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Retreat rates, modalities and agents responsible for erosion along the coastal chalk cliffs of Upper Normandy: The contribution of terrestrial laser scanning

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ABSTRACT

In order to follow all the changes affecting the coastal chalk cliff face in Upper Normandy and improve knowledge about cliff erosion, repeated terrestrial laser scanning (TLS) surveys were carried out frequently between 2010 and 2013 (every 4–5 months). They were conducted at two sites with similar lithostratigraphic characteristics but different exposures to marine actions (the former being an abandoned cliff and the latter an active cliff). They provide a quantification of the production of debris with centimeter precision (from ±0.01 to 0.04 m). These surveys provided three major outcomes: 1) cliff retreat rates were measured at high spatial resolution with retreat values, unsurprisingly, 3–4 times higher for an active cliff than for an abandoned cliff. This result highlights that marine actions should be seen as not only a transport agent but also a particularly effective erosion agent; 2) a significant proportion of debris fall production (about 25%) in the total active cliff retreat was identified; and 3) one of the modalities of retreat was visualized as the creation of a basal notch, which propagates instability towards the upper part of the cliff face. Later, this instability generates rock falls coming from the whole cliff face.

1. Introduction

To understand the regressive dynamics of coastal cliffs, the knowledge of retreat rates at fine scale and the study of agents leading to erosion are major challenges (Trenhaile, 1987; Sunamura, 1992; Griggs and Trenhaile, 1994; Stephenson et al., 2013). Erosion is traditionally quantified by studying the rates of retreat of a spatial object tracked over time, often the cliff top (Bird, 2008). However, these average retreat rates are incomplete information because they do not reflect the sudden nature of the hazard. This results in rock falls that threaten populations located at the cliff top and at the cliff foot. Thus, retreat occurs in “jerks”, generated by the interaction of both internal factors (e.g., rock strength and structure) and external factors (e.g., rainfall, temperature variations, and wave action). The contribution of the latter to triggering rock falls is difficult to determine (Letortu et al., 2015). “Rock fall” is used in this paper to describe movements of coherent rock (Varnes, 1978). From Varnes' typology, two types of movement can be distinguished according to the fallen volume: 1) debris falls describe the small-scale release of tiny blocks or flakes (up to decimeter) from across the cliff face; and 2) rock falls describe large-scale movements from all or part of the cliff face. The former are common on rocky slopes but are often omitted in quantification due to their fine scale or unsuitable point of view. Far from negligible, their participation is estimated at about 10% of the total retreat (May and Heeps, 1985; Hénaff et al., 2002) and may be an early sign of instability. Monitoring these jerks requires a high spatial and temporal resolution and a horizontal point of view that enables all changes to be monitored (Young et al., 2009).

Due to unstable and subvertical cliff faces, quantification is difficult and sometimes dangerous. For these reasons, remote sensing technologies are mainly used. Aerial images can be used but the data accuracy is, at best, pluridecimeter and the point of view is inappropriate (vertical or oblique). Recent advances in remote sensing technology, in particular the improvement in the spatial resolution, may provide effective measurement tools. They may also offer the opportunity of conducting surveys at higher temporal frequency. Satellite data are interesting but

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their spatial resolution still appears insufficient for monitoring debris falls. Photogrammetry is not used because its reliability is affected by the height of the cliffs (Lim et al., 2005) but new developments are promising. Terrestrial Laser Scanning (TLS) is particularly convenient because the temporal and spatial resolution, as well as the point of view, can be defined by the user.

The TLS technique, described as "*one of the most promising surveying techniques for rockslope characterization and monitoring*" (Abellán et al., 2009), has been widely used in the study of mass transfers to:

1) identify structural and geomorphological characteristics of landslides (Oppikofer et al., 2009; Sturzenegger and Stead, 2009; Rothmund et al., 2013), landslide mapping (Rowlands et al., 2003) and displacement tracking (Delacourt et al., 2007; Oppikofer et al., 2008, 2012; Teza et al., 2008; Travelletti et al., 2008, 2013; Abellán et al., 2009, 2010);
2) analyze rock falls including those affecting cliffs (Lim et al., 2005, 2010; Rosser et al., 2005, 2013; Quinn et al., 2010; Dewez et al., 2013; Abellán et al., 2014; Kuhn and Prüfer, 2014); and
3) analyze warning movements of falls (Rosser et al., 2007; Abellán et al., 2009, 2010; Royán et al., 2014).

In our study, TLS is used for repeated surveys in order to observe the evolution of the cliff face at two sites with a similar lithological context but subject to different marine forcing (abandoned and active cliffs). The aim is to quantify erosion at fine scale, to visualize the modalities of retreat and to contribute to the debate about the agents responsible for erosion of the Upper Normandy chalk cliffs. This paper first explains the study area and details the material and the TLS survey methodology. Then, the results of the cliff face monitoring are described and discussed.

2. Study area

2.1. Regional setting

Upper 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 with a tidal range of 8 m. Swell is limited but the wind sea can reach a significant wave height of 4 m in Dieppe (annual return period). Upper Normandy has a marine west coast climate. From Météo-France data (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 (ca. 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. The Upper Normandy cliffs, 60–70 m high on average, extend 120 km from Le Havre (SW) to Le Tréport (NE) (Seine-Maritime) (Fig. 1). At their foot, there is a marine erosion platform (from 150 to 350 m wide), hidden, at the upper part of the beach, by a thin gravel beach. The cliffs are intersected by numerous

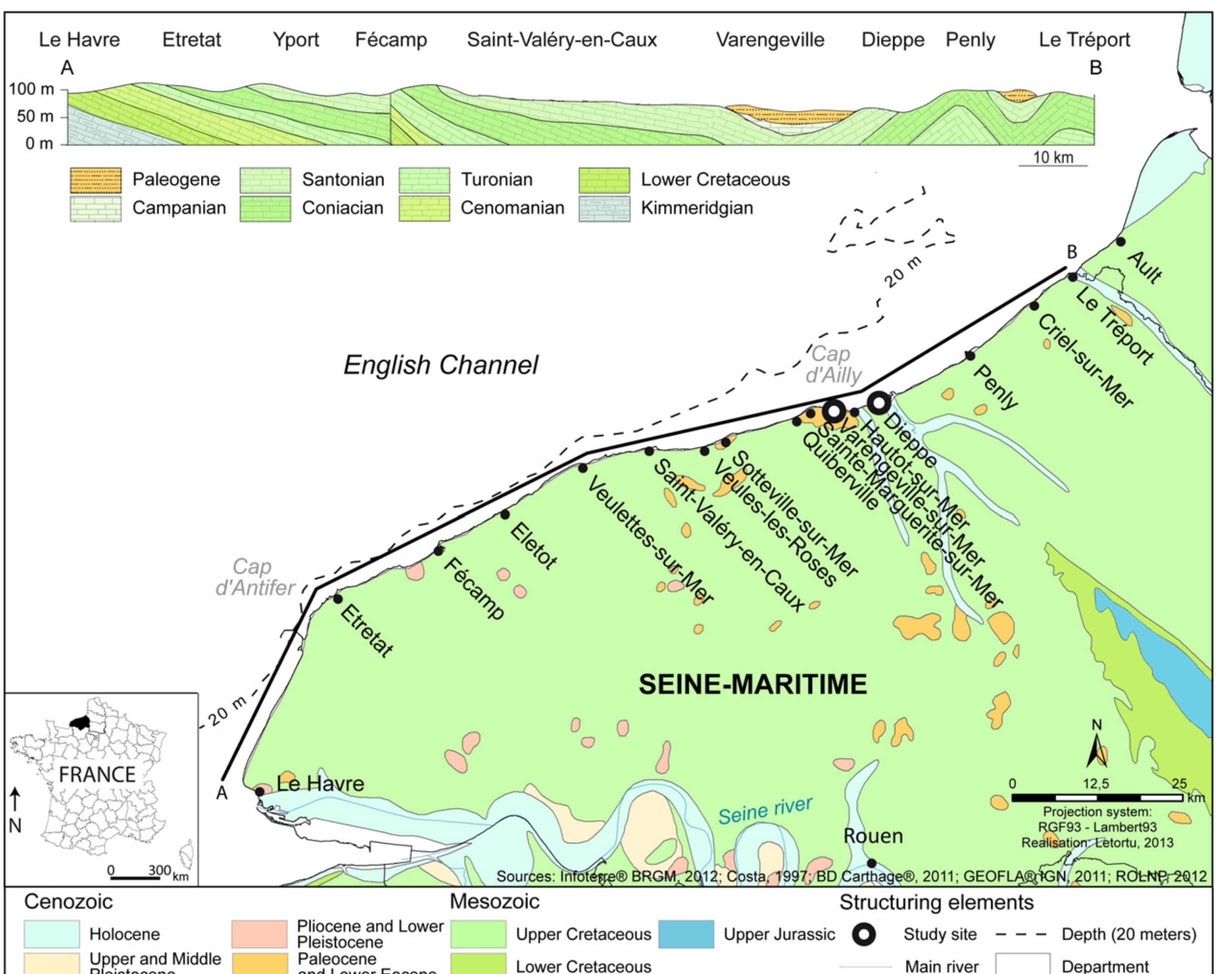

Fig. 1. Presentation of the study area.