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APPROXIMATING METEORIC ^{10}BE USING THE CONCENTRATION OF ACID-EXTRACTABLE GRAIN COATINGS: A CASE STUDY TRACING EROSION DEPTH ON DOMINICA, LESSER ANTILLES

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INTRODUCTION

Dominica, an island in the Caribbean, experiences the harmful social and economic effects of landslides (De Graff et al., 1989). Steep topography, geology and heavy precipitation create an environment conducive to damaging erosional processes. Intense rainfall events are the principle mechanism for inducing landslides (De Graff et al., 1989). Tropical Storm Erika in 2015 and most recently Hurricane Maria in September 2017 devastated the island and resulted in major landslides and flooding (van Westen et al., 2018). Due to the immediate and prominent impact, several studies have characterized and quantified landslides on Dominica. However, additional erosional processes in the Caribbean are relatively understudied (Portenga and Bierman, 2011).

We use sediment tracers to gain a larger scope of the geomorphic processes on Dominica. Sediment tracing is important to understanding the correlation between surface processes and factors such as climate, tectonics and human activity (Singleton et al., 2017). We assume the geochemical signature of detrital sediment is representative of an entire upstream basin. The tracer of our focus is meteoric beryllium-10 ($^{10}Be_m$), which is important in determining the depth of erosion in a watershed. Due to the expensive nature of $^{10}Be_m$ our study focuses on developing the concentration of grain coatings as a proxy for $^{10}Be_m$.

The purpose of this paper is twofold. We intend to characterize the erosional processes of an entire upstream basin using the elemental concentration of grain coatings on detrital sediment (Greene, 2016). We will develop a baseline understanding of the erosional processes within each watershed on Dominica, inferring landslide, riverbanks/scarps and surface erosion. Furthermore, we intend to determine the validity of using the concentration of grain coatings as a proxy for meteoric ^{10}Be in detrital sediment. With catchment sediment-source identification, our goal is to better assess sediment dynamics on Dominica and ultimately improve hazard mitigation.

Sediment Tracers

Meteoric ^{10}Be is a cosmogonic radionuclide (half-life of 1.39 million years) formed in the atmosphere by the spallation of oxygen or nitrogen (Graly et al., 2010). From the atmosphere, $^{10}Be_m$ is delivered to Earth's surface by precipitation or dry deposition (Graly et al., 2010). At the surface, $^{10}Be_m$ adheres to the upper few meters of soil and surface sediment (Willenbring, 2010). The concentration of meteoric $^{10}Be_m$ in detrital river sediments is an important metric in surface processes; specifically, $^{10}Be_m$on (Reusser and Bierman, 2010) and the residence time of sediment (Willenbring, 2010). Soils in slowly eroding landscapes tend to have higher concentrations of $^{10}Be_m$ due a greater residence time and shallow erosion. Low $^{10}Be_m$ concentrations are present in sediment from rapidly eroding landscapes and sediment sourced from below the $^{10}Be_m$ accumuluation zone (i.e. deeply penetrating gullies or deep-seated landslides) (Fig. 1) (Reusser and Bierman, 2010).

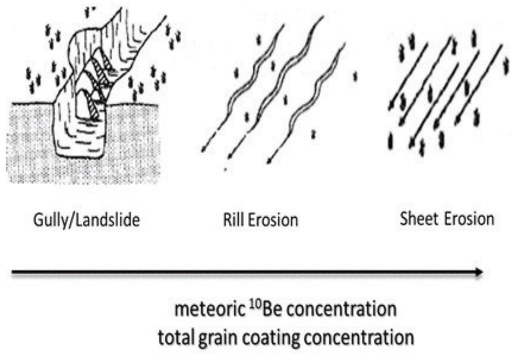

Figure 1. Relative concentration of meteoric ^{10}Be and total grain coatings in types of erosion. Adapted from Wallbrink and Murray (1993).

A strong, positive correlation exists between total $^{10}Be_m$ and acid-extractable grain coating concentrations, suggesting $^{10}Be_m$ is associated with weathering materials (Greene, 2016). Grain coatings form during podsolization, the process in which Fe^+, Al^+, and weathering products translocate through soil and form a thin film around grains in the B horizon (Birkeland, 1984). Atoms adhere to reactive surfaces of weathering materials such as oxides, hydroxides and 2:1 clay minerals. Thus, organic Be complexes sorb to sediment by associating with existing grain coatings (Greene, 2016). We measure depth of erosion using elemental concentration of grain coatings on detrital sediment as a proxy for $^{10}Be_m$ concentrations.

With the extensive landslide analysis that other studies have conducted, we evaluate erosional processes using previously mapped landslides. By quantifying the concentration of grain coatings, we determine the impact of landslides on the geochemical signature of river sediment. We hypothesize that watersheds with stabilizing landslide scars will have medium grain coating concentrations (Fig. 1). Watersheds with river bank/scarp erosion or active landslides will have low grain coating concentrations and watersheds with widespread surface erosion will have high elemental concentrations (Fig. 1). Furthermore, we will compare our grain coating concentrations with $^{10}Be_m$ data to evaluate the validity of our method in the Caribbean climate.

METHODS

Field Work

During two weeks in July 2018, a team collected detrital sediment from 20 active river channels of watersheds greater than 20 km^2 in Dominica. At each site, we wet sieved two sediment sizes, <63 and 250-850 µm. During sediment collection we spanned a 50 m radius to ensure a thorough collection of well mixed sediment (Sosa Gonzalez et al., 2017) and we sampled upstream of any tidal influence. In general, our sample sites were located near urban features. Vegetated banks were common at each location but bank steepness varied. Water depth ranged from 10 cm to 1m and channel width ranged from 20-50 m. Rock size varied greatly between each location. Some sites had a maximum rock size of gravel and other locations had large boulders up to 3-5 m.

Lab Analysis

The geochemical analysis, adopted from Greene (2016), leaches acid-extractable grain coatings as a proxy for meteoric ^{10}Be. I dried all sediment in the oven, powdered the coarse-grained sediment in a shatter box, and performed the following leaching procedure identically for both the <63 and 250-850 µm samples. I added 2 mL of 6M HCl to 0.5 g of sample, heated the sample in a sonic bath for 24 hours, and centrifuged and separated the leachate from the sediment. For using a ratio of the ICP-OES analysis, I diluted the leachate by 1:370 (sample:acid), where the acid is a 1% HCl and 1% HNO_3 solution. I sent the samples to the Nano Research Facility (EECE) at Washington University in Saint Louis where they analyzed the concentrations of Al, Fe, Mn, Na, Ca, K, Mg, Si and Ti in an ICP-OES. I also performed a microscopy analysis on two coarse-grained samples, Belfast and Mamelabou, under the microscope and SEM to understand grain composition and grain coating composition.

We measured $^{10}Be_m$ concentrations of both grain sizes from eight watersheds, including: Picard, Macoucherie, Belfast, Mamelabou, Pagua North, Pagua South, Castle Bruce, and White. Using methods from (Stone, 1998), the sediment was powdered, ^{9}Be carrier added and beryllium extracted at the University of Vermont. $^{10}Be_m$ concentrations were measured with accelerator mass spectrometry (AMS) at Lawrence Livermore National Laboratory.

ArcGIS analysis

I used GIS to quantify the following basin average parameters: geology, land use, slope, local relief, rainfall, and landslide frequency. The geology data layer classifies the rock types into Andesitic Dacite Lava, Block and Ash Flows, Block and Ash Flow Ignimbrites, Ignimbrites, Sedimentary and Volcanics. The land use map is from the Caribbean Handbook on Risk Information Management (CHARIM) database, generated by image classification of satellite images acquired between 1996 and 1999 as part of the Caribbean Land cover project. We simplified the categories into five main classifications: Forest, Urban, Agriculture, Grasslands, and Other. I downloaded global DEM layers of Dominica to create slope and local relief. To calculate precipitation we digitized the mean annual precipitation map from Lang (1967). Furthermore, I used the landslide layer from van Westen (2016)—which mapped landslides pre- and post-Tropical Strom Erika in 2015 using satellite imagery—and performed zonal statistics to quantify landslide area per watershed of pre- and post-TS Erika landslides.

RESULTS

Grain Coating Concentrations

The ICP-OES analysis revealed the elemental concentrations of HCl-extractable coatings for Al, Fe, Mn, Na, Mg, Si, and Ti. A strong positive correlation exists between relative concentrations of Al, Fe, and Mn. The correlation between Al, Fe, and Mn shows that an increase in one of these elements leads to a linear increase in the other two elements. Conversely, no relationship exists between Na, Mg, and Ti demonstrating no correlation in relative concentration. Furthermore, meteoric ^{10}Be correlates positively with elemental concentrations of Al, Fe and Mn, but inversely with Na and does not correlate at all with Mg and Ti (Fig. 2). The positive correlations between $^{10}Be_m$ and Al, Fe, and Mn confirms that the total concentration of grain coatings will be processed as the summation of Al, Fe and Mn concentrations

Landslides

Landslide density decreases within the northern and northeastern watersheds, ranging from 0.5 to 1.3% (Fig. 3). The lowest density watershed is Mamelabou, with a density of 0.05%. Landslide density increases in southern watersheds, ranging from 1.3 to 3.2%. The northwestern watersheds have an intermediate

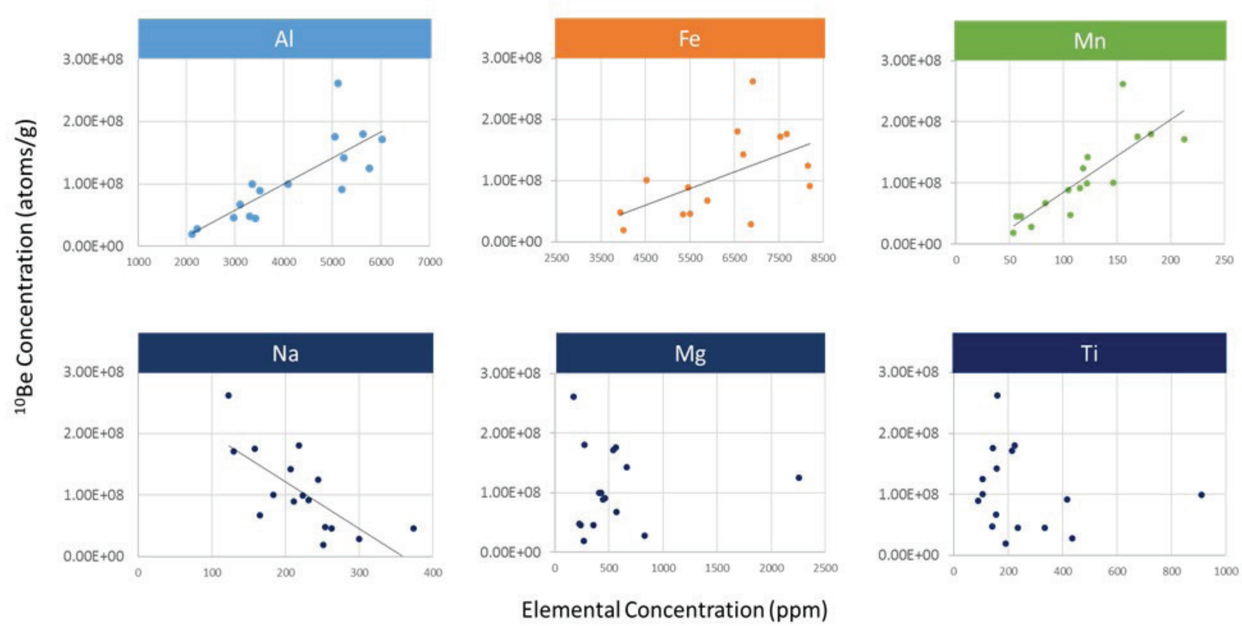

Figure 2. $^{10}Be_m$ vs. elemental concentrations of HCl-extractable grain coatings.

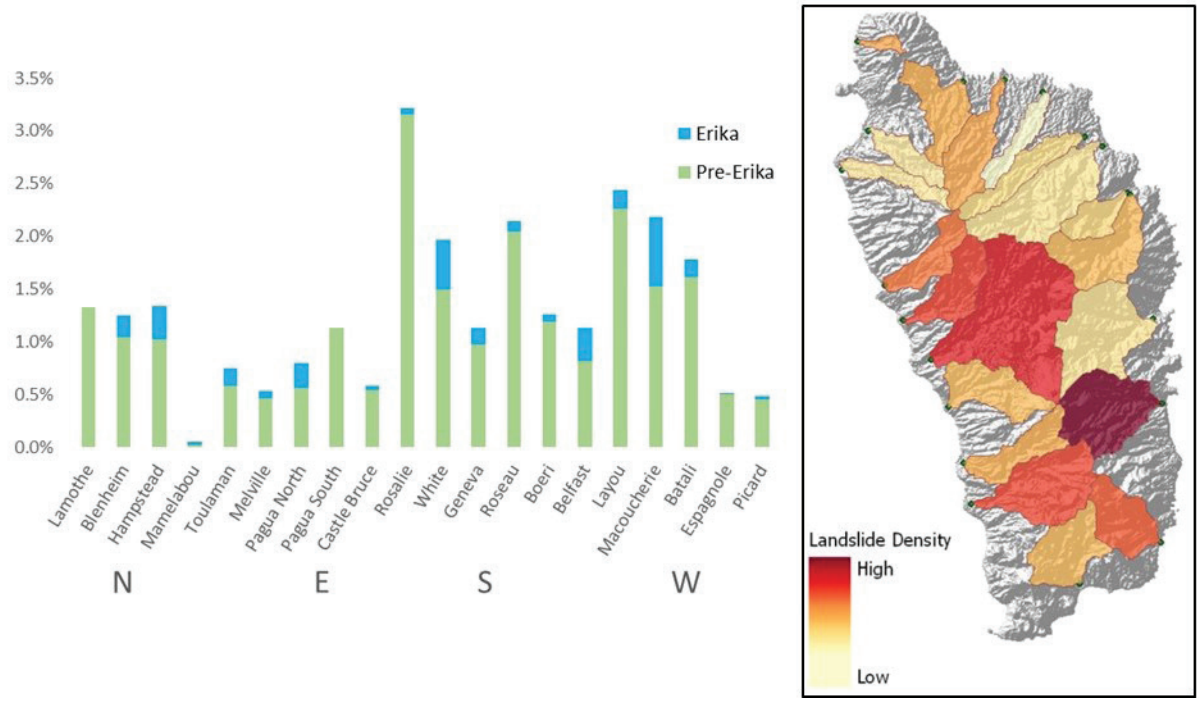

Figure 3. Landslide Density. (Left) Graphical representation (Right) Map representation.

landslide density of 1.1-2.4%. Landslide density is inversely and strongly related (R^2 value of 0.305) to total grain coating concentrations from fine-grained samples (Fig. 4a). Grain coatings from coarse-grained samples show an inverse but weak relationship (R^2 value of 0.032) with landslide density (Fig. 4b). In addition, $^{10}Be_m$ concentrations from all samples and landslide density (Fig. 4c), show a strong inverse relationship similar to the grain coating concentration from fine-grained sediment and landslide density.

Watershed Characteristics

Watershed characterization provides a broader view of controls on weathering and erosion within each watershed (Fig. 5). The relationship between mean annual rainfall and landslide density shows no significant relationship. Mean annual rainfall varies little between watersheds; the general trend shows consistent total rainfall with a range of 3.4-6.1 m/yr between each watershed. Slope generally correlates with landslide density. The northeastern watersheds have shallow slopes (15-18°), the southern watersheds are the steepest (20-27°), and the northwestern watersheds are intermediate (18-20°). Local relief shows similar trends to slope. The main variation of volcanic flows between watersheds is the abundance of ignimbrites and block and ash flows. Generally, watersheds with a landslide density less than 1.3% have a total ignimbrite abundance less than 10% and a block and ash flow abundance greater than 70%. Agriculture and forest abundance vs landslide density show a weak correlation. The main variation of land use is between forest and agriculture, while urban and grassland areas contribute only marginally to the total land use.

DISCUSSION

Acid-extraction of detrital sediment grain coatings from Dominica provides a valid proxy for $^{10}Be_m$. HCl-extraction predominantly leached Fe and Al, suggesting reactive grain coatings are composed of these minerals. The large concentrations of Fe found in the ICP-OES and SEM-EDS analysis suggest that the bulk of the grain coatings are composed of amorphous Fe oxy-hydroxides (Wittmann et al., 2012). Additionally, acid-extractable Al is part of the weathering material; the large concentrations of Al suggest some of the grain coatings are composed of Al oxy-hydroxides (Greene, 2016). The HCl method primarily leaches crystalline and amorphous oxides/hydroxides (Greene, 2016), therefore the grain coating concentrations are primarily composed of Fe and Al oxide sourced from weathering products.

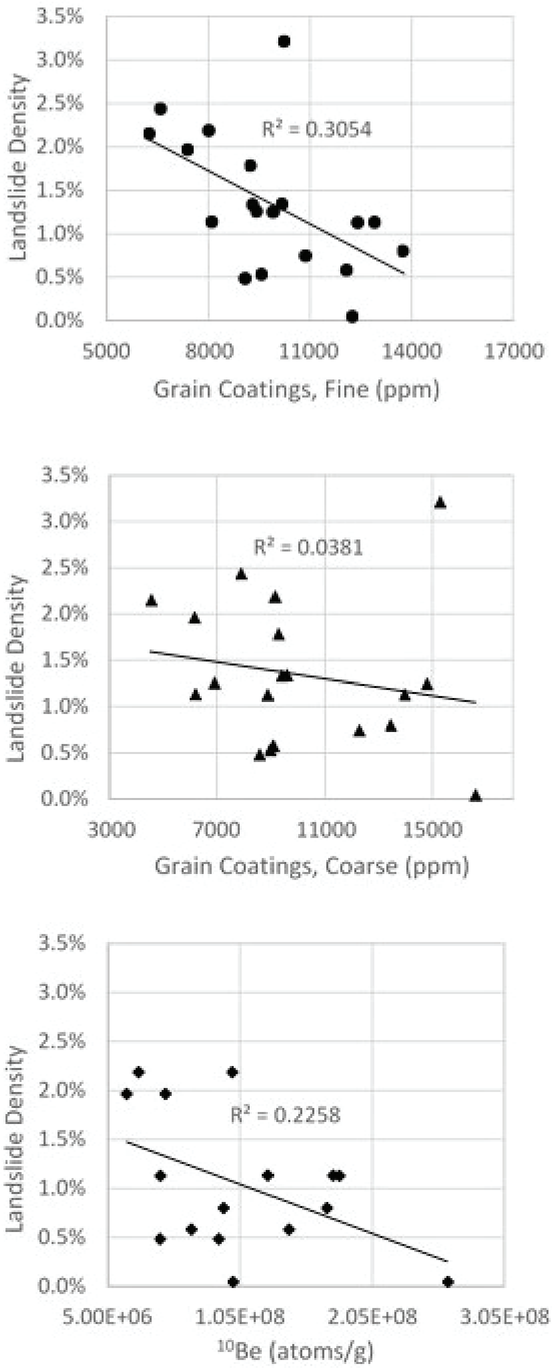

Figure 4. a) Fine Grain Coatings vs Landslide Density. b) Total Grain Coatings vs Landslide Density. c) ^{10}Be *atoms/g vs landslide density.*

Singleton et al., (2017) found $^{10}Be_m$ is strongly correlated with site-specific acid-extractable elements, which in turn is positively related to the accumulation of reactive phases during pedogenesis. It is likely, given a positive relationship between Fe, Al and Mn, that these elements accumulate directly within grain coatings during pedogenesis. Mn—which has a concentration an order of magnitude lower than Fe and Al—also showed a direct relationship with Fe and Al; suggesting Mn in the reactive phase accumulates directly within grain coatings. Furthermore, the HCl-extractable elements of Fe, Al, and Mn show a positive correlation with meteoric ^{10}Be; consistent with Greene (2016), who found acid-extractable Fe, Mn and Al strongly and positively correlate with $^{10}Be_m$ concentrations. Therefore, we use concentrations of Fe, Al and Mn, as the total concentration of grain coatings and exclude Na, Mg and Ti concentrations. Na may have an inverse relationship with grain coatings and $^{10}Be_m$ due to the leaching of Na through soil, rather than accumulating into grain coatings during pedogenesis (Birkeland, 1999). Mg and Ti may have a weak/lack of correlation due to the resistant weathering nature of Mg and Ti oxides (Birkeland, 1999). These elements do not behave in the same manner as Fe, Al and Mn during pedogenesis and this likely explains why they do not correlate with $^{10}Be_m$.

Based on the strong positive relationship between elemental concentration of grain coatings and $^{10}Be_m$, grain coatings will behave similarly to $^{10}Be_m$ as a sediment tracer. When compared to landslide density, both coatings from fine-grained sediment and $^{10}Be_m$ show a strong inverse relationship (Fig. 4a, 4c), suggesting both tracers reveal similar erosional processes. However, coatings from coarse-grained sediment compared with landslide density show an inverse but weak relationship (Fig. 4b); this trend may be a result of one of the major assumptions in sediment tracing. We assumed that grain coating concentrations are associated only with upland erosion processes and not transport processes. The abrasion of coarse-grained material may decrease the total concentration of grain coatings, depending on transport distance. Therefore in this study, grain coatings from fine-grained sediment are a more viable sediment tracer than coarse-grained coatings when assessing basin-scale erosional processes.

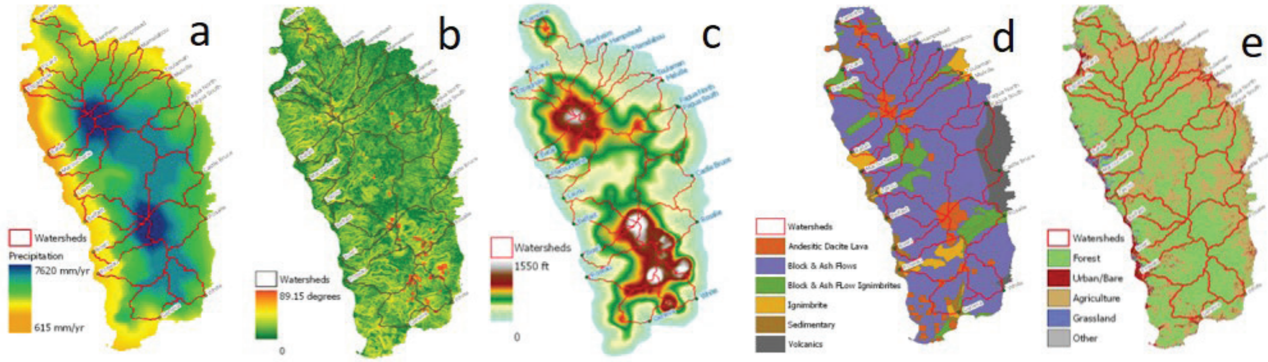

Figure 5. Watershed Characteristics. a) Rainfall b) slope c) local relief d) land use e) geology.

Using the fine-grained coatings as a sediment tracer proxy for $^{10}Be_m$ reveals the erosional processes on Dominica. The northeastern watersheds, with high grain coating concentrations, have mostly shallow erosional processes (Reusser and Bierman, 2010). Shallow erosion allows time for the accumulation of $^{10}Be_m$, as well as grain coating concentrations (Reusser and Bierman, 2010). Low landslide densities in the northeastern watersheds and high grain coating concentrations show that deeply sourced sediment is not a main contributor to outlet sediment. The southern watersheds contain lower concentration of grain coatings, suggesting that the erosional processes are sourcing rapidly eroded material or deep material. Rapidly eroding and deep-sourced sediment fail to accumulate $^{10}Be_m$ and correspondingly, grain coating concentrations (Reusser and Bierman, 2010). The correlation of low grain coating concentration with high landslide density in these watersheds supports the idea that landslides are significant contributors to the outlet sediment. Therefore, the outlet sediment is characteristic of the erosional processes in the corresponding watersheds.

Evaluating Watershed Characteristics

Even though precipitation is the main mechanism for inducing landslides (De Graff et al., 1989), the little variability of mean annual rainfall fails to explain changes in landslide density between watersheds. However, landslides instead can be initiated by single heavy precipitation events. Nugent and Rios-Berrios (2017) mapped radar-derived precipitation values for Tropical storm Erika over a 24 hour period on August 27, 2015. Mapped isohyets from this event correlate weakly but positively with TS Erika induced landslides (van Westen, 2016). Thus, landsliding events may be induced by single storm events, rather than mean annual rainfall. Additionally, slope and local relief correlate strongly with landslide density. Steep slopes are favorable for initiating landslides (Andereck, 2007), thus suggesting that steep slopes are a main driver for erosional processes on Dominica. The weak correlation between forest and agriculture abundance vs landslide density suggests that land use is not a major driver for landslides on Dominica. The weak correlation with landslide density and geology also suggests that variability in rock type plays only a minor role in erosional processes. Therefore, scatter in our landslide dataset falls to environmental factors such as rainfall distribution during a single storm event and variability in slope.

CONCLUSION

This work continues the nascent efforts to characterize erosional processes on Dominica. This study shows that fine-grained coating concentrations from detrital sediments works as a proxy for $^{10}Be_m$ in order to interpret upstream erosional processes. In Dominica, grain coatings primarily consist of Al, Fe and Mn. Total concentration of these elements negatively correlated with mapped landslides. The correlation between coatings from fined-grained samples and landslides suggests that landslides are a significant driving sediment source within Dominican watersheds. Additionally, individual rainfall events and slope variability are the main drivers for erosional processes on Dominica.

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