of
625 these various findings, it is still presumptuous to predict the location and time of
626 triggering of rock falls. However, the approaches adopted (statistical and naturalistic)
627 and the observations made in this study are from an original inventory, and constitute
628 a real starting point for the prediction and prevention of the hazard of rock falls in
629 Upper Normandy.

630

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635

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Dieppe (1971-2000)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Maximum temperatures (°C)	7.2	7.7	9.9	11.5	14.9	17.2	19.5	20.3	18.5	15.2	10.7	8.2	13.4
Mean temperatures (°C)	4.9	5.0	7.0	8.5	11.8	14.2	16.4	16.9	15.0	12.0	8.1	5.9	10.5
Minimum temperatures (°C)	2.5	2.3	4.1	5.4	8.6	11.3	13.4	13.5	11.5	8.8	5.5	3.6	7.5
Mean number of days with minimum temperatures <= 0°C	7.7	8.3	3.8	1.3	-	-	-	-	-	0.3	3.4	7	31.8
Mean number of days with minimum temperatures <= -5°C	2.2	1.4	0.3	-	-	-	-	-	-	-	0.2	0.8	4.9
Mean number of days with minimum temperatures <= -10°C	0.4	0.2	-	-	-	-	-	-	-	-	-	0.0	0.6
Maximum daily height of rainfall	29.5	38.5	32.0	27.0	52.5	40.6	58.5	100.8	56.1	77.5	46.1	42.0	-
Height of rainfall (mean in mm)	64.0	51.8	57.6	56.7	59.2	58.6	53.3	50.6	80.4	90.8	93.8	87.4	-
Mean number of days with rainfall >= 1 mm	11.7	9.9	11.9	10.3	10.3	9.6	8.3	8.5	10.8	11.4	13.8	13.2	129.6
Mean number of days with rainfall >= 5 mm	4.6	3.5	3.8	4.2	4.1	4.0	3.1	3.5	5.6	5.8	6.8	6.3	55.3
Mean number of days with rainfall >= 10 mm	1.7	1.1	1.1	1.3	1.5	1.5	1.6	1.2	2.5	2.9	3.4	2.8	22.5
Mean number of days with gust >= 16 m/s	13.6	10.4	11.3	9.0	6.7	5.6	5.1	-	7.9	10.5	10.9	11.8	102.8
Mean number of days with gust >= 28 m/s	1.2	1.4	0.7	0.3	0.1	-	0.2	-	0.2	0.7	0.5	1.4	6.7

Source of data: Meteo-France

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804 Table I: Meteorological data in Dieppe (Meteo-France, 1971-2000)

Rock fall date	Rock fall number	Town	Coordinate x (RGF93-L93)	Coordinate y (RGF93-L93)	Volume (m³)	Departure area of rock fall
02/06/02	1	Varengville	556,948	6,981,584	1,372	cliff foot
02/18/02	2	Varengville	554,542	6,981,917	942	whole cliff face
02/18/02	3	Varengville	554,661	6,981,894	20,100	whole cliff face
02/23/02	4	Dieppe	559,928	6,982,139	92	whole cliff face
03/04/02	5	Sainte-Marguerite	553,865	6,981,975	92	whole cliff face
03/04/02	6	Sainte-Marguerite	554,030	6,981,961	976	whole cliff face
03/25/02	7	Varengville	555,028	6,981,826	1,508	whole cliff face
⋮	⋮	⋮	⋮	⋮	⋮	⋮
12/14/09	325	Varengville	555,344	6,981,751	93	cliff foot
12/22/09	326	Sainte-Marguerite	553,626	6,982,019	202	whole cliff face
12/22/09	327	Sainte-Marguerite	553,683	6,982,013	1,581	whole cliff face
12/22/09	328	Varengville	554,798	6,981,867	448	whole cliff face
12/22/09	329	Varengville	555,137	6,981,789	478	whole cliff face
12/22/09	330	Varengville	555,157	6,981,785	259	cliff foot
12/23/09	331	Dieppe	563,951	6,983,619	31	cliff foot

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806 Table II: Extract of enriched inventory (volume, departure area of rock fall) used for
807 the next analyses

808

809 Figure 1: Presentation of the studied area (from Veules-les-Roses to Le Treport)
810 showing a cross-section with lithostratigraphy

811 Figure 2: Example of a rock fall (then a slide of tertiary strata) on the west side of
812 Dieppe that threatens urbanization (18/12/2012, *Les informations Dieppoises*)

813 Figure 3: Rock fall inventory (A: index card made by the ESTRAN organization for
814 rock fall n°123; B: spatial distribution of rock falls; C: temporal distribution of rock
815 falls)

816 Figure 4: Rock fall distribution (number and frequency) as a function of volume (A:
817 total distribution of the number of rock falls as a function of fallen volume; B:
818 thresholds observed to distinguish classes of volume as a function of rock fall
819 frequency)

820 Figure 5: Descriptive statistics of variables “factor” and “rock fall” over a 10-day
821 period

822 Figure 6: Bivariate regression between minimal temperatures and median fallen
823 volume over a 10-day period

824 Figure 7: Method of multivariate statistical analyses (with 3 steps)

825 Figure 8: Method of empirical analysis with the example of the rock fall of 02/08/02

826 Figure 9: PCA for 10-day periods with and without rock falls (distribution of variables
827 in insert) and seasonal distribution

828 Figure 10: Results of the typology (4 types deduced by the HCA) and their
829 meteorological and marine conditions per type (average analysis with histograms on
830 the right), superimposed on the PCA (previously performed on the 268 10-day
831 periods with and without rock falls)

832 Figure 11: Results of the typology (4 types deduced by the HCA) and their
833 meteorological and marine conditions per type (average analysis with histograms on

834 the right), superimposed on the PCA (previously performed on the 159 10-day
835 periods with rock falls)
836 Figure 12: Results from the empirical analysis with the first three triggering factors
837 (histograms of number of rock falls, sector diagrams of distribution of rock falls per
838 class of volume, and geomorphological specificities of rock fall per triggering factor)