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Erosive effects of the storm Helena (1963) on Basse Terre Island (Guadeloupe — Lesser Antilles Arc)

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ABSTRACT

Erosive effects of the tropical storm Helena that hit the volcanic island of Basse Terre (Guadeloupe — Lesser Antilles Arc) on 24 October 1963 has been measured using 80 aerial images acquired by the French geographic institute (IGN — Institut Géographique National) at the approximate scale of 1/8000 less than three months after the storm Helena. On these images, 253 landslides triggered during the storm were identified and mapped. These landslides were located in the central region of the island where catchments exhibit the highest relief. Even though the average thickness of the landslides was only 1 m, i.e., less than the thickness of the weathered layer, the total volume of displaced sediments corresponded to an average denudation of 2800 t km^{-2}, i.e., 1.4 mm, on the watersheds affected by landsliding. To assess the erosional significance of this single climatic event, we compare the volume of sediment mobilized by the storm Helena to the long-term denudation rate. The latter, estimated from a calculation of the total volume of material eroded since the emplacement of lavas using a digital elevation model, is found to be 0.14 mm/y. Assuming that Helena is representative of the storms that hit Basse-Terre Island during the Quaternary, we find that a return period of about 10 to 15 years is enough to account for the long term denudation rate recorded for this Island. Such a period is comparable with the actual return period of the tropical cyclones of the order of 4 to 5 years, suggesting that the erosion of Basse-Terre Island is entirely controlled by tropical hurricanes.

1. Introduction

Extreme meteorological events are responsible for intense sediment transport in mountainous regions of the tropical belt (Page et al., 1994, 1999; Reid and Page, 2002; Korup, 2010). Storms and hurricanes induce landslides and scars in the weathered layers. The sediments fall in overflowing rivers and are transported to the ocean (Lin et al., 2008). Relationships between landslide characteristics, watershed properties, seismic conditions, and intensity of the meteorological events have been evaluated in various geological contexts (e.g., Lin et al., 2008). These studies demonstrate that (i) landslides are controlled by precipitation amount, lithology, hydrology, and relief possibly affected by seismic history, (ii) single extreme meteorological events may result in a global catchment denudation up to several millimeters (Page et al., 1994; Hovius et al., 1997). However most parameters (lithology, relief, hydrology, etc.) vary from one study to the other making it difficult to draw a general conclusion.

The return period of extreme meteorological events is generally well known for the current conditions except for the very catastrophic events that occur with a period greater than 1000 years (Korup, 2012). The past calendar of these events is deduced from the study of recent sediments deposited or reworked by oceanic storms (Reid et al., 1996; Bertran et al., 2004; Donnelly and Woodruff, 2007; McCloskey and Keller, 2009). This technique is efficient for the Holocene period but lacks precision for older periods.

Atlantic volcanic islands located in the tropical belt are ideal places for testing and measuring the geomorphic effect of extreme meteorological events that occurred during the Quaternary period. Indeed, the tectonics is very low (Feuillet et al., 2002), and the relief is constructed during punctuated volcanic episodes that produce homogeneous lithology at the scale of the islands and that can be well dated by absolute geochronology (Samper et al., 2007). Moreover, these islands are subject to storms and hurricanes producing heavy rainfall associated with strong winds. This favors landslide development by the destabilization of the canopy and the decrease of the soil stability because of the increase of pore pressure. In this paper we describe the effects of the storm Helena (26–28 October 1963) on the Basse Terre Island in the archipelago of Guadeloupe. In the center of the island, this storm initiated numerous landslides visible on aerial images acquired <4 months after the event (December 1963 and January 1964). We estimate the amount of sediment displaced in the main watersheds during the storm and we

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compare these values to the total amount of erosion since the emplacement of volcanic rocks.

2. Context of the study

The volcanic island of Basse-Terre belongs to the archipelago of Guadeloupe located in the Lesser Antilles Arc (Fig. 1A), which results from the subduction of the Atlantic plate under the Caribbean plate at a velocity of 2 cm/y (DeMets et al., 2000). Basse-Terre is the westernmost island of the archipelago. It is around 45 km long in the north–south direction with a width of 20 km. The island is composed of five main volcanic andesitic massifs (Samper et al., 2007) whose timing of effusive events has been recently investigated by K–Ar methods (Samper et al., 2007). The results of absolute geochronology show a north to south gradient of age, with the older products (2.79 Ma) being at the north. The active volcano called *Soufriere de Guadeloupe* belongs to the *Grande Découverte* massif, which is dated from 0.2 Ma to present. The *Monts Caraïbes* massif located at the extreme south of the island is composed mainly of hydromagmatic products emitted between 0.555 and 0.472 Ma (Samper et al., 2007). This massif will not be discussed in this paper as its lithology and morphology are different from the rest of the island.

Basse-Terre Island is characterized by high relief. The maximum elevation is reached at the Soufrière de Guadeloupe (1467 m asl). The slope distribution is asymmetric with average slopes larger on the western side of the island than on the eastern side. A positive north–south gradient of elevation related to the gradient of age is also observed. The morphology of the island has been shaped by volcanic constructions eroded by rivers, runoff, and landslides and by two episodes of huge flank collapses (Deplus et al., 2001; Samper et al., 2007; Lahitte et al., 2011). The first one occurred at 640 ka (Samper et al., 2007) on the western side of the island. It was limited to the north by the Vieux Habitant River north escarpment that has a typical horseshoe shape. The second one, which occurred at 550 ka, affected the southeastern

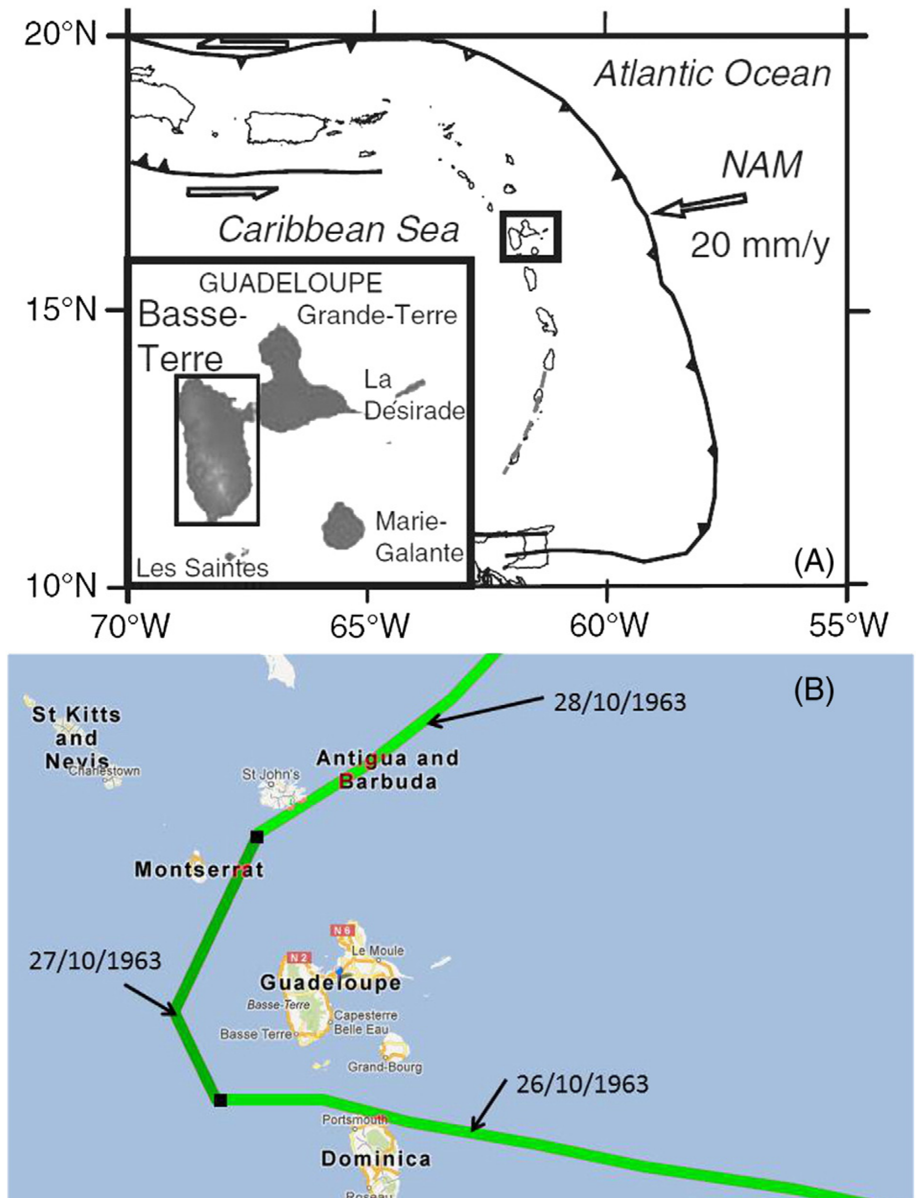

Fig. 1. (A) Geodynamic setting of Guadeloupe archipelago in the Caribbean arc. (B) Path of storm Helena (Dunn et al., 1964). Panel A: modified from Lahitte et al. (2011).

part of the island in the region of Capesterre. Volcanic massifs are downcut by concave-up bedrock rivers incising narrow V-shaped valleys. The river network is divided into 20 main watersheds (Fig. 2) each having a surface l > 10 km^2 drained by rivers with lengths that vary typically between 5 and 30 km. River beds are partially covered by a thin alluvial layer that can increase locally, likely because of overwhelming sediment supply from adjacent hillslopes, gullies, or tributaries. Closer to the sea, slopes become gentler and the river becomes alluvial. Granulometric sampling of sediment beds shows that the median diameter is comprised between 30 and 250 mm and reveals the presence of numerous blocks of metric size (Chatanantavet et al., 2010; Lajeunesse et al., 2011). The sand fraction is very small (<0.2%)

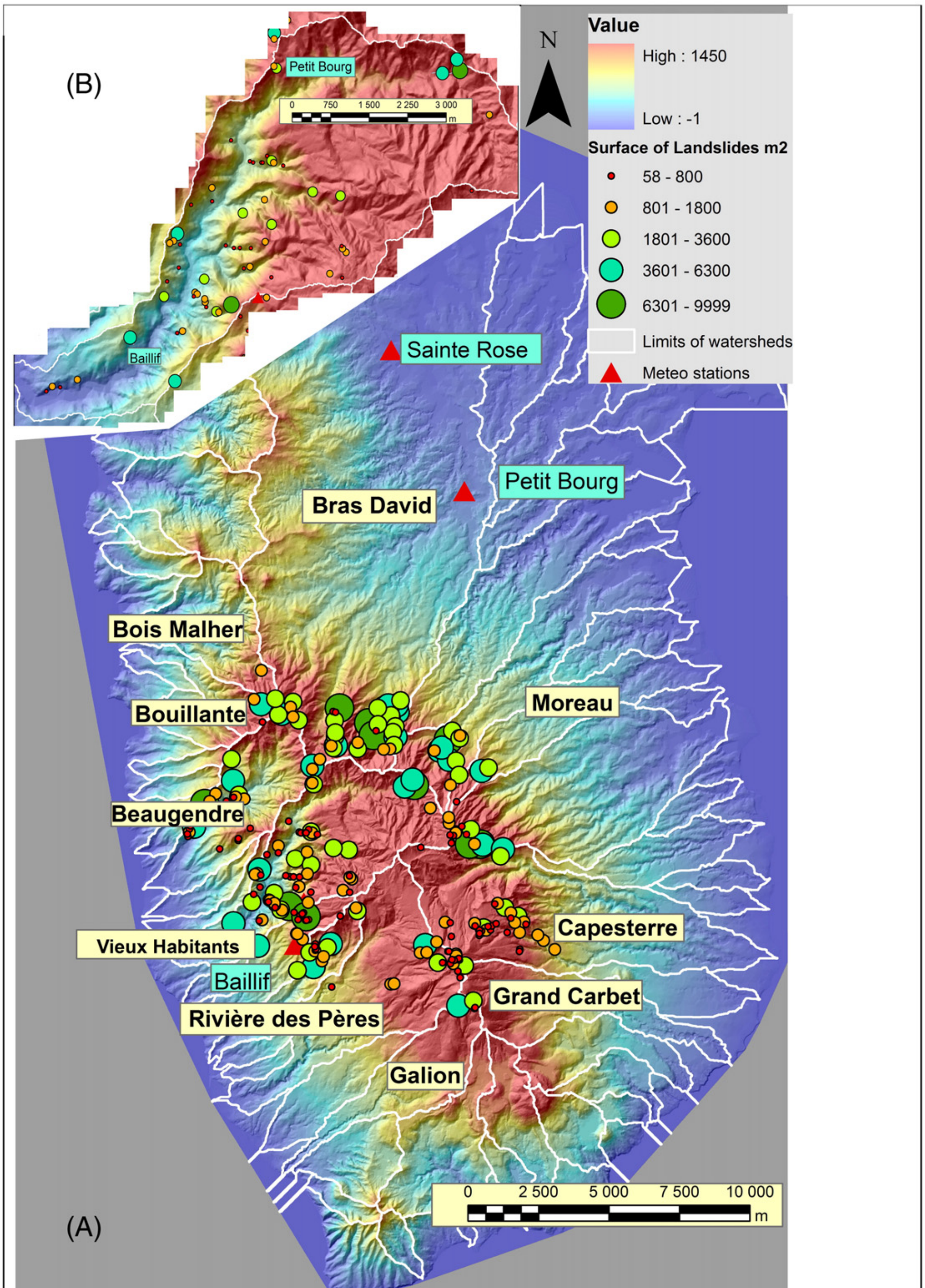

Fig. 2. (A) Elevation map of Basse-Terre on which the main watersheds are delineated. Their main characteristics can be found in Table 1. The landslides and scars that occurred during storm Helena are shown in red. They are located in the center of the Island in the Vieux Habitants, Beaugendre, and Capesterre watersheds. (B) Zoom on the watershed of Vieux Habitant; same symbology as (A).

except in the immediate vicinity of the sea. Hillslopes are covered by thick soils, which can reach 10 m (Rad et al., 2006). The chemical weathering responsible for the development of these soils is controlled by dense vegetation and by the tropical climate (White and Blum, 1995) characterized by high temperatures (24–28 °C) and intense rainfall (8000 mm/y registered at *La Soufrière* volcano). Tropical storms and hurricanes are frequent, particularly during the rainy season that spans from June to January. Average annual runoff is 2700 mm/y on the west (leeward) coast and 3100 mm/y on the east (windward).

Storms and hurricanes have been recorded in the Lesser Antilles since 1632 (Zahibo et al., 2007). The average period of return of storms on Guadeloupe is 3 to 4 years since the beginning of their record. This period is around 15 years for hurricanes of class 4 or 5 characterized by average wind velocities >210 km/h (Zahibo et al., 2007). The distribution of these extreme events is not homogeneous in time. From 1950 to 1975, the number of extreme events decreased relative to the previous 25 years from 28 to 20 events. Over the past 40 years, a large increase in the number of hurricanes reaching categories 4 and 5 (Webster et al., 2005) associated with an increase in the number of hurricanes developed on the Atlantic was observed. No data is available concerning the frequency of storms in the Atlantic since the beginning of the Quaternary. Various proxies have been used to estimate the frequency of storms during the Holocene (e.g., McCloskey and Keller, 2009; Nott, 2011). They indicate that storm activity is characterized by imbricated alternating periods ranging from 10 to 1000 years. During the Holocene, the frequency and intensity of storms seem to be correlated to ocean temperature (Emanuel, 2005; Webster et al., 2005). Other authors (e.g., Donnelly and Woodruff, 2007) suggested that the storms are also controlled by variations in the El Niño Southern Oscillation and by the strength of the West African monsoon. For the Holocene, Nott (2011) demonstrated that storm occurrence is not entirely stochastic over the last millennia but positively correlated to temperature evolution.

The tropical storm Helena developed from a tropical depression located 300 km east of Martinique Island on 18 October 1963. The storm intensified slightly before it weakened below the storm force as it passed between Dominica and Guadeloupe. It became almost stationary and started to move toward the north with its center located 50 km from the western coast of Basse-Terre. The depression disappeared near Antigua on the 30th of October (Fig. 1B). During its path close to Basse-Terre, wind velocities were around 50 km/h. On Basse-Terre, rainfall caused strong damage to roads and facilities. Five persons were reported dead, 500 were homeless. Daily rainfalls were registered by two stations only (Fig. 3). Cumulative rainfall reached 150 mm on 27 October 27 at Petit Bourg located in the north of the island and 300 mm on 28 October in Baillif located on the leeward coast. Despite this difference between the

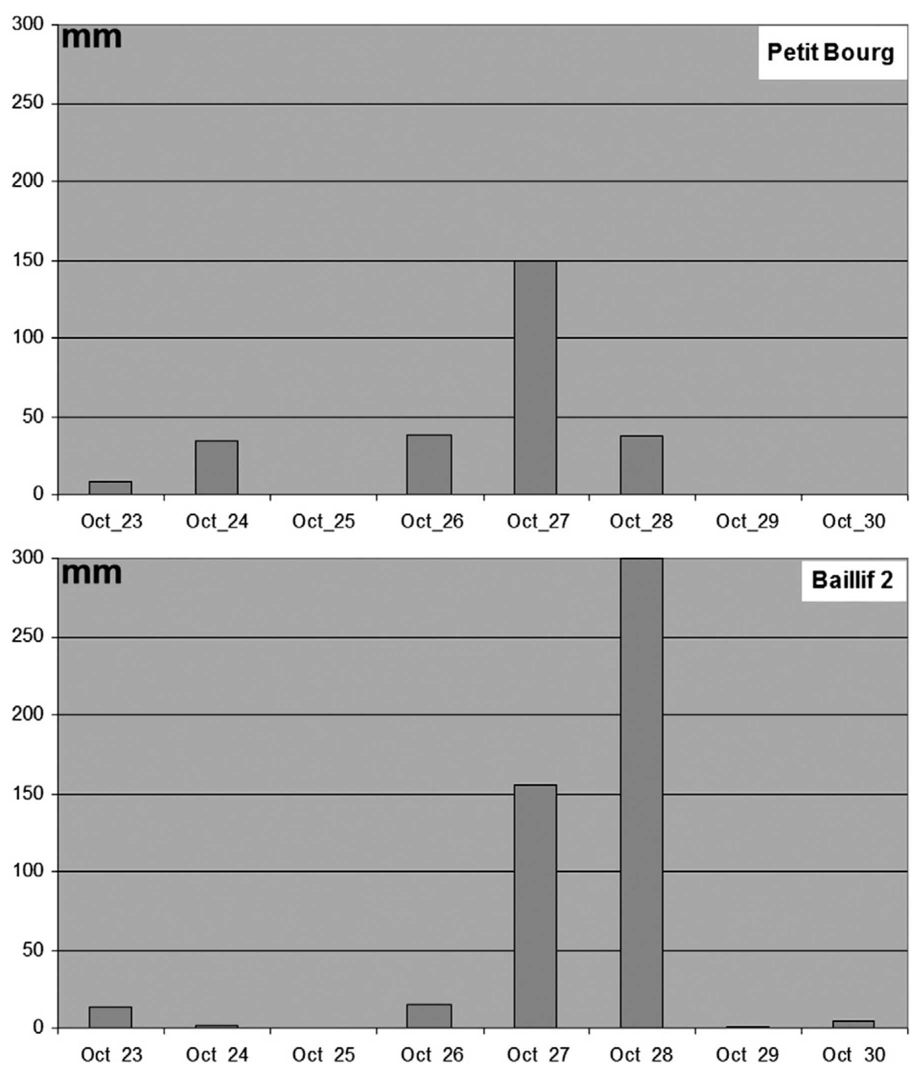

Fig. 3. Rainfall recorded during storm Helena at two meteorological stations located in Basse-Terre (Baillif and Petit Bourg; see Fig. 2). Rainfall was maximum on 28 October in the center of the island.

north and the west of Basse-Terre, these values are exceptional for Basse-Terre because these amounts of water were recorded in <12 h (Morel, 1990).

3. Data and method

Aerial images of Basse-Terre Island were acquired by the French geographic institute (IGN — Institut Géographique National) at the approximate scale of 1/8000 three months after storm Helena. This is the first time that these images have been used for a scientific purpose. The time between the storm and the aerial campaign was short relative to the resilience time of landslides, which is at least a few years even under a tropical climate. All the erosive structures that developed during the storm are therefore fully visible on these images. The complete set of the aerial images of the island has been scanned at 600 dpi, which corresponds to a ground resolution of about 50 cm. The images have been pseudo orthorectified and georeferenced by matching characteristic points on an orthorectified image of Basse-Terre provided by the IGN from aerial images taken in 2004. A second-order polynomial adjustment computed from around 15 points on each image has been found to be sufficient. The maximum position error in the central part of the images is <50 m. Angular distortion has not been measured. It seems negligible in the central part of the images and clearly increases near the borders. However, the images have an overlap that is around 80%, which limits the use of their peripheral parts. The management of the data has been achieved by GIS software. A 10-m resolution digital elevation model (DEM) obtained from digitizing the level curves on a 1:25,000 topographic map has been added to the GIS. The limits of watersheds have been computed from the DEM and added to the GIS. Scars and landslides appear as bright elongated surfaces that do not exist on images of the aerial campaign of 1955 and that are difficult to distinguish on images of the aerial campaign of 1968 (Fig. 4). Their limits have been manually digitalized with a tolerance of 2 pixels, which represents ~1 m. For a 100 m by 10 m scar that has a surface of 1000 m^2, the maximum error is 110 m^2, which is 11% of the real surface. This error value is a maximum because the shape of scars and landslides is seldom so elongated and because errors of digitalization generally compensate. Classical tools of GIS have been used to measure the surface and perimeter of scars and landslides. The cumulated surface of landslides is around 532,276 m^2. The cumulated perimeter of the landslides is around 74,077 m. If the error of digitalization is one pixel, the resulting error on the surface of landslides is 3.5%. If the error of digitalization is 2 pixels, the resulting error on the surface of landslides is 7%.

The volume of displaced rocks has been estimated assuming that the thickness of the mobile layer is 1 m that is observed in the field (Fig. 5). In tropical conditions, landslides generated by storms are rooted at the soil/regolith interface or above it (Hovius et al., 1997; Hovius and Stark, 2006). A thickness of 1 m for landslides is probably an underestimation as the thickness of the weathered layer in Basse-Terre climatic and geologic conditions can reach 10 m (White and Blum, 1995). Direct measurements of channel erosion by debris flows have been realized by Berger et al. (2011) in the Swiss Alps. The authors showed that channel erosion can reach locally more than 3 m along the path, for an average value around 1 m. It is thus very difficult to estimate an error bar for the eroded thickness. We used a minimum value of 1 m; thus the result will be underestimated.

The position of each scar and landslide has been checked relative to the DEM. If the position of the scar or the landslide was on a slope coherent with the expected movement, the value was kept. Otherwise the image and the shape of the scar or the landslide were displaced toward a more realistic position on the DEM. Less than 10% of the polygons have been displaced and always over less than 100 m. These polygons were on the borders of the images where the positioning error is at a maximum.

4. Results

Results are summarized in Table 1. Two hundred fifty-three landslides and scars have been identified on the aerial images. Some structures are clearly identified as landslides; other structures are clearly reactivated scars (Fig. 4). However, most of them are difficult to classify and it is impossible to propose a clear repartition. In the following, they will be called landslides without distinction of structure. Landslides have developed only in the center of the island (Fig. 2), mainly in the watersheds of Beaugendre, Vieux Habitants, Capesterre, and the upper parts of Bras-David and Goyave. These watersheds are those with major relief, and landslides are mainly located on the steepest slopes of the watersheds. The cumulated surface of landslides has been measured for each watershed (Table 1). This cumulated surface per watershed reaches a maximum for the watershed of Vieux Habitants, for which it is close to 0.15 km^2. If one assumes that the thickness of the landslides is 1 m, the total exported volume represents an equivalent denudation of 5 mm on the whole surface of this watershed. The total volume of displaced rocks represents an equivalent thickness of 1.4 mm if distributed over the surface of the watersheds affected with landslides and a thickness of 0.6 mm if distributed over the whole Basse-Terre island surface (Table 1). This value corresponds to an erosion of 2800 t km^{-2} on the watersheds affected by landslides.

5. Discussion

The results presented above raise two questions concerning (i) the parameters of landslide initiation during a storm, and (ii) the erosive effects of a storm relative to the average long-term erosion rate.

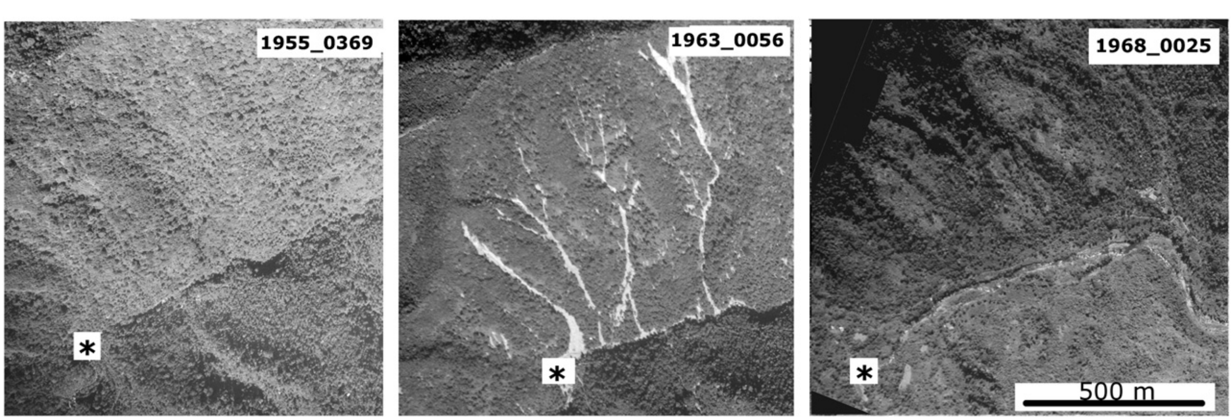

Fig. 4. Aerial images of a part of the Beaugendre watershed in 1955 (8 years before Helena), 1963 (just after Helena), and 1969 (6 years after Helena). No trace of landslides can be seen on 1955 images. Scars and landslides are clearly visible on the 1963 images acquired just after the storm. The evidence of landslides has disappeared on 1968 images indicating that the time of resilience of a landslide is <5 years. The * is located on the same position on successive images that do not have exactly the same geometry.

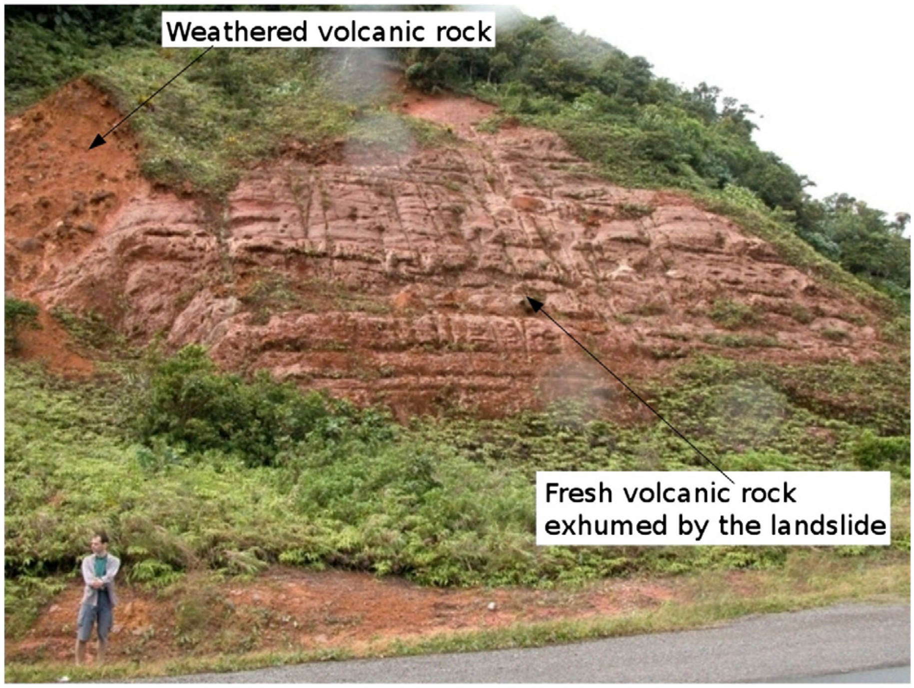

Fig. 5. Mark of a landslide that occurred in September 2009 on the border of road D23 near Mahaut (632229–1789831 UTM 20 coordinates) just after or during storm Erika characterized by important rainfall. The landslide occurred just after or during storm Erika. The weathered cover slipped on the limit with the fresh basalt to produce a 10 m high by 40 m long landslide. The weathered cover has been removed leaving an outcrop of unweathered lavas. The thickness of the cover was around 2 m. In the geological and climatic conditions of Basse-Terre, the thickness of landslide ranges from 1 to 2 m that represents the thickness of weathered rock.

The landslides initiated during storm Helena occurred only in the center of the island. The watersheds of Bouillante and Bois Malher on the leeward side of the island (Table 1) are the northern limit of the occurrence of landslides. On the windward side, this limit is located in the watershed of Bras David Goyave where some landslides occurred in the upper part of the watershed (Fig. 2). If one assumes the mean elevation of the watersheds as a proxy for their average slope, landslides develop if this value exceeds 400 m (Table 1). The watershed of Bouillante is located <7 km from the meteorological station of Baillif, which registered 300 mm of rainfall in one day (Fig. 3). Rainfalls are homogeneous in such small distances for extreme meteorological events. For example, rainfalls measured during hurricane Hugo (September 1989) were the same in Baillif and in Bouillante (Morel, 1990). These data suggest that slope is the main controlling parameter of landslide initiation in Basse-Terre. This slope threshold could explain the small variability of the average elevation of the watershed of the north of Basse-Terre despite their large age variability (Table 1). These observations are also consistent with the Ahnert law (Ahnert, 1970), which suggests a positive correlation between mean relief and denudation rate.

To assess the erosional significance of a single Helena-like climatic event, we compared the volume of sediment mobilized by Helena to the long-term denudation rate of the catchments. The latter was estimated from the reconstruction of the initial topography of each watershed by fitting a second-order polynomial surface through its border in a way similar but simpler to that proposed by Lahitte et al. (2011). This work was realized only on the less eroded volcanoes of the center of the island for which the initial topography is preserved in the interfluves that display a regular slope parallel to the youngest lava layers on each side of the watersheds. This slope corresponds to the original surface of the volcanoes. The points located on a band of 100 m at the limit between the interfluves and the watersheds were selected on the DEM and fitted by a second-order polynomial surface.

Long-term denudation rates (D) were then calculated for each catchment as:

$$D = V/(AT) \tag{1}$$

where T is the age of the catchment, A its area, and V is the total volume eroded. The latter was estimated as the sum of the difference between the elevation measured on the DEM and the elevation at the same position modeled by the polynomial surface. This method is precise for the watersheds located in the center and in the south of the island because the crest lines are located on the original surface of the last deposited lava flows (Lahitte et al., 2011). These calculations would not be realistic for the watershed located at the north of the island where most of the surfaces have been eroded.

We see two error sources in this approach, which are the uncertainty associated with the age of the lavas and the uncertainty associated with the eroded volume. The ages of lavas have been estimated by Samper et al. (2007) by K/Ar methods. For the rocks of the center of the island, the error bar on the ages is 20 ky, which is <2% of the measured age and negligible. The error bar on the eroded volume is more difficult to estimate. For a given watershed, the polynomial surface is in continuity with the interfluve surface on both sides of the incision. The error on the eroded volume, which is then low, has two origins: (i) the topography before erosion is unknown, and the model we use is not correct because it is too smooth and not representative of the heterogeneities that have been eroded; and (ii) the second one results from the calculation process. One way to estimate this error is to measure the difference between the elevation of the points used to compute the parameters of the polynomial surface and the elevation of these points computed by the polynomial model. The average difference is <5 m. For each watershed, the calculations of the eroded volume were made for two extreme cases by varying the elevation of the polynomial surface of ± 5 m. The resulting uncertainty on the eroded volumes is about 10%. Long-term denudation rates reach a maximum for the watersheds of Capesterre and Vieux Habitants where they are close to 0.4 ± 0.1 mm/y. This value probably integrates the effect of the flank collapses, which have been identified by Deplus et al. (2001) and Samper et al. (2007). For the other watersheds, the denudation rate is between 0.1 ± 0.025 and 0.2 ± 0.05 mm/y. The flank collapse represents at least half of the denudation rate of the watershed of Vieux Habitants and of Capesterre.

Table 1
Geometric characteristics of the main watersheds of Basse-Terre Island (Guadeloupe).[a]

Caribbean side								
Watershed	A (km^2)	L (km)	Hmean (m)	T (My)	NL	SL (m^2) ±7%	ET (mm) ±7%	DR (mm/y) ±10%
Ferry	4.35	4.59	355	1.72	0	0	0	
Caillou	2.98	4.15	352	1.64	0	0	0	
Petit	13.88	5.93	333	1.71	0	0	0	
Colas	10.06	5.04	318	1.15	0	0	0	
Bois-Malher	12.72	7.64	312	1.16	2	2772	0.2	
Bouillante	4.18	4.44	371	0.791	1	3052	0.7	0.073
Beaugendre	16.41	10.4	447	0.864	30	58,347	3.6	0.224
Vieux Habitants	29.40	18.9	647	0.435	98	148,150	5.0	0.250
Riv. Des Pères	26.00	14.98	703	0.447	21	21,187	0.8	0.097
Gallion	11.91	12.27	628	0.447	4	8116	0.7	0.137
Atlantic side								
Watershed	A (km^2)	L (km)	Hmean (m)	T (My)	NL	SL (m^2)	ET (mm)	DR (mm/y)
Vieux Fort	2.79	4.41	230	2.68	0	0	0	
Baille-Argent	3.96	4.4	321	1.61	0	0	0	
Jenikeete	3.15	4.07	258	1.26	0	0	0	
Bras-David-Goyave	142.2	7.09	274	1.46	34	114,498	0.8	0.065
Moreau	6.10	5.3	400	0.659	12	44,751	7.3	0.155
Capesterre	16.56	11.51	561	0.447	41	57,151	3.5	0.336
Capesterre	37.3	18.61	563	0.447	52	71,523	1.9	0.171
Grand Carbet	13.59	12.58	560	0.447	1	2729	0.2	0.102
Sum or weighted average	341				253	532,276 ± 37,259	1.6 ± 0.1	0.14 ± 0.014
On whole Basse-Terre	848					532,276	0.6 ± 0.01	

[a] The basin order in the table reflects their geographic position. Notice the negative correlation between the age of volcanic rocks (T) and the mean elevation (Hmean) of the watershed. A, surface of the watershed; L, length of the river; Hmean, mean elevation of the watershed; T, age of the oldest volcanic product (Samper et al., 2007); NL, number of landslides; SL, cumulative sum of the surface of landslides; ET–SL divided by A, average denudation of the watershed; DR, denudation rate: rock volume exported since the initiation of the watershed divided by the age of rocks and by the surface of the watershed.

An extreme event such as Helena is able to transport the equivalent of 0.6 ± 0.01 mm of thickness of Basse-Terre in a few days. If one considers only the watersheds where landslides occurred, this represents a denudation rate of 1.6 ± 0.1 mm in one extreme meteorological event. This value therefore is 4 to 12 times the long-term denudation rate (Table 1) for individual watersheds and 10 times the long term denudation of the center of the island. Excluding the watersheds that have been affected by flank collapses (Vieux Habitants and Capesterre), the denudation produced by storm Helena represents 10 to 14 years of the long-term denudation. The recurrence of storms is 4 to 5 years since their description is collected in Guadeloupe. Some of these storms have produced the same effects as Helena. Others, registered also as storms or hurricanes, produced damages only on the coastal areas or affected the other islands of the Guadeloupe archipelago. The variability of storm effects remains to be studied. However, storm-induced erosion appears to be of the same magnitude as the long-term erosion rate, thus strongly suggesting that the erosion of the watersheds of higher relief is mainly driven by landslides since the initiation of the erosion. An important constant of the system is the time of resilience of the watersheds after the storm that is not taken into account in this discussion. If two storms of equal intensity occur with a time interval lower than the resilience time of the watershed, the erosion effect of the second storm will probably be lower than the effect of the first one. Similar effects have been demonstrated for the combination of earthquakes and storms in Taiwan (Lin et al., 2008). They have to be quantified for storm effect. Guadeloupe could be the ideal region to study such effects.

6. Conclusion

The storm Helena that affected Basse-Terre Island in October 1963 initiated numerous landslides localized in the center of the island. The landslides were mainly controlled by slope rather than rainfall with a strong threshold effect. The denudation produced by landslides reaches a maximum of 5 mm for the most impacted watersheds. On average, the denudation is 1.4 mm when normalized to the area of the watersheds affected by landslides and 0.6 mm when normalized to the whole surface of Basse-Terre — 1.4 mm of denudation is 10 to 14 times the average denudation value measured in one year. Such a period is remarkably close to the present return period of tropical storms, which is 4 to 5 years. That suggests that the denudation of Basse-Terre Island could be entirely controlled by tropical storms that trigger landsliding during the Quaternary period.

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References

Ahnert, F., 1970. Functional relationships between denudation, relief, and uplift in large mid-latitude drainage basins. Am. J. Sci. 268, 243–263.
Berger, C., McArdell, B.W., Schlunegger, F., 2011. Direct measurement of channel erosion by debris flows. J. Geophys. Res. 116, F01002. http://dx.doi.org/10.1029/2010JF001722.
Bertran, P., Bonnissent, D., Imbert, D., Lozouet, P., Serrand, N., Stouvenot, C., 2004. Paléoclimat des petites Antilles depuis 4000 ans BP: l'enregistrement de la lagune de Grand-Case à Saint-Martin. C. R. Geosci. 336, 1501–1510. http://dx.doi.org/10.1016/j.crte.2004.09.009.
Chatanantavet, P., Lajeunesse, E., Parker, G., Malverti, L., Meunier, P., 2010. Physically based model of downstream fining in bedrock streams with lateral input. Water Resour. Res. 46. http://dx.doi.org/10.1029/2008WR007208.
DeMets, C., Jansma, P.E., Mattioli, G.S., Dixon, T.H., Farina, F., Bilham, R., Calais, E., Mann, P., 2000. GPS geodetic constraints on Caribbean–North America plate motion. Geophys. Res. Lett. 27, 437–440.
Deplus, C., Le Friant, A., Boudon, G., Komorowski, J.C., Villemant, B., Harford, C., Ségoufin, J., Cheminée, J.L., 2001. Submarine evidence for large-scale debris avalanches in the Lesser Antilles Arc. Earth Planet. Sci. Lett. 192, 145–157.
Donnelly, J.P., Woodruff, J.D., 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon. Nature 447, 465–468.
Dunn, G.E., Moore, P.L., Clark, G.B., Frank, N.L., Hill, E.C., Kraft, R.H., Sugg, A.L., 1964. The hurricane season of 1963. Mon. Weather Rev. 22 (3), 128–142.
Emanuel, K., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436, 686–688.

Feuillet, N., Manighetti, I., Tapponnier, P., 2002. Arc parallel extension and localization of volcanic complexes in Guadeloupe, Lesser Antilles. J. Geophys. Res. 107, 1–29.
Hovius, N., Stark, C.P., 2006. Landslide-driven erosion and topographic evolution of active mountain belts. In: Evans, S.G., Scarascia, Mugnozza G., Strom, A., Hermanns, R.L. (Eds.), Landslides from Massive Rock Slope Failure. Springer, Dordrecht, Netherlands, pp. 573–590.
Hovius, N., Stark, C.P., Allen, P.A., 1997. Sediment flux from a mountain belt derived by landslide mapping. Geology 25 (3), 231–234.
Korup, O., 2010. The role of landslides in mountain range evolution. Geomorphology 120, 77–90. http://dx.doi.org/10.1016/j.geomorph.2009.09.017.
Korup, O., 2012. Earth's portfolio of extreme sediment transport. Earth Sci. Rev. 112, 115–125. http://dx.doi.org/10.1016/j.earscirev.2012.02.006.
Lahitte, P., Samper, A., Quidelleur, X., 2011. DEM-based reconstruction of southern Basse-Terre volcanoes (Guadeloupe archipelago, FWI): contribution to the Lesser Antilles Arc construction rates and magma production. Geomorphology 136, 148–164. http://dx.doi.org/10.1016/j.geomorph.2011.04.008.
Lajeunesse, E., Delacourt, C., Allemand, P., Limares, A., Dessert, C., Ammann, J., Grandjean, P., 2011. Monitoring riverine sediment fluxes during floods: new tools and methods. River, Coastal and Estuarine Morphodynamics: RCEM2011. Tsinghua University Press, Beijing.
Lin, G.W., Chen, H., Hovius, N., Horng, M.J., Dadson, S., Meunier, P., Lines, M., 2008. Effects of earthquake and cyclone sequencing on landsliding and fluvial sediment transfer in a mountain catchment. Earth Surf. Process. Landforms 33, 1354–1373. http://dx.doi.org/10.1002/esp.1716.
McCloskey, T.A., Keller, G., 2009. 5000 year sedimentary record of hurricane strikes on the central coast of Belize. Quat. Int. 195, 53–68. http://dx.doi.org/10.1016/j.quaint.2008.03.003.
Morel, M., 1990. Ouragans, crues et inondations en Guadeloupe. Colloque Les risques naturels et technologiques dans le bassin caribéen. Université Antilles Guyane.
Nott, J., 2011. Tropical cyclones, global climate change and the role of quaternary studies. J. Quat. Sci. 26, 468–475. http://dx.doi.org/10.1002/jqs.1524.
Page, M.J., Trustrum, N.A., Dymond, J.R., 1994. Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. Geomorphology 9, 169–188.
Page, M.J., Reid, L.M., Lynn, I.H., 1999. Sediment production from cyclone Bola landslides, Waipaoa catchment. J. Hydrol. 38, 189–308.
Rad, S., Louvat, P., Gorge, C., Gaillardet, J., Allègre, C.J., 2006. River dissolved and solid loads in the Lesser Antilles: new insight into basalt weathering processes. J. Geochem. Explor. 88, 308–312. http://dx.doi.org/10.1016/j.gexplo.2005.08.063.
Reid, L.M., Page, M.J., 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology 49, 71–88.
Reid, P., Carey, S.N., Ross, D.R., 1996. Late Quaternary sedimentation in the Lesser Antilles. GSA Bull. 1008, 78–100.
Samper, A., Quidelleur, X., Lahitte, P., Mollex, D., 2007. Timing of effusive volcanism and collapse events within an oceanic arc island: Basse-Terre, Guadeloupe archipelago (Lesser Antilles Arc). Earth Planet. Sci. Lett. 258, 175–191.
Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.-R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 293, 474–479.
White, A.F., Blum, A.E., 1995. Effect of climate on chemical weathering in watersheds. Geochim. Cosmochim. Acta 9, 1729–1747.
Zahibo, N., Pelinovsky, E., Talipova, T., Rabinovich, A., Kurkin, A., Nikolkina, I., 2007. Statistical analysis of cyclone hazard for Guadeloupe, Lesser Antilles. Atmos. Res. 84, 13–29.