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RIVER DEVELOPMENT AND INCISION ON DOMINICA, WEST INDIES

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INTRODUCTION

Understanding the tectonic and climatic forces influencing the shape and history of Earth's surface has become a key undertaking in geomorphology (Gonzalez et al., 2016). Throughout the world, controls on river development include tectonics, bedrock lithology, storm pulses, landslides, and glaciers (Pike, 2010). Climatic and topographic variables such as mean basin slope, basin relief, seismicity, and precipitation have previously shown strong influence on erosion and incision rates (Portenga and Bierman, 2011; Covault et al., 2013; Willenbring et al., 2013; Harel et al., 2016). Although controls on erosion rates have been determined in many diverse landscapes, there has been little work on understanding river development and controls in the Lesser Antilles (Allen, 2017).

The tropical volcanic rivers on Dominica make up one of the largest river densities in the world and are accompanied by steep slopes, high mean annual rainfall, many landslides, and tropical storms creating a highly erosive landscape (Table 1; Neumann et al., 1978; Reading, 1991; Goldsmith et al., 2010; Ogden, 2016). Determining spatial patterns of geomorphic characteristics such as local relief, slope, rainfall, and channel steepness across Dominica brings insights of the effects of volcanic activity, tropical humid climate, great relief, and tropical storm pulses on geomorphic processes occurring on Caribbean islands. Minimum incision rates provide insights into the pace of river incision following pyroclastic flows filling the valleys. Long profiles show trends in channel gradients and are used to understand lithological influences on river down cutting (Duvall et al., 2004; Cyr et al., 2014). Comparisons between incision rates to local climatic, lithological, topographic variables and long profiles allow for relative controls on geomorphic process to be established.

Table 1. Climatic and topographic geomorphic characteristics of the 20 largest rivers on Dominica.

Name	Local Relief (m)	M.A.P (mm/year)	Mean Basin Slope (%)	Area (km²)	% Area Landslide Covered (landslides mapped)	Mean chi coordinate
Geneva River	1471.9	4592.7	26.2	1723.8	24.69% (140)	3.04
Lamothe River	597.7	3312.2	23.2	306.9	0.00% (0)	2.73
Blenheim River	590.7	3684.6	18.8	1850.1	2.67%(23)	3.25
Hampstead River	1132.4	5156.2	18.9	1994.5	0.27%(7)	4.81
Picard River	781.9	3774.9	18.9	685.9	0.00%(0)	3.56
Espagnole River	1132.2	3577.5	16.8	1371.8	3.33%(5)	4.71
Batali River	1099.3	4653.6	20.8	1245.5	5.40%(18)	3.71
Macoucherie River	786.3	5235.8	19.7	1787.0	40.51%(103)	4.41
Layou River	1429.4	5555.2	16.6	6389.7	17.23%(139)	5.89
Belfast River	1485.6	4197.3	19.0	1832.1	5.48%(41)	3.35
Mamelabou River	568.1	4435	15.1	1254.5	11.93%(12)	4.66
Toulaman River	1057.4	5062.3	16.6	1543.3	1.92%(17)	5.36
Melville Hall River	949.1	5512.8	16.0	3086.6	5.09%(7)	4.66
Pagua River (North)	621.3	4866.6	19.0	694.9	2.89% (4)	3.21
Pagua River (South)	629.6	5069	17.2	1732.8	2.69%(16)	4.25
Castle Bruce River	1340.2	5624.9	17.2	2545.1	8.79%(84)	3.12
White River	1500.1	5157.2	27.1	1588.4	20.14%(82)	2.92
Rosalie River	1452.1	5922	23.7	3113.6	19.74%(75)	3.68
Boeri River	1474.4	4694.9	20.3	1407.9	11.74%(35)	4.05
Roseau River	1461.1	5091.5	21.0	2815.8	31.59%(126)	4.29

METHODS

A variety of topographic, climatic, and geologic variables (elevation, slope, rainfall, lithology) are compared to minimum rates of incision. To analyze spatial patterns of steepness, local relief and basin-average slope were calculated using the Advanced

Spaceborne Thermal Emission and Reflections Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 2 (NASA et al., 2009). Basin-averaged mean annual rainfall was calculated using precipitation data from Lang (1967). Landslide data was collected by Marcus Hall (Oberlin College) and Haley Talbot-Wendlandt (Ohio Wesleyan University), determining the total amount of landslides in each watershed and the area covered by landslides using Google Earth (Tomenchok et al., 2017). Channel profile analysis was completed using LSDTopoTools (Mudd et al., 2014). LSDTopoTools extracts the (chi) χ coordinate value, which represent the steepness of the river normalized for the upstream area and show the channel gradient throughout the entire river (Mudd et al., 2014). Long profiles of the rivers were created using LSDTopoTools then resampled using the geologic map of Dominica to determine the type of rock that is underlying the channel (Roobol and Smith, 2004). The steepness of the channel typically increases as the streams experience transitions in rock strengths, while consistently weak rock strengths yield lower channel slopes (Duvall et al., 2004).

Incision rates were determined for nine of the rivers on Dominica using ArcGIS (Fig. 1). Ignimbrite age dates for the sampled rivers were previously established from zircon dating (Howe et al., 2014; Frey et al., 2015). Transects across the channels were created within the extent of the dated ignimbrites. Once transects were created, the changes in elevation from the top to the bottom of the channels were recorded and divided by the age of the ignimbrites to determine minimum incision rate.

RESULTS

Geomorphic Characteristics

To quantify the characteristics of the rivers of Dominica, basin average statistics were determined for topographic and climatic variables that influence erosional processes. Digitalizing and extracting mean annual rainfall data from Lang (1967), average annual rainfall of the 20 watersheds on Dominica is 4759 mm/yr. Watersheds on the eastern side of the island have mean annual precipitation rates approximately 600 mm/yr greater than the watersheds on the western side. The local relief, difference of the minimum

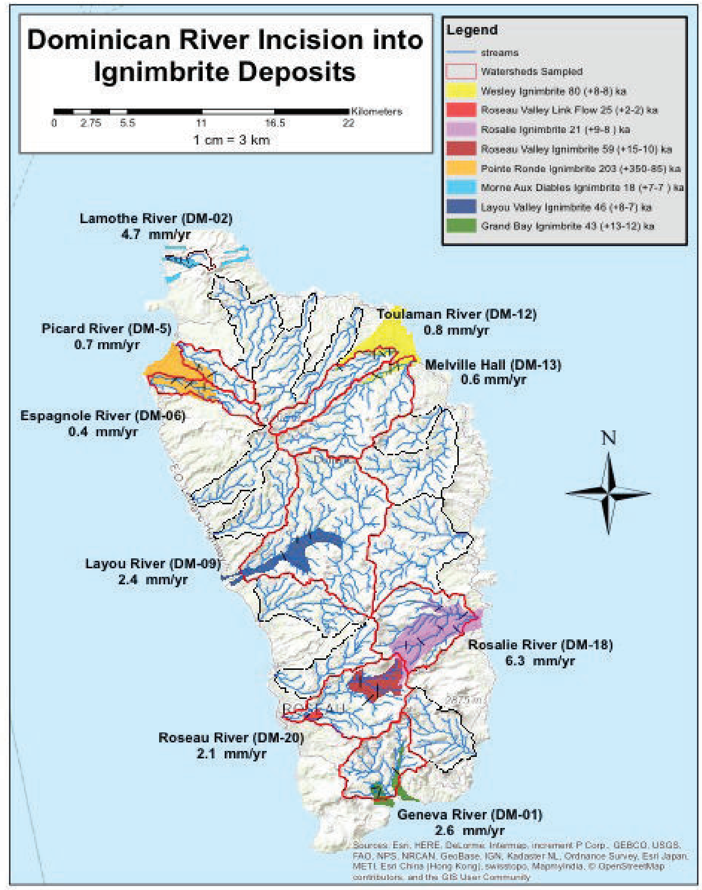

Figure 1. Average rates of minimum incision into the underlying ignimbrite deposits are the greatest in the southern rivers. Lowest rates of incision are in the northern rivers, with the exception of the northern-most Lamothe river.

and maximum elevations, and mean basin slope are the highest in the southern watersheds while local relief and slope are much lower in northern watersheds (Table 1). Linear regressions comparing the geomorphic characteristics of Dominica show that mean annual rainfall correlates strongly with mean normalized channel steepness (chi). Of the 934 landslides mapped, the southern watersheds tended to have the greatest number of landslides and percentage of area covered in landslides.

Incision Rates

Minimum incision rates were established for nine rivers on Dominica (Fig. 1) using transects across the river channels that flow through dated ignimbrite deposits (Howe et al., 2014; Frey et al., 2015). Incision rates of the rivers are relatively higher in the south of the island, except for the northernmost Lamothe River, which had the second highest average

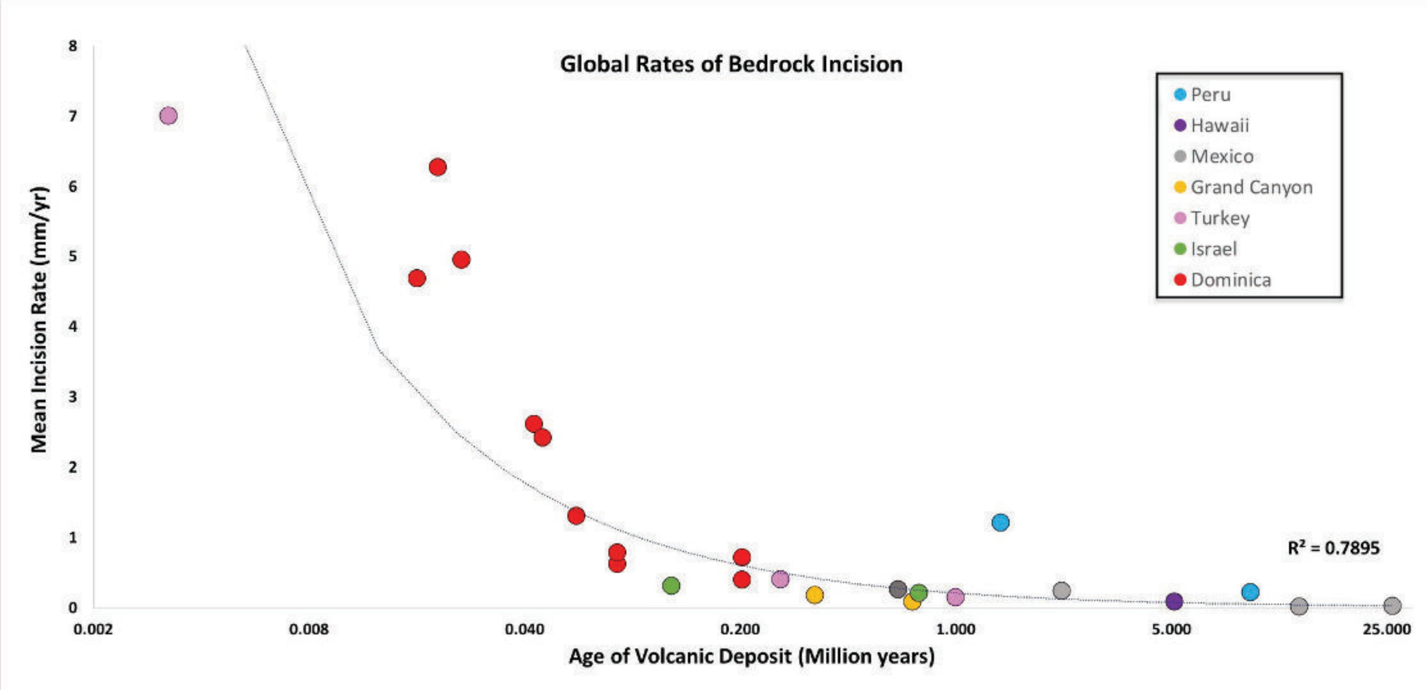

Figure 2. Incision rates show an exponential decrease with increasing ignimbrite age until ~80 ka where incision rates decrease much slower (Howe et al., 2014; Frey et al., 2015). The rivers that are incising into younger ignimbrite deposits that are less than ~50ka, showed higher incision rates and had a broader range in rates. Rivers incising older ignimbrites (~80 – 200ka) have more consistent lower incision rates. Previous studies show that this trend continues as bedrock ages increase, showing minor decreases in incision after ~200 ka.

incision rate (4.7 mm/yr) (Fig. 1). The Rosalie River in the southeast had the highest minimum incision rate (6.3 mm/yr) into the Rosalie ignimbrite (Fig. 1). The Rosalie, Roseau, Geneva, and Layou Rivers in the south, with the higher incision rates, tended to have the greatest local relief and mean basin slope (Table 1). Linear regressions show incision rates of the nine rivers are significantly correlated with mean normalized channel steepness (chi) ($p < 0.05$) and the percent of the basin area covered in mapped landslides ($p < 0.05$).

Incision rates tended to also be higher in younger ignimbrite deposits (Fig. 1, 2). Rivers with ignimbrite deposits less than ~50 ka have the highest rates of incision ranging from 2.1 – 6.3 mm/yr (Fig. 2). Although the Wesley Ignimbrite is slightly younger than the Pointe Ronde Ignimbrite, the rivers flowing through both are experiencing similarly low rates of incision (0.4 – 0.7 mm/yr) (Fig. 2).

Channel Analysis

Long profiles show that rivers with high incision rates into ignimbrite deposits have steeper slopes in the ignimbrite sections of the main channel, while rivers with low incision rates show lower slopes in ignimbrite sections (Fig. 3). The Roseau, Layou, and Rosalie Rivers, with high incision rates display the greatest slope in the channel segments of ignimbrite which occur frequently throughout the profiles (Fig. 1, 3). In the Toulaman, Melville Hall, and Espagnole Rivers, with low incision rates, long profiles show decreased slopes in ignimbrite sections and primarily consist of block and ash flow deposits rather than ignimbrite deposits (Fig. 3). The slope gradient in these channel profiles is greater in the block and ash flow deposits and display a much more linear shape, lacking any distinct knickpoints.

DISCUSSION

The rivers on Dominica, like many volcanic landscapes that are responding to eruptions, show increased initial incision followed by exponential

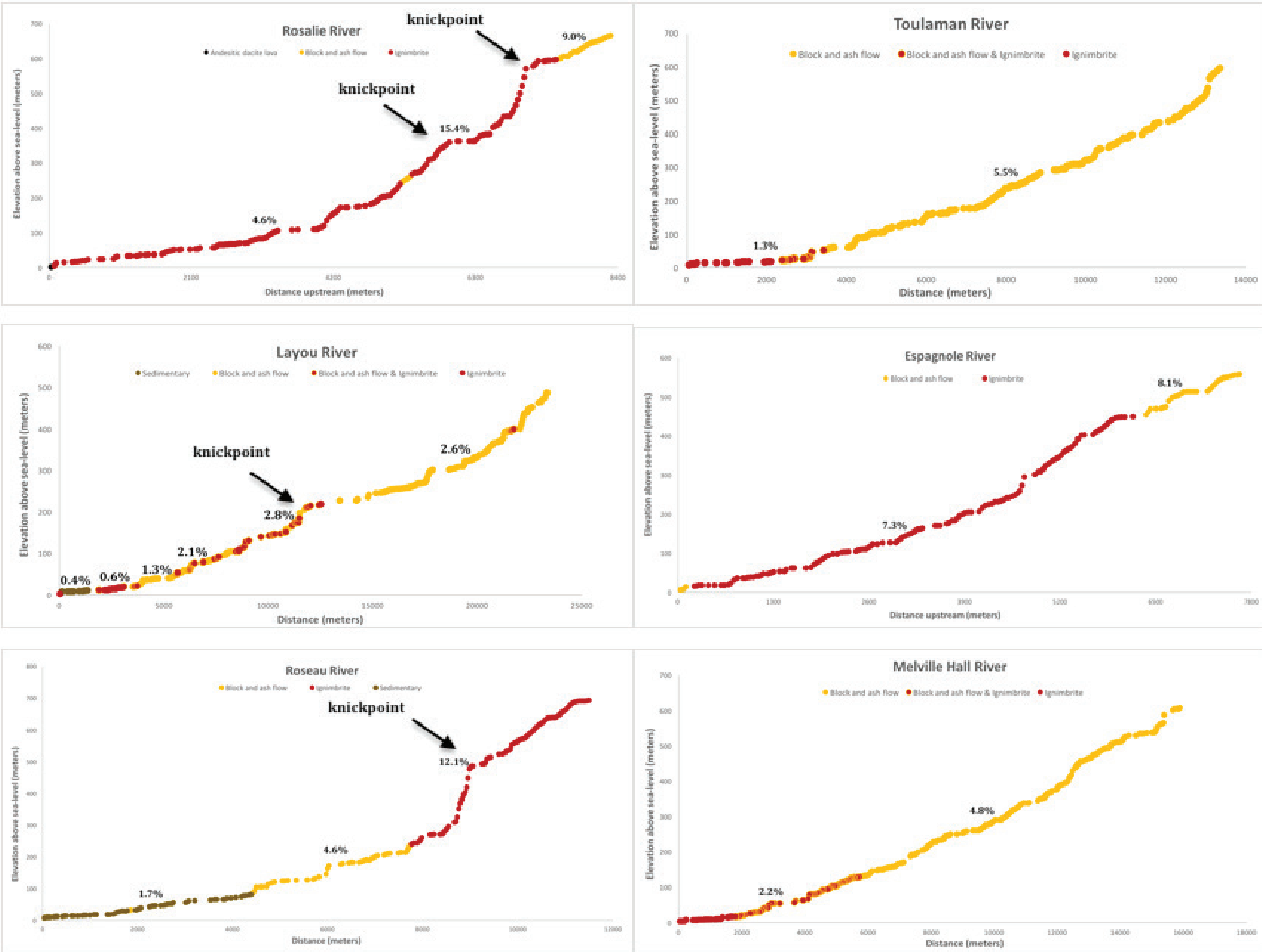

Figure 3. (Right) The Espagnole, Melville Hall, and Toulaman Rivers show steeper slopes in channel segments of block and ash flow deposits than segments of ignimbrite. These northern rivers also had the lowest minimum incision rates (0.4 -0.8 mm/yr), than the southern rivers with higher incision and steeper channels in ignimbrite segments. (Left) Ignimbrite deposit segments are the steepest in The Roseau, Layou, and Rosalie Rivers showing distinct knickpoints in these areas. The increasing steepness in ignimbrite sections in these channels align well with the higher rates of minimum incision (6.3 – 2.4 mm/yr) that the rivers are experiencing.

decrease over time (Thouret, 1999). Incision rates into young ignimbrite deposits less than ~25 ka are very high and are reduced to approximately half in ignimbrite deposits that are between ~43 – 46 ka (Fig. 2). This pattern continues with increasing ignimbrite age as deposits ~59 ka drop approximately 50% again. (Howe et al., 2014; Frey et al., 2015). Incision rates into ignimbrite deposits show a distinct tendency of decreasing around 50% every ~20 ka (Fig. 2). After ~80 ka, incision rates begin to decrease at a progressively slower pace. Incision rates into much older ignimbrite deposits in Peru (Thouret et al., 2007) and Mexico (Montgomery et al., 2003) demonstrate a similar result with incision in deposits < 1.4 Ma being five times greater than incision into deposits 9 – 13 Ma and continuing to decrease as ages increase (Fig. 2). Studies on river incision into basalt lava flows followed a similar trend, where local incision rates were lower in the oldest deposits, with all deposits >100 ka having incision rates below 0.4 mm/yr (Fig. 2; Seidl et al., 1994; Righter et al., 1997; Karlstrom et al., 2007; Seyrek et al., 2008; Maddy et al., 2012; van Gorp et al., 2013; Shtober-Zisu et al., 2017). Long profiles further express this pace of incision as rivers with higher incision rates and younger ignimbrite deposits show multiple knickpoints that represent changes in lithology and erodibility (Cyr et al., 2014) and steeper channel slopes throughout ignimbrite segments (Fig. 3).

On the other hand, rivers with lower incision rates lacked knickpoints and had less lithological changes throughout the channels, suggesting that the rivers have fully incised through these ignimbrite deposits reaching the less erodible underlying bedrock.

The incision rates of Dominica's rivers into the ignimbrite deposits are greater in southern watersheds that tended to have both higher mean basin slopes, local relief, and more area covered by landslides (Fig. 4). Although relief and slope have been shown to correlate with erosion, the percent of watershed area covered in landslides and mean (chi) normalized channel gradient show the strongest influence on incision rates ($p < 0.05$). Increased landsliding is how hillslopes adjust in response to rapid fluvial incision (Burbank et al., 1996) and is a primary mechanism in which landscapes respond to high rates of tectonic uplift (Montgomery and Brandon, 2002; Larson and Montgomery, 2012). Mean incision rates significantly influence mean channel steepness as increased down-cutting leads to channels becoming steeper and have been directly linked to increased erosion especially after hillslopes reach their slope threshold (Kirby and Whipple, 2001; Lague and Davy, 2003; Safran et al., 2005; Wobus et al., 2006). Ultimately, the high annual rainfall, basin slope, and local relief, causes increased landslides and channel steepness, allowing incision to be higher in the southern watersheds.

CONCLUSION

Dominica gives us insights into younger Pleistocene ignimbrite incision rates over the past ~ 200 ka. Our data suggest that mean incision rates of 4.67 – 6.26 mm/yr since ~ 18 – 25 ka, decrease approximately 50% every ~20 ka until ~80 ka, when incision rates reach 0.61 – 0.78 mm/yr and remain similar in

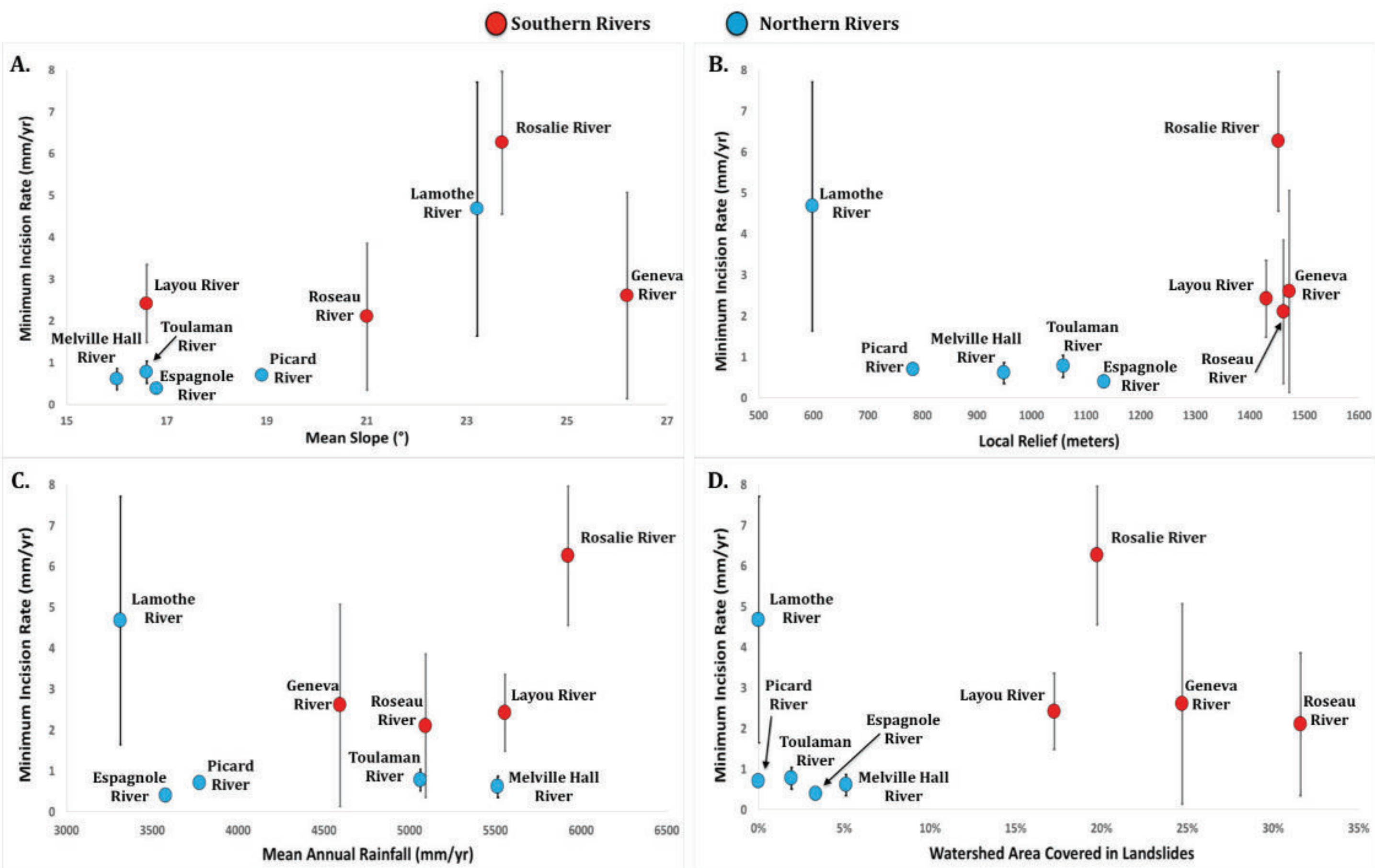

Figure 4. Incision rates across Dominica compared to influential geomorphic characteristics exhibiting both higher rates of incision and topographic/climatic variables in the southern watersheds (red). Northern watersheds (blue) with lower incision rates typically had lower (A.) mean basin slopes, (B.) local relief, (C.) mean annual rainfall, and (D.) area covered in landslides.

~203 ka ignimbrite deposits at 0.39 – 0.7 mm/yr (Fig. 2). Incision rates were most significantly correlated with the percent of watershed area landslide covered, identifying that hillslopes respond to fast fluvial incision through increased frequency of landsliding (Burbank et al., 1996, Montgomery and Brandon, 2002). Normalized chi coordinate values correlated significantly with mean incision rates, strengthening the relationship between river incision and channel steepness that lead to increased erosion (Safran et al., 2005). Long profiles of the rivers on Dominica present lithologic controls on incision, where steep slopes and knickpoints are prominent in segments of the channel consisting of ignimbrite (Fig. 3). Correlations between mean (chi) normalized channel steepness and landslide coverage with incision rates, show that increased climatic and topographic variables drive incision process through landsliding and channel steepening.

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