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Sedimentary Coastal Cliffs of Normandy: Modalities and Quantification of Retreat

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ABSTRACT

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This paper examines the spatial and temporal variations of cliff retreat rates over multi-temporal data of the Normandy cliffs. Data are derived from historical maps and aerial photographs and from recent lasergrammetry and photogrammetry monitoring. The diachronic analysis of all these data gives retreat rates of -0.1 to -0.5 m/yr. in line with the international literature. The spatial variations of the cliff retreat rates, at the Normandy scale, can be explained by geological structure, especially at the cliff foot, but also by the influence of cliff collapses or anthropogenic obstacles that disrupt the longshore drift. Multi-temporal data shows that the evolution of the cliffs occurs on scales from 10 to 70 years according to the lithology. The high resolution and frequency monitoring also provide information about the factors responsible for triggering gravitational landslides (rockfalls, slides, debris falls). The study proposes a regional warning threshold for the cliff characterized by landslides, under the dominating influence of rainfall and groundwater level evolution. In this respect the monitoring is inconclusive for chalk and limestone cliffs, because the origin of evolutions is more multifactorial (combination of more continental and marine processes).

ADDITIONAL INDEX WORDS: *Coastal cliff, landslide, retreat rate, lasergrammetry, photogrammetry, Normandy.*

INTRODUCTION

Before the 1990s, the vast majority of coastal geomorphology work focused on accretion coasts, on which many economic challenges threatened by rapid regressive changes potentially accelerated by contemporary mean sea level rise (Kennedy, Coombes, and Mottershead, 2017; Trenhaile, 2000; Woodroffe, 2002). However, rocky and cliffy coasts are said to represent between 75% (Davis and Fitzgerald, 2003; Emery and Kuhn, 1982) and 52 % (Young and Carilli., 2019) of the world's coastline and are now one of the few sources of sediment for beaches. It is only in the last two to three decades that studies on these retreating coasts have increased (Kennedy *et al.,* 2014; Kennedy, Coombes, and Mottershead, 2017). This is probably due to the rising impact of their retreat on coastal activities and populations, and to the development of tools and methods to understand the slow but abrupt dynamics of these complex rocky coastal systems (Bird, 2000; Brunsden and Lee, 2004; Costa *et al.,* 2004; Gomez-Puyol *et al.,* 2014; Guiliano, 2015; Letortu *et al.*, 2015b; Paskoff, 1998; Sunamura, 1992; Thenhaile, 1987; 2016; Young *et al.,* 2009, 2019). The Norman morphostructural environment (between the Bay of Mont Saint Michel and the Tréport) is vulnerable to favorable to the development of retreating coasts, the evolution of which can be significant (Costa, 1997; Costa *et al.,* 2004; Elineau, 2013; Letortu *et al.,* 2015b; Lissak, 2012; Lissak *et al.,* 2013; Maquaire, 1990; Maquaire *et al.*, 2013; Medjkane *et al.,* 2018). Armorican Massif (Figure 1), located at the extreme west of the study area (Cotentin) is composed of ancient sedimentary, metamorphic and volcanic soils (crossed locally by granitic intrusions). These rocky coasts are made up of Paleozoic materials (Dugué, Fily, and Rioult, 1998) with very slow retreat rates. In the rest of the study area, the ancient Armorican lands to the north, are covered, sometimes discordantly, by the northwestern termination of the Paris sedimentary basin (Benabdellouahed *et al.,* 2014; Juignet, 1974; Lasseur, 2007; Le Cossec, 2010). The latter is characterized by relatively high, undulating and sometimes faulted plateaus, explaining the lithostratigraphic diversity of the outcrops, and the variety of types of gravitational landslides encountered (Costa, 1997). Thus, in contact with the epicontinental sea that is the Eastern and Central Channel, these plateaus are carved into cliffs

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with a much faster retreat due to the outcropping of sedimentary formations (from the Jurassic to the Upper Cretaceous) vulnerable to weathering. This article has a twofold objective: first, to provide, the values of the retreat of Norman sedimentary cliffs on a historical scale and using traditional photo-interpretation methods. Secondly, on specific sites monitored at high frequency and resolution (SNO-Dynalit and SNO-OMIV sites, photogrammetry and lasergrammetry monitoring), the objective is to provide a synthesis of results on some of the main issues that drive the research community working on cliff coasts, namely, the spatial distribution of the retreat and evolution rates on the cliff face, the evolution rhythms, and the factors responsible for triggering gravitational landslides (rockfalls, slides, debris falls).

STUDY AREA

The coastal cliffs studied in this paper exclude cliffs carved from Paleozoic rocks in the Cotentin region (from Saint Vaast la Hougue to Bay of Veys). The Norman cliffs studied therefore correspond to the north-western termination of the Paris sedimentary basin and have an average amplitude of about 50 m, although they can exceed 100 m in the Seine Maritime area. At the foot of the latter is a large shore platform (150 to 700 m wide), with a low slope (0.2 to 2%), sometimes covered with thin sandy veneers. In Seine-Maritime the upper part of the shore platforms are hidden by a flint gravel barrier or resistant limestone and sands of multi-metric thickness in Calvados (Costa, Henaff, and Lageat, 2006). With regard to the morphostructural characteristics of the study area, we can observe (Figure 1):

1- To the west of Calvados, between Grandcamp-Maisy and Saint-Côme de Fresné, lie the active cliffs of the Bessin plateau, which range in height from 10 to 75 m (section C-D, Figure 1). These cliffs are composite in their cliff profile and geological structure. The profiles are different in relation to the relative thicknesses between the limestones (Bajocian and Bathonian stages) and the marls of Port-en-Bessin (Bathonian stage). Three types of cliffs have been defined (Maquaire, 1990): a cliff with a soft marly pedestal topped by a limestone cornice, a cliff with a resistant pedestal in the marly limestone of the Lower Bathonian or the Bajocian limestone, and a simple subvertical cliff reinforced by Bathonian limestone.

2- In the 'Caen Countryside', a similar system exists between Saint-Aubin-sur-Mer and Lion-sur-Mer on a lower altitude plateau. There are several small areas of low active cliffs (Bathonian limestone) which do not exceed 10 m in height.

3- Along the Pays d'Auge plateau, the cliffs of the Jurassic and the Lower and Upper Cretaceous are discontinuous and loose (section E-F, Figure 1). The Vaches Noires cliffs, of the Oxfordian stage, are called mudflow cliffs, forming a landscape

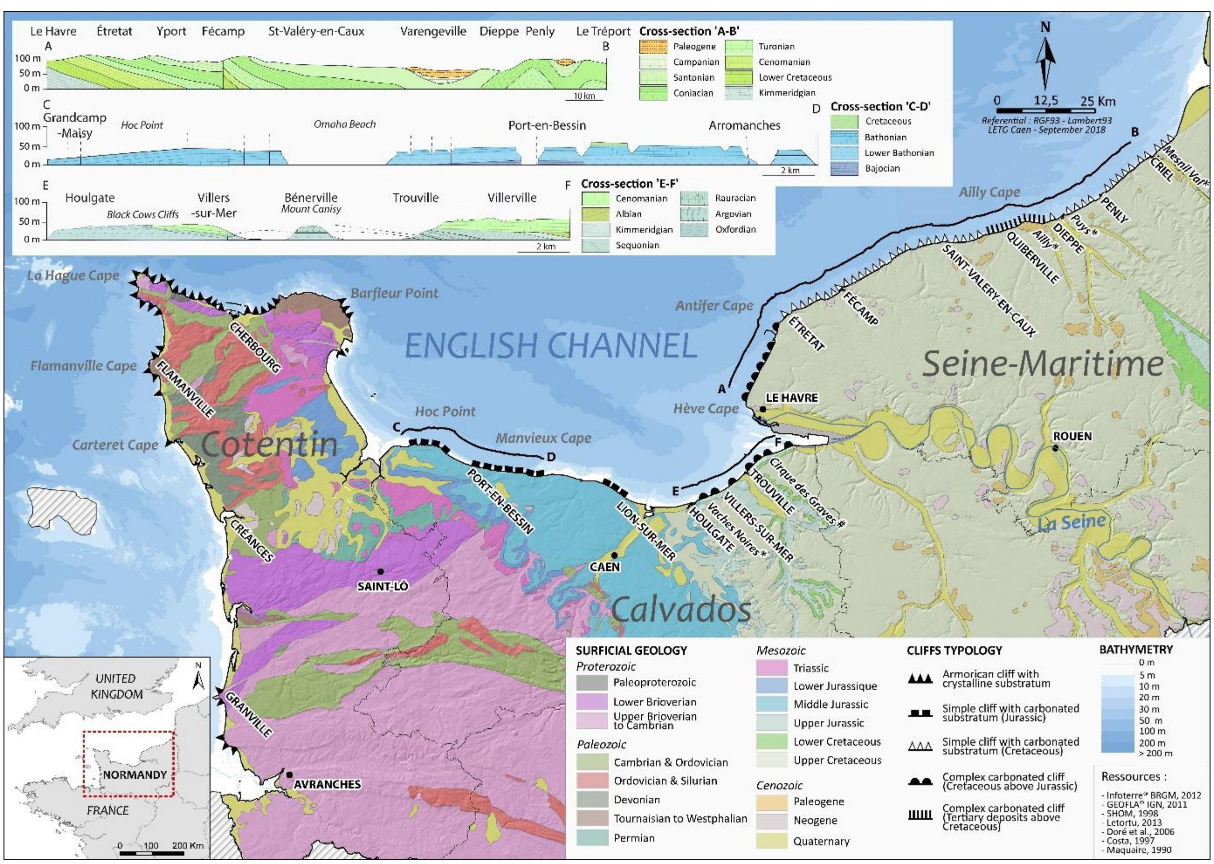

Figure 1. Simplified geological map (from BRGM, French geological survey) and litho-stratigraphic profiles of cliffs of the Normandy study site.

of badlands and pinnacles. In Benerville-sur-Mer, east of Mont Canisy (110 m), and especially between Trouville-sur-Mer and Honfleur, the cliffs reappear (section E-F, Figure 1). Their foot is comprised of Jurassic age materials (limestone and marl) topped with Albian sand (Lower Cretaceous) and Cenomanian chalk (Upper Cretaceous) suitable for deep-seated landslides (Lissak, 2012; Maquaire, 1990).

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

Variations in resistance between the various outcrops (Dugué, 1989; Dugué, Fily, and Rioult, 1998; Juignet, 1974; Juignet and Breton, 1992; Laignel, 1997; Lasseur, 2007), visible in cliff profiles, reflect various gravitational mechanisms (falls, slides, flows, etc.), but also different retreat rates and evolution rhythms. The difficulty in quantifying cliff retreat lies in the slowness of the dynamics (the time taken to prepare the rock material, often several decades before the rupture), the combination of marine and sub-aerial factors responsible for the dynamics, and the punctual dimension of the evolution (spatially localized phenomenon).

Normandy is located in the northwestern part of France, on both sides of the 50th northern parallel, along the English Channel (epicontinental sea, 86 m deep on average). The environment is macrotidal (Table 1) with a tidal range of 8 m (south) to 10 m (north). Waves (Table 2), which impact the cliff foot during high tide, are limited but the wind sea can produce significant wave heights of up to 4 m at Dieppe (annual return period) measured in deep water.

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

MATERIAL, METHODOLOGY AND DOCUMENTS

With regard to the objectives of this paper, the diachronic approach is central. Two main techniques and documents are used (Figure 2).

Historical Scale Quantification for All Normandy Sedimentary Cliffs

This quantification (several decades) was carried for the Calvados region by comparing classical photo-interpretation with ancient cartographic documents (cadastral register and the Terrier plan of the 19th century). The main documents used were vertical aerial photographs provided by the IGN (National Geographic Institute). The time interval between the two series of aerial photographs is nearly 50 years (1947-2013) for the various territories. After georeferencing and rectification of the images from 1:10,000 to 1:20,000 scale (Costa *et al*., 2004; Letortu *et al*., 2014; Lissak *et al*., 2013; Maquaire *et al*., 2013; Roulland *et al*., 2019; Vioget, 2015), digitization of the coastline was carried out (cliff top for the Seine Maritime, top and bottom for the Calvados cliffs). The margins of error of the results are not negligible (+/- 0.5 m to +/- 4.0 m). Airborne lidar data (RGE Alti- IGN) provided a new layer of more accurate information (margin of error +/- 0.2 m) that completed the analysis. Finally, old documents (cadastral registers) were integrated for the Calvados cliffs. The land registration system in France is called ‘cadastre’ and the first of these cadastral registers, called Napoleonic, was established in the 19th century by order of Napoleon I. Carried out on a very large scale (from 1/1,000 to 1/2,500), this document has been updated. These documents exclusively detail the limits of taxable parcels, which are perfectly mapped. Consequently, the correct setting of these plots is logical, but they do not describe the exact position of a very unstable steep slope of several tens of meters. Even if the margins of error around the position of the shoreline are large, the loss of perfectly located plots of land by erosion makes it possible to replace the cliff retreat rates obtained over a few decades in a wider time period. In addition, the multiplicity of aerial images used for different dates also makes it possible to provide initial information on the evolution rates of the studied cliffs.

High Resolution Quantification and Frequency Diachronic Monitoring

In order to participate in the current debate on (1) the evolution of the cliff face, to monitor the height and basal coastline (Brooks and Spencer, 2010; Cerema, 2015; Costa *et al.*, 2004; Dewez *et al.*, 2007; Dornbusch *et al.*, 2008; Jaud *et al.*, 2019; Hénaff *et al.*,

Table 1. *Tide level (in m IGN69) along the Normandy coast (SHOM, 2007).*

	Barfleur	*Le Havre*	*Dieppe*	*Le Tréport*
Higher Astronomic Tide (HAT)	3.62	4.18	5.66	35.78
Lower Astronomic Tide (LAT)	-2.98	-4.08	-4.52	-4.43
Higher level observed during storm	4.02	/	5.95	/

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

	Cherbourg	*Le Havre*	*Antifer*	*Dieppe*	*Penly*
Annual height	4.2	3.5	4.1	4.3	3.8
Decennial height	5.7	4.6	5.7	5.7	4.7

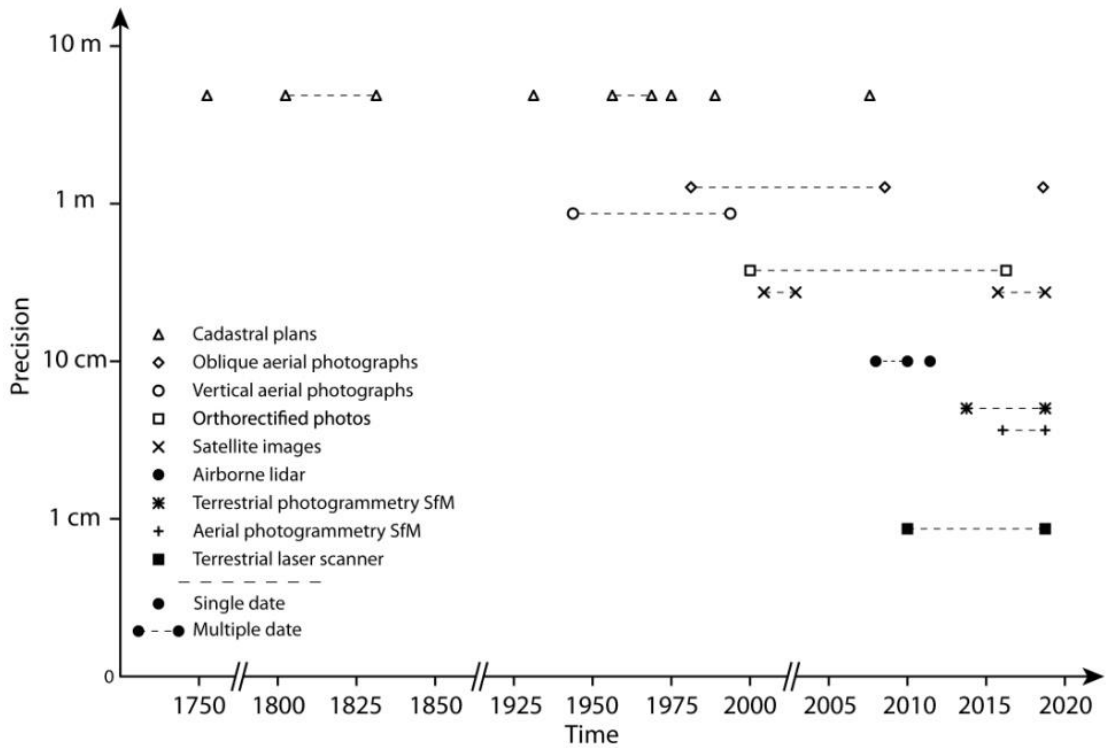

Figure 2. Techniques and documents used to study the evolution of Normandy sedimentary coastal cliffs.

2002; Lahousse and Pierre, 2002; Letortu, 2013; Letortu *et al.*, 2015b; Lim, 2014; Lim *et al.*, 2005, 2010; Marques, 2006; Michoud *et al.*, 2014; Moore, 2000; Moore and Griggs, 2002; Moses and Robinson, 2011; Rosser *et al.*, 2005, 2013; Young *et al.*,2006; Young *et al.*, 2009) (2) the rates of evolution (3) the processes responsible for triggering gravitational movements, a high resolution and frequency diachronic monitoring was carried out on some sites by lasergrammetry (TLS) and photogrammetry (SfM-MVS, *Structure-from-Motion - Multi-View-Stereo*) methods (Costa, Freire-Diaz, and Di-Nocera, 2001; Costa *et al*., 2004; Dewez *et al.*, 2007, 2013; Giuliano *et al.*, 2015; Kuhn, and Prüfer, 2014; Lahousse and Pierre, 2002; Letortu *et al.*, 2015b; Lim *et al.*, 2010; Michoud *et al.*, 2014; Olsen *et al.*, 2011; Rosser *et al.*, 2013; Young and Ashford, 2006; Young *et al.*, 2009), and completed on two sites by several continuously operating permanent GPS stations. This work was undertaken within the framework of the SNO-Dynalit and SNO-OMIV.

For fast retreating cliffs, the emergence of techniques such as airborne and terrestrial lidars, terrestrial and UAV photogrammetry have made it possible to better estimate cliff retreat rates by integrating a fundamental dimension, the cliff face.

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

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

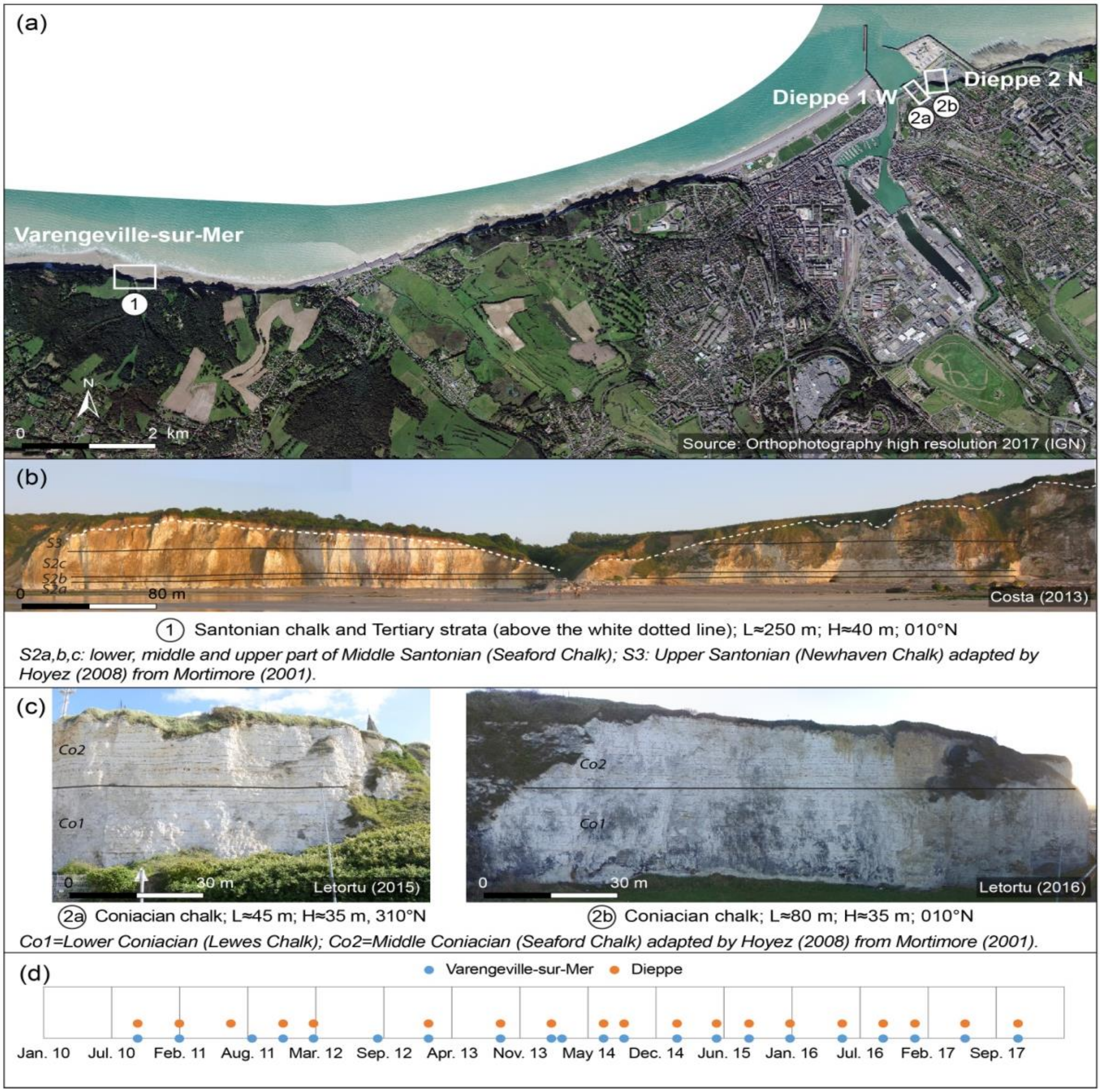

Figure 3. (a) Location of the sites; (b) Main characteristics of Cap d'Ailly/Varengeville-sur-Mer site; (c) Main characteristics of Dieppe sites; (d) Terrestrial Laser Scanner (TLS) acquisition.

The Vaches-Noires coastal cliffs site is located at the north-western part of the Pays-d'Auge region between Houlgate and Villers-sur-Mer (Figure 4) and has Jurassic limestone with clayed and marly formations. Their formations evolved under the action of continental and marine subaerial processes through the accumulation of deposits resulting from rotational landslides and/or mudflows at the base of the cliff which are then undermined by the sea (Maquaire *et al*., 2013; Medjkane *et al*., 2018). Since September 2014, on a 200 meter stretch of coastline, the cliff has been monitored using 3D models created by terrestrial laser scanner (3-4 surveys / year), terrestrial "Structure from Motion" photogrammetry (7-8 surveys / year) and Unmanned Aerial Vehicle (UAV) photogrammetry (2-3 surveys / year). Nine single-frequency GPSes were installed on site to continuously monitor the surface displacements (landslides and mudflows). A rain gauge and four piezometers were also installed to monitor rainfall values and oscillations of the water table.

The SNO-OMIV survey is focused on the Villerville slope site. This site is affected by a deep-seated rotational-translational complex landslide. It has been monitored since the early 1980s, following the major landslide event of 1982 (Maquaire, 1990). In order to measure the seasonal displacements affecting the landslide from upstream to downstream, 24 cemented landmarks were installed, and their positions are regularly measured by GNSS. In 20093 GNSS receivers were installed in the East part of the unstable area, which record their XYZ position hourly and provide better knowledge of the evolution rhythms (velocity, distance, direction and thresholds) (Lissak, 2012; Lissak *et al.*, 2013). Groundwater fluctuations are observed across a network of a set of 20 piezometers and inclinometers, mainly distributed on the eastern two thirds of the landslide, which is known to be the most active area (Maquaire, 1990; Lissak, 2012; Lissak *et al.*, 2013). Six of these devices are continuously tracked with multiparameter sensors (temperature and depth), the others are surveyed monthly with a contact gauge to highlight seasonal trends. Lastly, various hydro-meteorological parameters are registered by meteorological stations that record rainfall, temperature, solar radiation, wind speed and direction, nearby (the unstable slopes at Villerville and on the plateau located at Saint-Gatien-des-Bois from 5 kilometres of the cliffs).

Along the Bessin cliff, on a local scale, four sites have been surveyed by TLS and terrestrial photogrammetry SfM (4-5 times per year) since December 2017 in order to assess the rate of retreat of the cliff base following triggering factors. These sites are representative of the diversity of the landslide (falls, rotational and translational landslides) which occur in marly and limestone environments (Maquaire, 1990; Vioget, 2015). In addition, on a regional scale, the evolution of the Bessin cliffs is studied through the comparison of oblique aerial photographs taken since 1983 (Compain, in prep).

The TLS instrument used in this study is a RIEGL VZ-400 emitting a wavelength laser of 1,550 nm, which records unique echo digitization (RIEGL Laser Measurement Systems, 2014). The laser beam covers the environment with vertical scanning by an oscillating mirror and horizontal scanning by rotating the head. The point cloud is therefore centered on the position of the scanner. To obtain georeferenced data, the process of data acquisition requires additional equipment: target(s), a total station or a DGPS. The total station or the DGPS station is used to register the point cloud acquired in a relative coordinate system

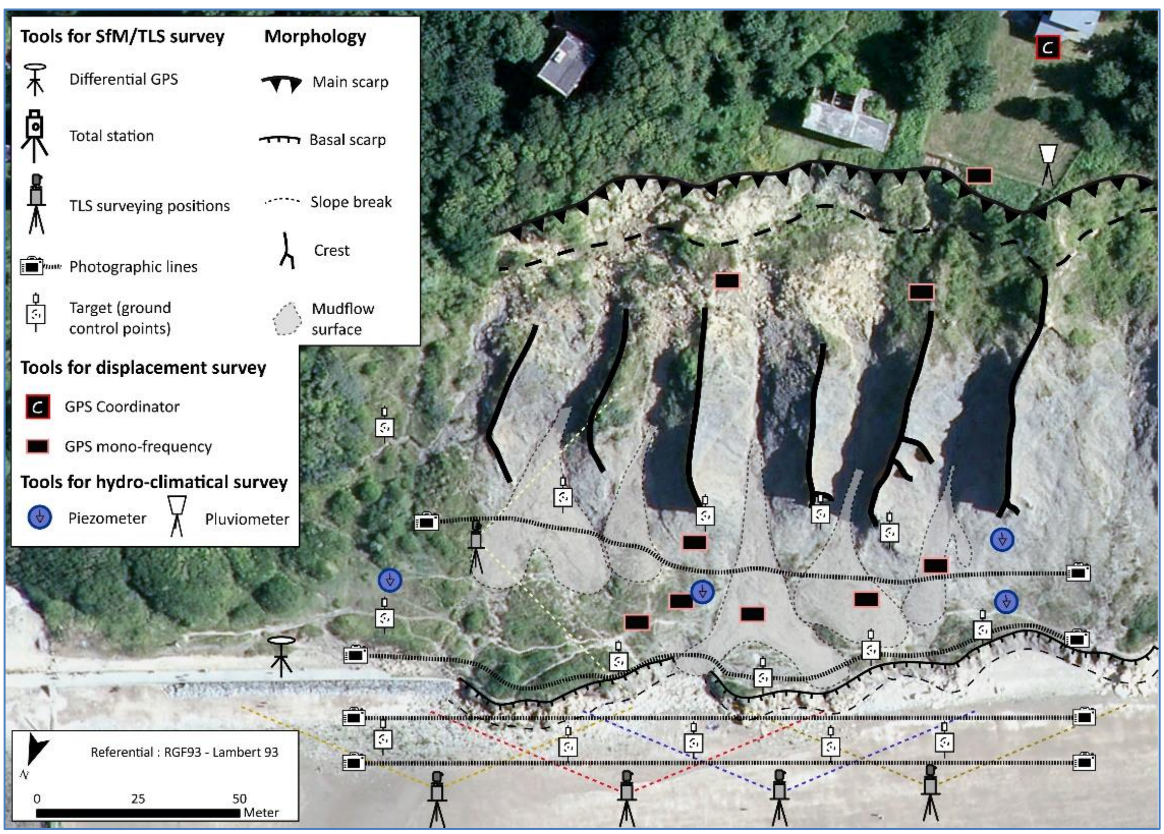

Figure 4. Scheme of the measurement tools and equipment used for the monitoring of the Vaches Noires cliffs.

to an absolute coordinate system thanks to target(s) (RGF93/Lambert93, EPSG:2154). Data processing has 4 steps: (1) georeferencing and point cloud alignment; (2) manual point cloud filtering (vegetation, people, foreshore); (3) meshing using Delaunay triangulation and generation of a 3D Digital Elevation Model (DEM); (4) creating a DEM of Difference (DoD). Precision is the most important parameter in our monitoring, thus all the point clouds are fitted to a selected reference point cloud using best fit alignment algorithms (Cloudcompare® or 3DReshaper®). This adjustment reduces the error margin as it includes the TLS instrumental error (0.005 m at a range of 100 m, RIEGL Laser Measurement Systems, 2014) and the cloud adjustment error (fitting) only. To assess precision, fixed parts of the point cloud are compared using the usual data processing. The precision in planimetry is 0.03 m for Cap d'Ailly and Dieppe 2 N, 0.02 m for Dieppe 1 W and Villers-sur-mer. The volume precision is ± 156 m3 in Cap d'Ailly (surface of 5,214 m²), ± 9 m^3 in Dieppe 1 W (434 m²) and ± 30 m^3 in Dieppe 2 N (1,018 m²), and ± 3 m^3 in Villers-sur-Mer (111 m²) (Medjkane *et al.*, 2018). These improved resolutions, particularly over the whole cliff face, and the higher frequency of acquisitions provide valuable information on retreat rates, spatial distribution, temporalities and the processes and factors responsible for triggering gravitational movements.

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

RESULTS

Historical Approach for All Normandy Sedimentary Cliffs

The study of the Normandy sedimentary cliffs shows that their retreat is decimetric, from 0.1 to 0.5 m/yr over the last decades.

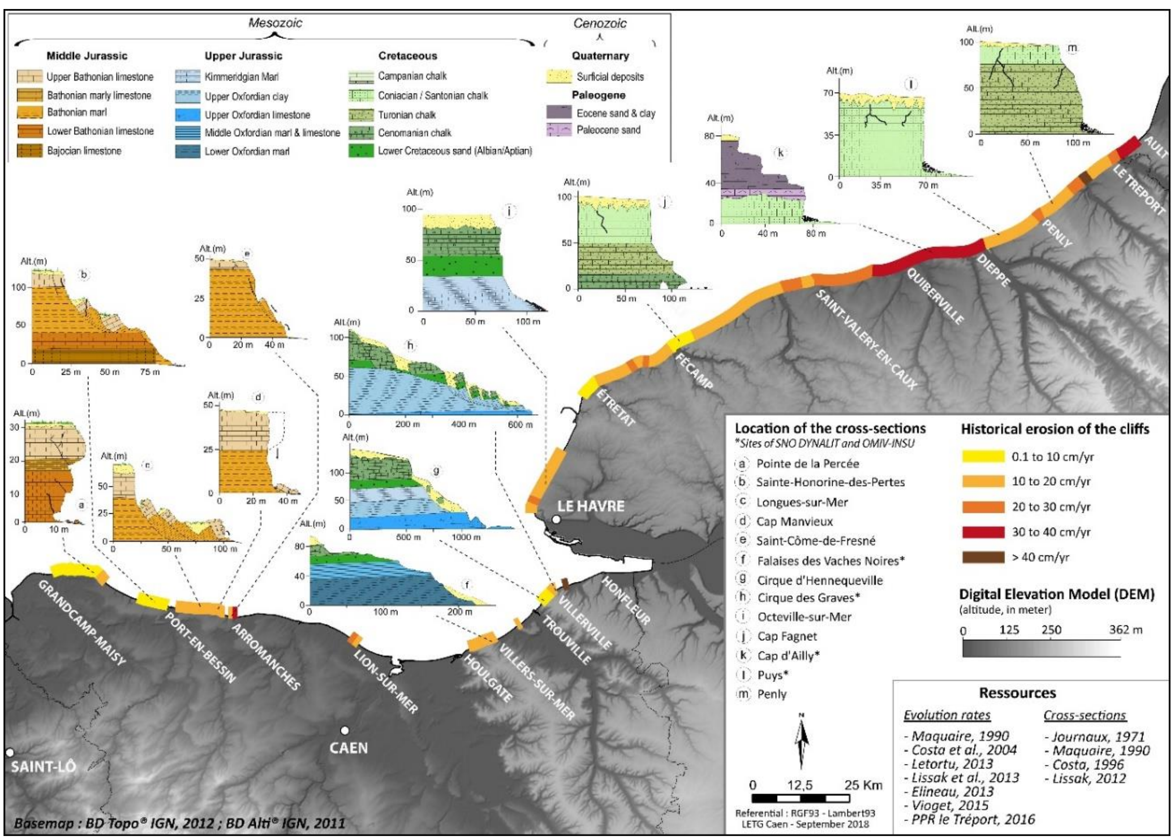

Figure 5. Synthesis of historical retreat rates of the Normandy sedimentary cliffs (in cm/year).

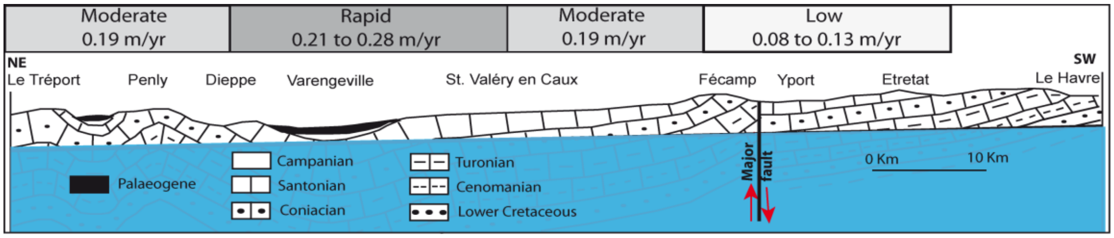

Figure 6. Relationship between chalk cliff retreat rates and lithology (from Costa *et al.,* 2001; 2004; Letortu *et al.,* 2014).

The spatial variations of the cliff retreat rates, at the scale of Normandy, can be explained by the geological structure from which the cliffs were formed (Figures 5 & 6). However, the differences are not excessive while various materials, of significantly different resistance, are exposed (limestones, chalks, marls, clays). The greatest variations of retreat appear for the cliffs of Seine Maritime which are nevertheless carved in materials, a priori more homogeneous, Cretaceous chalks.

Various authors have proposed cliff typologies that relate profile, resistance and disposition of rocks (Costa, 1997; Dornbusch *et al.,* 2008; Guilcher, 1954; Kennedy *et al.,* 2014; Maquaire, 1990; Senfaute, Duperret, and Lawrence, 2009; Trenhaile, 1987; Woodroffe, 2002;). These classifications sometimes make it possible to deduce the effectiveness of the marine and continental processes involved (Emery and Kuhn, 1982; Kuhn, and Prüfer, 2014). With apparent lithological homogeneity, the variability of the facies of the Seine Maritime chalk (Lasseur, 2007; Mortimore *et al.,* 2004; Pomerol *et al.,* 1987) very clearly influences the modalities and evolution rates of the Seine-Maritime cliffs. Photogrammetry analyses were carried out to quantify the retreat of chalk cliffs. The 1966 and 1995 vertical aerial photographic surveys (1:10,000) from the French National Geographic Institute were used (Costa *et al.,* 2001; Costa, Freire-Diaz, and Di-Nocera, 2004). The mean retreat rate of the entire shoreline under study was approximately 6 m between 1966 and 1995, which yields a rate of 0.21 m/yr. This average rate, however, masks a very high spatial variability of cliff retreat (Figure 6). In fact, the analysis highlighted three distinct areas: (i) an area of low retreat rate (0.8 to 0.13 m/yr.) between Antifer and Fécamp; (ii) an area of moderate retreat rate (approximately 0.19 m/yr.) between Fécamp and Saint-Valéry-en-Caux, and between Dieppe and Le Tréport; (iii) an area of rapid retreat (0.21 to 0.28 m/yr.) between Saint-Valéry-en-Caux and Dieppe (Costa *et al.,* 2001; Costa, Freire-Diaz, and Di-Nocera, 2004; Letortu *et al.,* 2014).

Contributions of High Resolution and Frequency Measurements

This work (Figure 7), carried out every 3-5 months on active and abandoned chalk cliffs (Cap d'Ailly and Dieppe, respectively), but with similar lithology, shows that over the period studied (2010-2017): (1) The retreat rate evaluated by TLS on active cliffs over a period of 7 years corroborates that established by photo-interpretation (observed over nearly 50

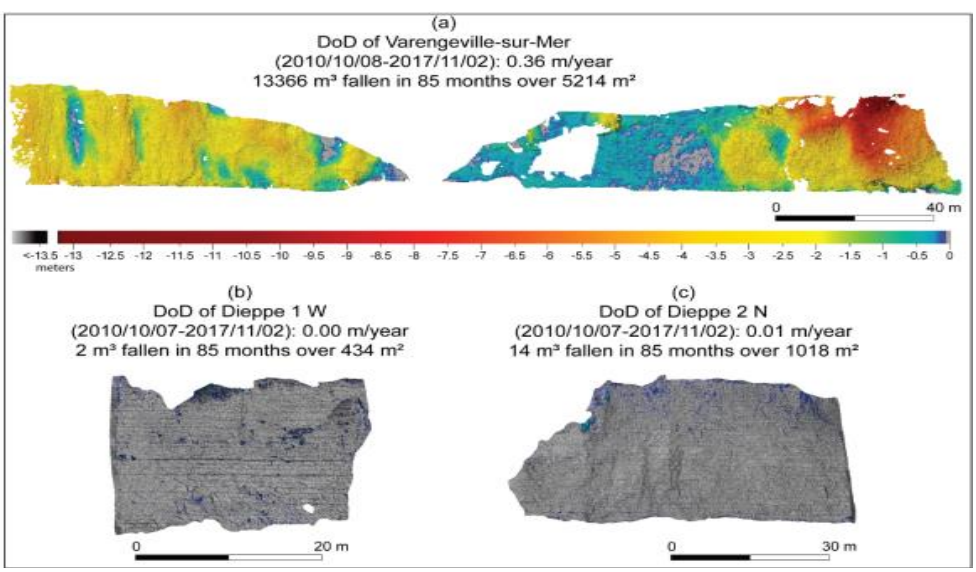

Figure 7. Erosion results of DoD over 7-years of monitoring of Cap d'Ailly/Varengeville-Dieppe site.

years), *i.e*., around 36 cm/year for the Cap d'Ailly and almost zero for the abandoned cliffs of Dieppe; (2) in 7 years, the entire front of the active cliff is affected by debris and mass movements; (3) scree movements (debris falls) represent 100% of the evolution of the abandoned cliff faces (for the moment!), while they represent 2% of the total retreat of the active cliff of Cap d'Ailly. This quantification highlights the poor contribution of debris falls and explains in more detail the first assessments made on the same Normandy chalk cliffs and East Sussex (Lageat, Hénaff, and Costa., 2006; May, and Heeps, 1985); (4) Abandoned cliffs have evolved up to 36 times more slowly than active one, highlighting the importance of marine actions in the active cliff retreat (Letortu *et al.*, 2015b).

For the Vaches Noires cliffs, the TLS differential model (March 2015 and October 2017) clearly identifies erosion areas (red) and accretion areas (blue) especially during a rainy autumnal and winter periods (Figure 8) at high spatial resolution. The main eroded areas are the upstream scarp, the flanks of the interfluve ridges, and the basal scarp. The debris are accumulated at the outlet of the gullies and very locally at the top of the basal scarp. However, we noted that the erosion and accumulation sectors follow one another spatially in the gullies, at their outlet and at the level of the basal scarp. These values reveal the seasonal activity of the cliffs of the Vaches Noires with a contribution of materials upstream of the cliffs and the finest elements that will then be partially cleaned and deposited into the sea. After these observations, the high temporal frequency survey allowed assessment of the different accumulated / eroded volumes according to the processes and associated morphologies (ablation zone and accumulation zone) between the different dates to better understand the seasonal temporality and the role and weight of each controlled factor (sea erosion and groundwater elevation) (Roulland, 2019).

DISCUSSION

Rhythms of Evolution

The identification of several sectors with distinctive retreat rates raises questions about the causes of this spatial distribution of the cliff retreat rates (especially its relation to the outcropping of different chalk strata), and the time between two cliff collapses (pluri-annual to pluri-decennial) at the same location (Evrard and Sinelle, 1980; Kennedy *et al.*, 2014; Prager *et al.*, 2008; Sunamura, 1992; Trenhaile, 1987, 2011). Knowledge of cliff evolution rhythms is as fundamental as that of their rates, because this information is needed to develop sustainable coastal management strategies (displacement of people threatened). As Figure 9 for the chalk cliffs of Seine Maritime shows, the sectors with "low" and "moderate" retreat, are affected by infrequent but voluminous rockfalls (Costa, 1997; Costa *et al.*, 2003; 2004; Letortu, 2013), and correspond to cliff foot cut into Turonian, Cenomanian, and even Coniacian outcrops (Antifer/Fécamp ; Fécamp/Saint-Valéry-en-Caux ; Dieppe/Le Tréport). By contrast, the rapidly retreating sectors, affected by frequent but less

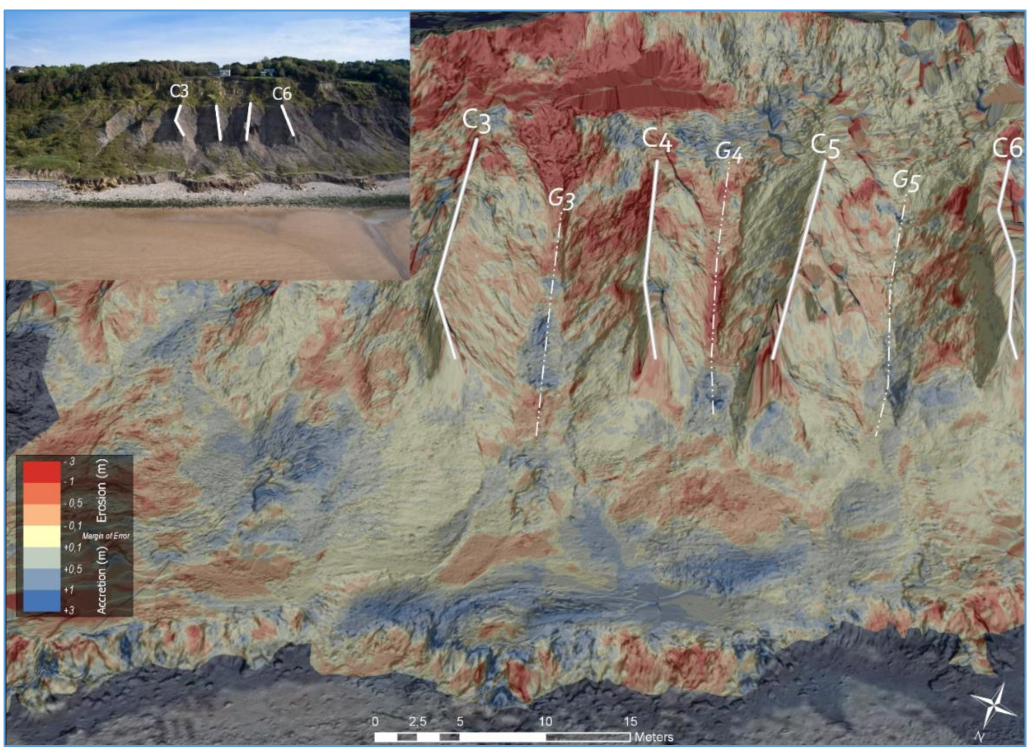

Figure 8. Erosion and accretion areas: TLS differential model of Vaches Noires cliffs (March 2015 - October 2017).

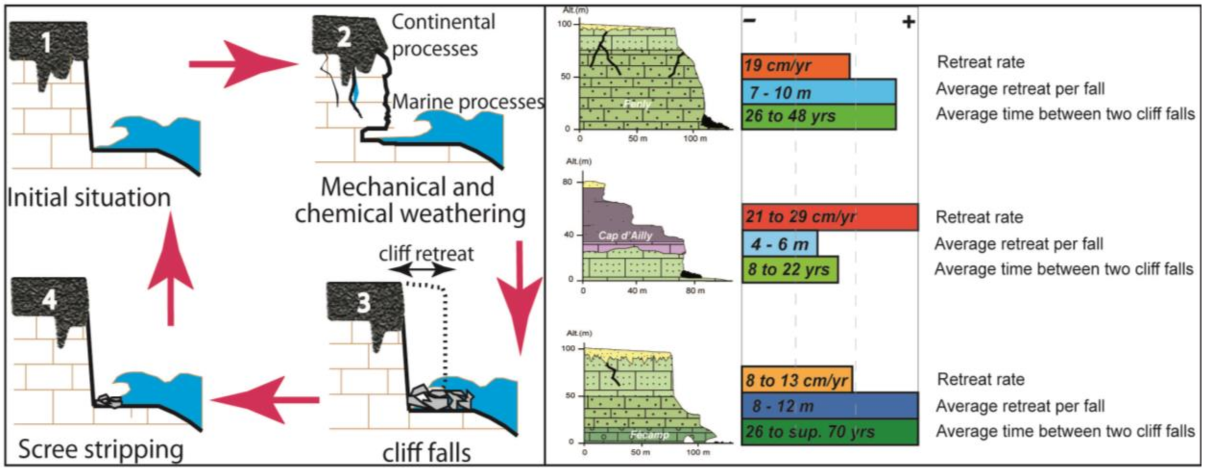

Figure 9. Cliff retreat, average retreat per fall and average time between two cliff falls for Seine Maritime chalk cliffs.

voluminous rockfalls, correspond to Santonian and Campanian outcrops (Saint-Valéry-en-Caux/Dieppe).

Even within each of these coastal sections, important variations exist. These sharp variations are linked with the influence of cliff collapses or anthropogenic obstacles, such as harbour arms or major groynes that disrupt the gravel transit from the south-west to the north-east. Down current of these obstacles, the cliff retreat can be doubled (Costa *et al.*, 2006). These observations are confirmed by the analysis of the retreat at 50 m intervals. For example, in each part of the groyne of Criel, the cliff retreat rate increased from 0.19 m/yr. to 0.34 m/yr. (Figure 10).

By comparing historical documents (Terrier Plan, land registry maps, aerial photographs, postcard photography) and more contemporary data (orthophotographs, satellite images, dGPS surveys, LIDAR surveys) of the Vaches Noires from between 1759 and 2016 (257 years), the results show a marked decline in the top of the cliff (limit plateau/slope) estimated at - 0.39 m/year, but also an average annual decline of - 0.27 m/year between 1837 and 2016 (179 years). The basal scarp (contact cliff/sea) has a more contrasted evolution, with some sectors in erosion, others in progradation, and some sectors without significant evolution (or included in the margins of error). The erosion values are generally between - 0.02 m/year to - 0.15 m/year between the different periods. The progradation values range from + 0.02 m/year to + 0.15 m/year. Comparison with the average evolution rates (in m/year) of other Normandy clay and marl cliffs (ranging from - 0.15 m/year to -0.30 m/year) showed that the foot of the basal scarp suffered a slight overall decline. These studies show that distinctions need to be made in the evaluation of shorter time step velocities due to the reactivation and progression of major

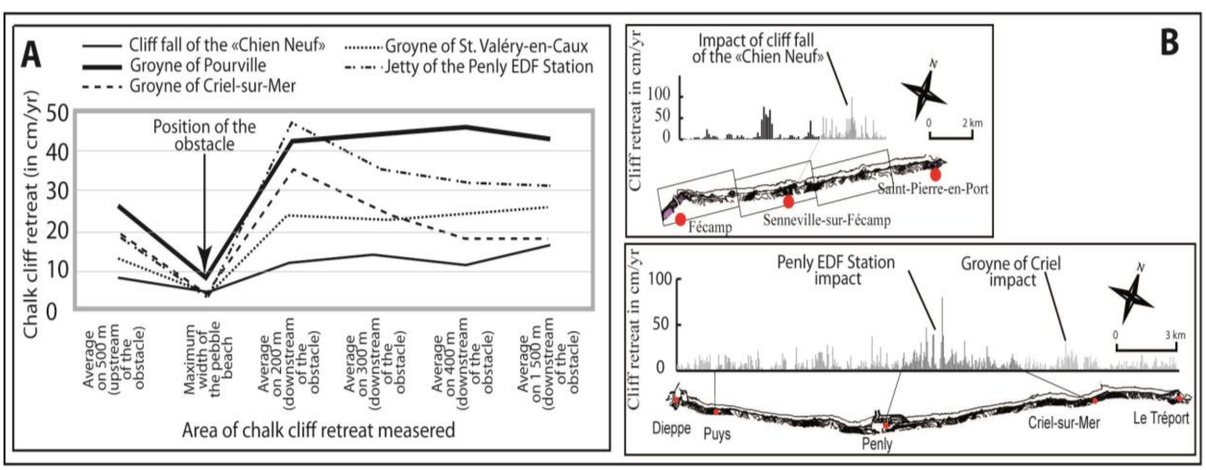

Figure 10. Impact of major cliff falls or anthropogenic obstacles on chalk cliff retreat of Seine Maritime between 1966 to 1995 (A), and some examples of measurements at 50 m intervals (B).

foreshore landslides that alter the coastline. This is visible on the Vaches Noires cliffs where a large landslide occurred between 1837 and 1947, causing the top of the cliff to retreat by more than 120 m and the coastline to advance by more than 50 m (Maquaire *et al.,* 2013; Roulland *et al.,* 2019).

There is a high spatial and temporal variability in cliff sectors affected by landslides and mudflows. Thus, the evolution calculated over a long period is probably more significant when considering the cliff evolution cycle. Contrary of the cycle shown in figure 9 for chalk cliff, the Vaches Noires" cliff is more complex. Hutchinson (1973) showed that an evolution could occur within cycles of 30 to 40 years in London clays. Moreover, in the Gault clay cliffs of Dorset, Brunsden, and Jones (1980) demonstrated an evolution cycle of a hundred years. These differences in the activation of summit flows depends largely on the retreat of the lower part of the cliff (Pierre, 2005). Thus, for the "Vaches Noires" cliffs, the duration of the cycle would be at least around 250 to 300 years to be able to set a long-term evolutionary trend of decline.

Factors Responsible for Triggering Gravitational Landslides (Rockfall, Slide, Debris Fall) and Thresholds

The cross-referencing of multi-date and multi-document data as well as that of some agents such as erosion processes can provide information about the factors responsible for triggering gravitational landslides. At the SNO-OMIV landslide of Villerville, the link was clearly established between efficient rainfall, groundwater level and displacement of unstable slopes (Lissak *et al.,* 2009; Lissak, 2012; Maquaire, 1990). Efficient rainfall increases the roof level of the groundwater until it exceeds a threshold rain quantity, considered in the literature as the main triggering factor of worldwide landslides Guzzetti *et al.,* 2008; (Peruccacci *et al.,* 2017; Zezere, 2002; Zezere *et al.,* 2015).

In order to highlight the relationship between rain, groundwater and displacement of the Villerville deep-seated landslide, long-term chronicles of data should be used (Figure 11). To this end, data from a Danestal piezometer (in the hinterland, on the Pays d'Auge plateau) were cross-analysed with efficient rainfall data measured by the Météo-France weather station at Saint-Gatien-des-Bois (located 5 km behind the landslide). These chronicles were then linked to the known major events which affected this significant coastal landslide.

This correlation analysis, initially expressed by Lissak (2012), revealed a small-scale causal relationship between the hinterland groundwater level and the four major accelerations observed on the coast (Figure 11). From this observation, a regional warning threshold has been proposed in cases in which the Danestal piezometer exceeds a depth of 11m/GL and the effective rain is over 250mm on a 4-month-period (Lissak *et al.,* 2013).

For the chalk cliffs of Seine Maritime, determination of the triggering factors of rock falls is more difficult. Based on a census of 331 chalk cliff rock falls collected weekly between 2002 and 2009 from Veules-les-Roses to Le Treport the relationship between dates of cliff rock falls and external factors commonly agreed as triggers (rainfall, temperature variations, tide and wind) is studied (Figure 12). The combination of multivariate statistical and empirical analyses indicates (Letortu *et al.,* 2015a) that, (1) high rainfall is an essential triggering factor especially on the most massive chalk rock falls (mostly larger than 10,000 m^3) (confirmed by Duperret *et al.,* 2002; 2004; 2005; Pierre and Lahousse, 2006), (2) but also the freeze/thaw cycles which are responsible for scree production phenomena (individual particles), (3) marine factors are not negligible but their influence is difficult to quantify because small volume rock falls may be quickly removed during a stormy period. However, the contribution of each factor as a trigger is difficult to determine because of combinations of factors (84 % of 331 cases), relays of

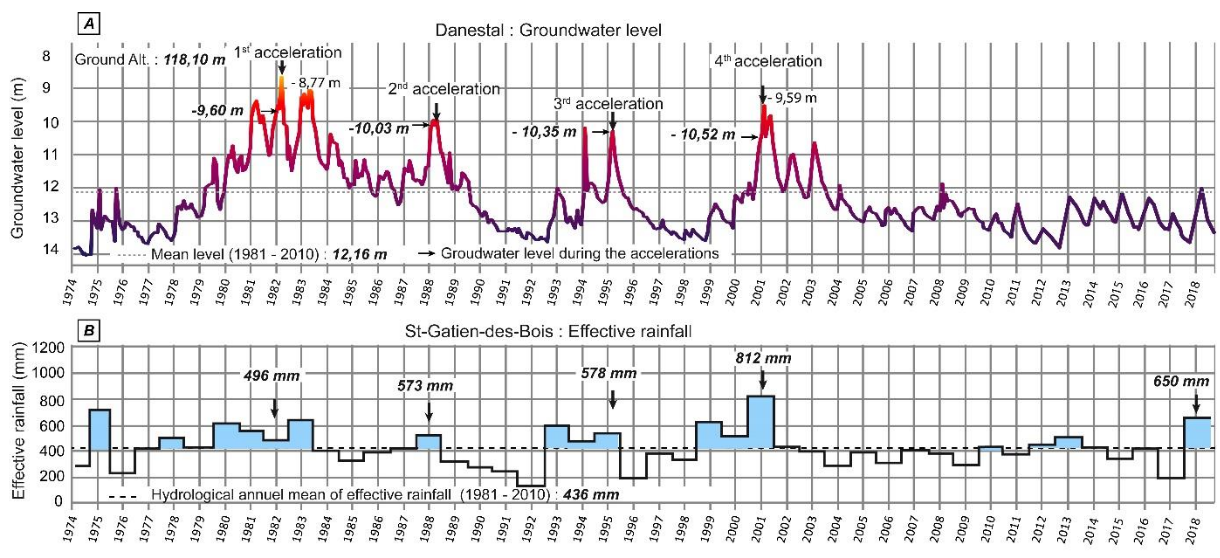

Figure 11. Evolution of the Danestal well groundwater levels and of the effective annual rainfall of the St-Gatien-des-Bois weather station from 1974 to 2018.

processes and hysteresis phenomena. In view of these first results, it is still presumptuous to predict the location and time of triggering of rock falls. However, the statistical and naturalistic approaches adopted, and the observations made in this study are from an original database and are a real starting point for the prediction and prevention of the hazard of coastal chalk cliff rock falls.

CONCLUSIONS

The retreat rates of the sedimentary cliffs of Normandy are about 20-30 cm/year. These values are in line with what is generally observed for this type of geology (Donrbush *et al.*, 2008; Kennedy, Coombes, and Mottershead, 2017; Moses and Robinson, 2011; Woodroffe, 2002). Spatial disparities are due to lithological variations (outcrop less resistant at the foot of cliffs), and above all to the existence of obstacles to coastal drift (structures or cliff falls) which considerably increase the retreat rates. These values are also comparable to those observed on English coasts for similar materials (Dornbush *et al.*, 2008) although the orientation of swells is different. However, beyond the lithological variations there may be other factors that explain the spatial variation in retreat rates such as the platform width, the cliff height, the width of the beaches at the foot of the cliffs, the intensity of the fracturing of the rocks, the presence of more or less important groundwater etc.

This work also shows the interest of diachronic analysis using a multisource and multitemporal approach (comparison of historical documents of modest precision allowing observation of large areas with high frequency and high resolution data, and for the cliff face to be studied locally). This work provides information on the periodicities of the evolution of the various cliffs that are essential for the temporal management of the movement of goods and people.

The high frequency and high resolution monitoring carried out as part of SNO-Dynalit and SNO-OMIV greatly improves the knowledge of these sites. Even if the monitoring is carried outin fairly small areas, it allows fine spatialization of the evolutions, especially on the cliff face. It makes it possible to distinguish between screes and mass movements, to quantify the production of debris brought to the sea. However, the development of these new techniques (laser and photogrammetry) is recent (a decade). The results therefore have limited temporal representativeness. To be exhaustive, high-resolution data will have to be acquired over the entire cliff evolution periodicity (evolution cycle), which for some of them is at least two decades.

Similarly, the frequency of surveys should be well above 3-4 per year to define the agents and processes responsible for weathering cliffs or triggering gravity movements. It is also for these reasons that it is very difficult to estimate the impact of climate change and sea level rise on cliff recession rates. Moreover, the extent of anthropization on coastal dynamics in recent decades masks the possible influence of these global changes.

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

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