Marine Geology 382 (2016) 37–55

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

A comprehensive hydro-geomorphic study of cliff-top storm deposits on Banneg Island during winter 2013–2014

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ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 20 September 2016
Accepted 24 September 2016
Available online 05 October 2016

Keywords:
Cliff-top storm deposit
Block transport
Extra-tropical cyclone
Run-up
Coastal erosion
Brittany

ABSTRACT

Large clastic cliff-top storm deposits (called CTSDs) are one of the most remarkable signatures that characterizes extreme storm wave events on coastal cliffs. Hence, the study of CTSDs is of key importance for understanding and predicting the impacts of extreme storm wave events on rocky coasts or establishing proxies for storm intensity. The present study uses new data including hydrodynamic measurements in both deep and intertidal waters, and records of CTSDs displacement and deposition across Banneg Island during the stormy winter 2013–2014. Two drone-based surveys were carried out in January 2013 (pre-storms) and in April 2014 (post-storms). In addition, complementary field observations were carried out during the winter, providing a comprehensive and detailed dataset. Concerning the hydrodynamic measurements, nine pressure sensors deployed along four cross-shore profiles on the western coast of the island, recorded wave and water level conditions between December 2013 and April 2014. Aerial orthorectified photographs and digital elevation model of differences provide a detailed spatial description of cliff erosion and the reworking of cliff-top storm deposits. After the storms, 172 fresh scars corresponding to quarrying in the bed rock were localized above high spring tide water level, 507 blocks were transported up to 40 m inland, at altitudes of 8 to 14 m above mean sea level, and the tracks of 170 of them were identified. The water levels and wave parameters estimated from the pressure sensor measurements provided accurate information on the maximum water elevation reached during the largest storms at the sensor locations and were extrapolated to provide run-up elevation along the four survey profiles for the whole winter 2013–2014. The results demonstrate that a large number of overwash episodes occurred, at times of high tides and energetic waves. These episodes generally correspond to morphological changes. This study confirms the major role played by extreme storm wave events on CTSDs quarrying, transport, and deposition on Banneg Island, and clearly identify the events of major evolutions.

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1. Introduction

On rocky cliffed coasts facing deep water and exposed to storm waves, large blocks may accumulate on top of the cliffs. On the European North Atlantic coasts such accumulations are known as cliff-top storm deposits (CTSDs) due to their mobility during storm wave activity (Hall et al., 2006; Fichaut and Suanez, 2011). The formation of these deposits is both controlled by the lithostructural characteristics of the cliff allowing the quarrying of blocks, and by the hydrodynamic conditions that induce the uplift, transport and deposition of these blocks on the cliff-top (Hall et al., 2006; Fichaut and Suanez, 2011; Paris et al., 2011). Hence, the nearshore bathymetry also plays an important role in CTSDs formation as it affects the propagation and dissipation of the incident wave energy (Hansom et al., 2008). Within the North Atlantic basin, storm-induced CTSDs were described in Brittany (Fichaut and Suanez, 2008; Suanez et al., 2009), British Isles, Republic of Ireland (Williams and Hall, 2004; Cox et al., 2012) and Iceland (Etienne and Paris, 2010; Autret et al., 2016). These authors provided evidences that tsunami were not responsible of the formation of these deposits during the last centuries. Although previous studies present a number of quantitative measurements of morphologic characteristics (e.g. historic maps, aerial photographs, topographic and sedimentological measurements, geomorphological indicators), they did not include hydrodynamic measurements (Paris et al., 2011; Richmond et al., 2011; Cox et al., 2012). Some authors derived the hydrodynamic

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http://dx.doi.org/10.1016/j.margeo.2016.09.014
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conditions inducing these processes from mathematical models based on lithostructural and morphometric characteristics (Nott, 2003; Hansom et al., 2008; Nandasena et al., 2011; Lau et al., 2015). Although these models can be used to estimate the magnitudes of the water level and velocity necessary for the quarrying, transport and deposition of blocks, they can hardly characterize the realistic hydrodynamic conditions occurring during storm events (Naylor et al., 2016). Therefore, a better understanding of the link between the action of these hydrodynamic processes and their implications in terms of morphosedimentary response appears as a key issue (Goto et al., 2011; Scheffers et al., 2012; Naylor et al., 2014). Similarly, in several studies focusing on the quantification of extreme water levels causing cliff-top submersion and/or transport of blocks, the methodological approach is based only on the use of theoretical equations including run-up, without validation based on field measurements (Suanez et al., 2009; Fichaut and Suanez, 2011; Carbone et al., 2013). As reported by Ardhuin et al. (2011) and Sheremet et al. (2014), the characteristics of hydrodynamic processes acting on the elevation of water level (setup and run-up) along very steep cliffs make extremely difficult the use of equations established on the sandy beaches. It is therefore necessary to perform high frequency field measurements in order to calibrate these theoretical formulas for each specific coastal environments. The ongoing work on extreme water levels and their geomorphological impacts on rocky coasts in a context of climate change is of strong interest for coastal managers (Naylor et al., 2014). Moreover, hydro-geomorphic study combining morphodynamic and hydrodynamic data are needed to improve mathematical and numerical modelling of coastal boulder transport (Nandasena et al., 2011; Lau et al., 2015; Kennedy et al., 2016).

For the European North Atlantic coastal zone, the winter 2013–2014 was particularly morphogenetic. This winter was characterized by a cluster of storms that hit the coasts of Western Europe (Matthews et al., 2014; Wadey et al., 2014; Dissanayake et al., 2015; Masselink et al., 2015). Based on a 67-year (1948–2015) wave model hindcast, Masselink et al. (2016) showed that winter 2013–2014 was the most energetic winter along the European Atlantic coast since at least 1948, inducing extensive coastal impacts along the coastline. The 110-km long Gironde coast (SW France), suffered unprecedented beach and dune erosion (Castelle et al., 2015). On Brittany coasts, shoreline have also been severely impacted by at least twelve major storms, inducing an average shoreline retreat of sandy/shingle beaches reaching −6.3 m, with a minimum of about −0.2 m and a maximum of −30.1 m (Blaise et al., 2015).

Although recorded on the Aran Islands (Erdmann et al., 2015), the effects of the winter 2013–2014 on CTSDs of the Western European coast have not been studied yet. Our paper provides a comprehensive assessment of the impacts of the 2013–2014 winter storms on CTSDs on Banneg Island, based on hydrodynamic measurements and morphological surveys. The highest water levels that occurred during winter 2013–2014 are first identified from the wave and water level measurements. Secondly, field measurement are used to calibrate the run-up formula of Stockdon et al. (2006) in order estimate the flooding events that may have caused CTSDs quarrying and/or transport. Thirdly, a diachronic analysis of CTSDs morphosedimentary changes allows the quantification of quarrying, displacement and deposition of megablocks over three periods during the winter. Finally, a description of the processes related to the impact of waves and flooding on the dynamics of CTSDs is provided, as well as a quantification of erosion processes during the whole winter period.

2. Study area

2.1. Geological and geomorphological setting of Banneg Island

The archipelago of Molène is located in the Iroise Sea, off the western tip of Brittany peninsula (Fig. 1A–B). It consists of 18 main vegetated islands and 111 small islets and reefs amount to a surface of land of 229 ha lying above highest astronomical tide (AHAT) and corresponding to the emerged part of a shallow submerged plateau covering 15.286 ha between 0 and 25 m above mean sea level (AMSL) (Fig. 1B).

Banneg Island lies in the north-western edge of this archipelago and is separated from Ouessant Island by the deep Fromveur Channel (Fig. 1B). This island is the largest of a group of four islands that are Banneg itself, and southward Enez Kreiz, Roc'h Hir and Staon Vraz (Fig. 1D). The four islands are separated by saddles (due to erosion) oriented from WSW to ENE corresponding to one of the main fault axis in the archipelago of Molène (Le Gall et al., 2014). Between Banneg, Enez Kreiz and Roc'h Hir, low-lying areas emerge at low tide, while the island of Staon Vraz is always isolated from the others whatever the tidal level.

Banneg Island constitutes a granite batholith, oriented north-south, 0.8 km long and 0.15 to 0.35 km wide (Fig. 1C). The western coast is cut into sub-vertical cliffs made up of a series of high headlands (16 m to 20 m AMSL) with steep slopes (>50%), and lower (12 m to 13 m AMSL), less steep cliffs in embayments (15 to 35%). As indicated by Suanez et al. (2009) and Fichaut and Suanez (2008, 2011), these morphological characteristics and evolution of the cliffed west coast are related to the structure and joint system of the bedrock. At the headlands, which constitute the summits of the island, massive jointing organized in a loose orthogonal pattern make the rock body more resistant to marine erosion. They generally exhibit high towering rocky outcrops, except for Lachat Amaric Ler headland between the south and centre-south areas (Fig. 2). In this area, the upper part of the cliff shows a higher density of fine sheet horizontal joints that cut the rock face into large horizontal slabs and shape the headland in rounded domes. In contrast, at the embayments the granite has very dense sheet jointing from the middle to the upper cliff face, promoting large horizontal or box-shaped clasts of smaller size. Therefore, these lithostructural characteristics make the embayments much more sensitive to marine erosion. However, at the base of cliffs along the embayments, massive, orthogonal jointing may engender enormous quadrangular clasts accumulated on the tidal zone as an armor layer of rounded blocks or quadrilateral-shaped blocks with smoothed edges, weighing from one to several dozens of tons.

More than 1000 m^3 of CTSDs, whose individual weights vary from several kilograms to several tons (up to 42 tons), have been quarried and transported from the cliff-top (Fichaut and Suanez, 2008; Suanez et al., 2009). They are accumulated mainly at the rear of the cliff top edge backing embayments. The furthest inland accumulation lies 100 m from the western cliff edge on a slope that gently dips toward the eastern coast of the island. CTSDs have different forms and organization depending on the sector. They may locally correspond to a spread of isolated blocks. However, more often they form clusters or rectilinear ridges parallel to the cliff edge (like in the centre and north areas), or arcuate trains at the rear of embayments, mirroring the area's coastline (like in the centre-south and south areas). More than 60 accumulations lying at altitudes between 7 m and 14 m AMSL and up to 75 m from the edge of the cliff (like in the centre-north area) were inventoried for the entire island (Fig. 2). The largest ridge is located in the centre sector; it is 2.5 m high, stretches over a 60 m × 20 m surface area, and it has a volume of around 350 m^3. In this sector, a 1 m deep gully has been dug over time by erosion of the bedrock (Fig. 1D). This erosion form corresponds to a topographic saddle that crosses the island from west to east. The low altitude of the gully and the eastward slope facilitated the passage of particularly high velocity flows during submersion of the island (Fichaut and Suanez, 2011). These flows are expected to be the transporting agent leading to the construction of a delta of blocks located directly at the mouth of the gully on the eastern coast (Fig. 1D). Locally these CTSDs accumulations are deposited in double or triple parallel ridges, separated by areas of turf or rock surfaces, like in the south and the centre – centre-south part of the island (Fig. 2). In triple ridges, the accumulations closest to the cliff edge are the largest ones.

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