Collaborative Research: From rock to regolith to rivers: weathering, grain size, and controls on soil production and fluvial incision

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1. SCIENTIFIC MERIT

Soil blankets 94% of Earth's ice-free subaerial surface (NCRS, 2005), yet, this dynamic soil layer is often ignored when attempting to understand how landscapes respond to tectonic perturbations. Even worse, we don't understand how soil–a critical natural resource–responds to state change and environmental or tectonic perturbations. We know that soil erosion impacts fluvial sediment loads (e.g., Gran et al., 2013), but this is generally not considered in models of fluvial incision following a tectonic perturbation. Here we address the knowledge gap around how soil is impacted by and, also, impacts landscape evolution following a tectonic perturbation.

Rock uplift leads to a 'bottom-up' progression of erosion across landscapes that can last for millions of years as baselevel signals propagate upstream through river networks and, eventually, to soil on hillslopes (e.g., Crosby and Whipple, 2006; Mudd and Furbish, 2007; DiBiase et al., 2015; Brocard et al., 2016). In a landscape that has experienced rock uplift or baselevel fall, upstream-migrating knickpoints often separate slowly eroding, low-relief, 'relict' topography upstream, from rapidly eroding, steep, 'adjusting' topography downstream (e.g., Whipple et al., 2013). Although erosion rates downstream of a knickpoint, are often thought to be higher than those in the relict topography, they need not be (Willenbring et al., 2013). Understanding landscape adjustment to baselevel change is critical for: (1) understanding landscape resilience, or the ability of a landscape to keep pace with external forcing; (2) understanding the history of landscapes from modern topography (e.g., Wobus et al., 2006; Binnie et al., 2007; Harkins et al., 2007; DiBiase et al., 2010); and (3) testing steady state assumptions or for using transient landscapes for discriminating between different surface process models that often predict similar steady-state morphology (e.g., Hack, 1960; Schumm and Lichty, 1965; Whipple and Tucker, 2002; Crosby et al., 2007; Gasparini et al., 2007; Attal et al., 2008).

There has been extensive work to characterize the response of river morphology (Kirby and Whipple, 2012 and references therein), and to a lesser degree hillslope morphology (Gallen et al., 2011; Hurst et al., 2013; Mudd, 2017), to changes in base level. However, there has been much less focus on how soil – depth, grain size distribution, and production rates - respond to migrating knickpoints (Ferrier and West, 2017) and the 'top-down' controls that soil can have on fluvial incision. In other words, how soil affects knickpoint evolution (Brocard et al., 2016). Thus, many first-order questions remain, including:

What are the relative timescales of knickpoint propagation and soil development following uplift, fluvial incision, and erosion?

What controls soil production and resilience in relict landscapes, which probably cover a large fraction of the Earth's surface?

Do interactions among climate, soil particle size, and river systems impose feedbacks in the geomorphic system that sustain mountainous topography even after rock uplift ceases and allow preservation of stable topography over long periods of geologic history?

We will address these questions in a coupled field, geochemical, and numerical modeling study. Our field area, the Rio Blanco in the Luquillo Critical Zone Observatory serves as an ideal setting to tackle these questions, given both its evolutionary history and the NSF investments that have already been made to understand this landscape. We will also use numerical models, which are ideal tools to isolate how different processes influence each other. For example, we can explore exactly how variables, such as soil grain size, change through time in response to an external perturbation and whether a change in one variable results in cascading process changes across the landscape. We will use Landlab, which is also a product of NSF investments, to explore feedbacks between weathering and fluvial incision.

2. BACKGROUND AND RESEARCH NEEDS

Slowly eroding relict topography delivers a limited flux of potential bedload to streams. The grain size distribution of this sediment flux depends on rock properties and weathering rates (Sklar et al., 2017). For crystalline rocks, the size distribution of individual mineral grains will influence the particle size distribution that results from rock disaggregation due to chemical weathering. Slow erosion rates in the uplands lead to longer residence times, thus greater time to weather grains. Increased comminution of rocks in soils and saprolite on slowly eroding surfaces further reduces the grain size of sediment conveyed to streams. In a less simple case, rock properties (bedding and joint spacing) govern the maximum size of particles produced by weathering and erosion on slopes (e.g. Thaler and Covington, 2016; DiBiase et al., 2018).

In all cases, biotic effects, temperature, precipitation, and erosion rate are key in determining the size of weathered particles when they eventually reach the soil surface. Where surface soil grain size is large, but clasts are transportable by rivers, river incision is likely enhanced by the presence of 'sediment tools' that abrade the bed (e.g. Whipple et al., 2013). In this case, rivers can more effectively cut down through landscapes, conveying a change in base-level more quickly upstream than in landscapes with highly weathered small grains. Where grains fed to the channel are too large and not often transported, they may armour the bed and reduce fluvial incision rates (e.g. Johnson et al., 2009).

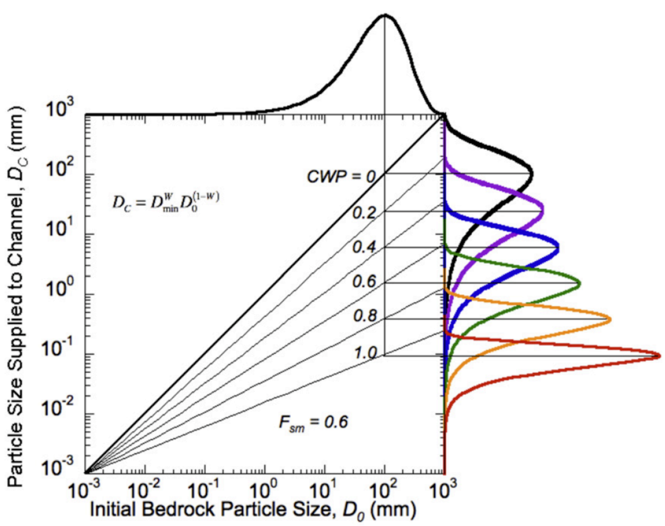

***Figure 1**: Figure 13 from Sklar et al., 2017. Modeled transformation of initial bedrock particle size (based on rock properties, black line on top axis) to particle size supplied to channels, as a function of the chemical weathering potential, CWP (colored lines on right axis). CWP varies with rainfall and temperature. Other controls that are fixed in this figure are the erosion rate and F_{sm}, or fraction of soluble minerals, which is a function of rock type.*

Feedbacks among rock type, weathering rate, grain size, and fluvial incision have not been included in landscape evolution models. There are many reasons for this, but one key limitation has been the lack of a general model for predicting the size of sediments produced on a hillslope and supplied to channels. However, Sklar et al, (2017) present a model for the transformation of an initial grain size distribution, (governed by rock properties) as it weathers in the soil column. This transformation is a function of climate, encapsulated by the chemical weathering potential (*CWP*), and erosion rate, which controls soil residence time. Figure 1 illustrates the transformation of grain size through the saprolite and soil column as a function of *CWP*. It is important to note than increased *CWP* does not just 'shift the distribution'; it also changes the shape of the distribution. What impact these differences in distribution – both shape and mode – will have on incision rates, knickpoint migration rate, and fluvial morphology is an unexplored question that we will tackle using the Landlab modelling toolkit (Hobley et al., 2017).

2.1. Why Puerto Rico?

The Luquillo Critical Zone Observatory (LCZO) in the Luquillo Mountains of eastern Puerto Rico presents a well-constrained setting to examine the critical zone response to tectonic forcing. We focus on the Rio Blanco watershed in the Luquillo Mountains. The watershed consists of Cretaceous volcanoclastic sedimentary rocks intruded by a quartz diorite pluton of Eocene age that is presently extensively exposed in the watershed (**Fig. 2**). The entire island is located above an oblique subduction zone. It has experienced rapid changes in tectonic uplift rates throughout its history, and the erosion systems are still responding to this uplift.

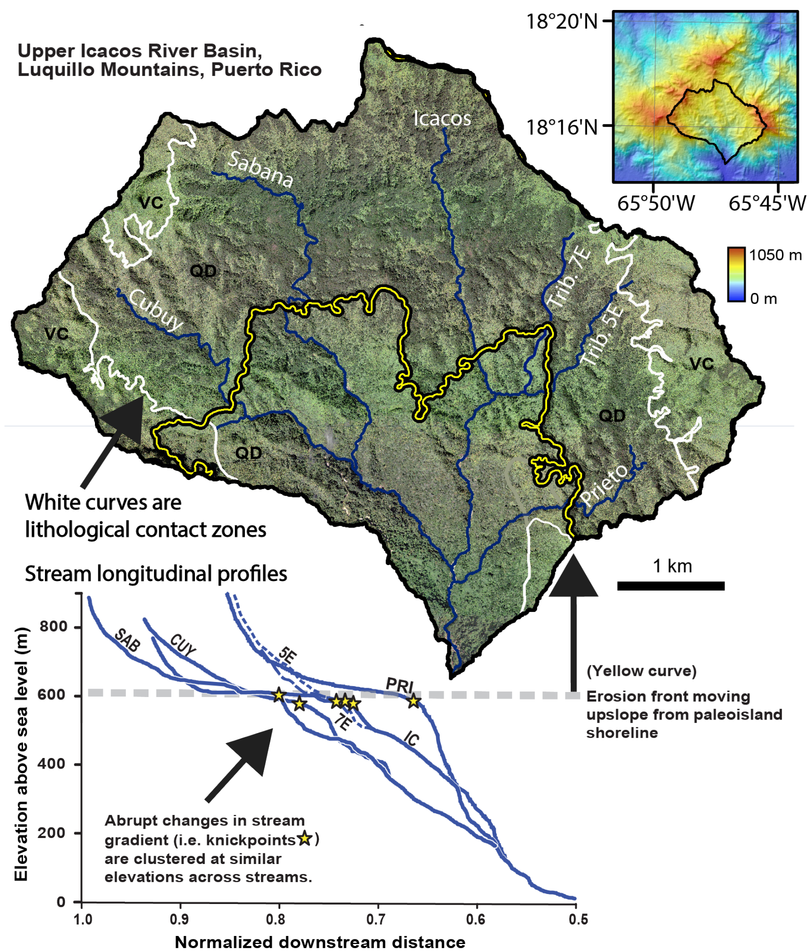

Figure 2*. Upper right shows the elevation and location of the field area. Center is a view of the study watershed. The yellow line demarks the location where the landscape transitions from relict to adjusting. White lines demark changes in rock types, with QD = Quartz diorite, VC = Volcanoclastic. Blue lines indicate the major tributaries, with their profiles shown in the lower left plot. SAB = Rio Sabana; CUY = Rio Cabuy; IC = Rio Icacos; PRI = Rio Prieto.*

The topography of the LCZO is a patchwork of domains eroding at various rates, separated from each other by knickpoints. Above the knickpoints, rivers draining the relict landscape have concave-up alluvial reaches with low gradients and limited stream power (Pike et al., 2010)(**Fig. 2**). Along the knickpoint faces, streams flow directly over bedrock. The knickpoint lips are located entirely within the homogeneous interior of the quartz diorite stock and cluster around 600-m altitude. Their presence is interpreted as the front of a headward-migrating wave of incision propagating along the branches of Río Blanco (Brocard et al., 2015), as a consequence of uplift around 4 million years ago (Brocard et al., 2016). The episode of uplift has sparked erosion waves that are still propagating across the landscape, generating sharp retreating knickpoints in the topography that migrate through the landscape at an average rate of ~1 km/My, although the rate varies among the channels (Brocard et al., 2016).

The Rio Icacos differs from the other tributaries of the Rio Blanco system in that it is the only catchment that drains entirely quartz diorite. The quartz diorite weathers into a thick saprolite that contain corestones typically several meters large. The saprolite directly weathers to sand-sized fragments, and as a result, the Rio Icacos and its tributaries are sandy rivers with little to no gravel load (Pike et al., 2010). Conversely, all the other tributaries (Rio Sabana, Rio Cabuy, Rio Prieto) drain small portions of hornfels and volcaniclastic lithologies that fringe and surround the quartz diorite. Volcaniclastic and hornfels rock types weather predominantly to gravel and clay in this setting, and as a result, the streams maintain a steeper gradient and are paved with volcaniclastic and horfels gravel as they cross the quartz diorite stock, down to the knickpoint lips. The Rio Icacos knickpoint migrates at about half the rate of the other knickpoints in the network (Brocard et al., 2016), and this provides an ideal natural experiment to test the impact of gravel on knickpoint velocity while other variables remain constant. Downstream of the knickpoint, all streams have a very steep gradient and, in addition to any gravel coming from upstream, are abundantly fed in quartz diorite gravel and cobbles from the surrounding steep slopes with thin saprolite.

All knickpoints are incised into the same, massive quartz diorite, which exhibits little lateral variability in joint spacing (Brocard et al., 2016). Wherever observed, bedrock foliation was weakly developed and generally perpendicular to the streams, indicating that bedrock anisotropy does not control knickpoint propagation. Pike et al. (2010) showed that the shear stress along the knickpoint face of Río Icacos and other large knickpoints is much higher than the threshold for sediment mobility. This suggests that gravel is rapidly transported downstream. Under these conditions, the effect of grain size on particle mobilization would be minimal, and bedrock abrasion and plucking increase with bedload grain size (Foley, 1980, Sklar and Dietrich, 2001), and gravel flux (Jansen et al., 2011; Cook et al., 2013). Given the lack of gravel-sized sediment tools (**Fig. 3a**), the Icacos knickpoint lip retreats more slowly than the knickpoints of other tributaries that contain gravel (**Fig. 3b**)(Brocard et al., 2016). Also, because of the increase in bedload downstream of the knickpoint (from surrounding hillslopes), we expect the knickpoint face to steepen over time because of the downstream increase in incision rates, and non-fluvial processes of erosion such as mass wasting to develop (Weissel and Seidl, 1998; Tucker and Whipple, 2002). This expectation correlates well with the anatomy of the knickpoints: of all streams, the Icacos River has the shallowest gradient and lowest steepness upstream of the knickpoint lip, together with the steepest knickpoint face, excluding the knickpoint of Río Prieto that partially sits on hornfels – a lithology resistant to weathering to small sand-sized particles (**Fig. 4**). We did not find other sources of systematic variation between the knickpoints that could account for the factor of almost-two difference in knickpoint velocities; all upstream catchments share similar average elevations and hence similar precipitation and average unit discharge (Pike et al., 2010).

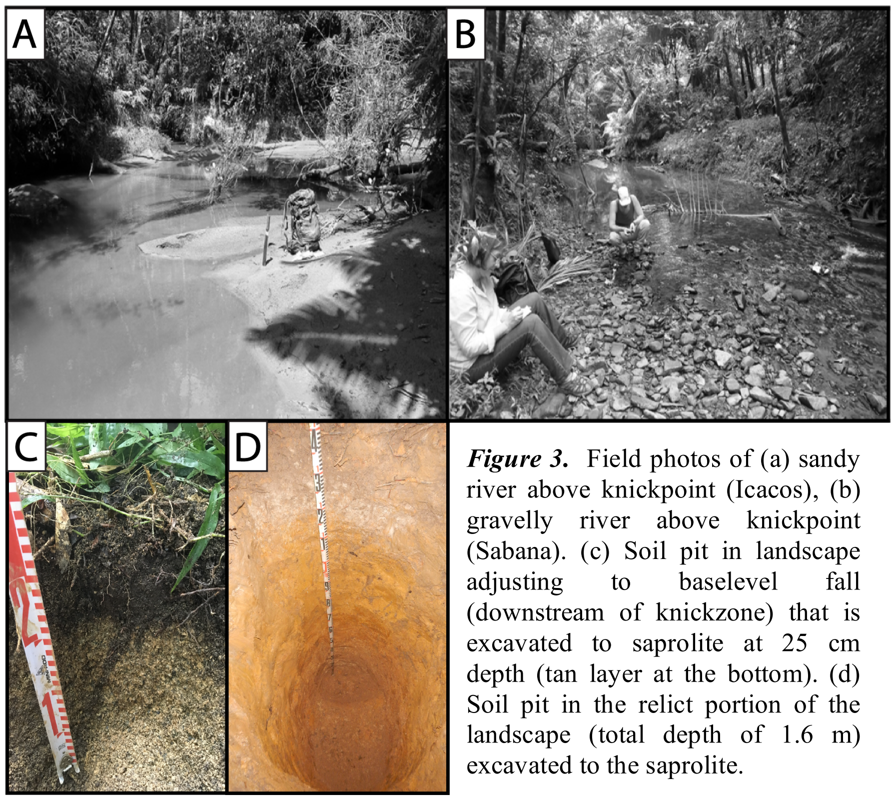

Figure 3. Field photos of (a) sandy river above knickpoint (Icacos), (b) gravelly river above knickpoint (Sabana). (c) Soil pit in landscape adjusting to baselevel fall (downstream of knickzone) that is excavated to saprolite at 25 cm depth (tan layer at the bottom). (d) Soil pit in the relict portion of the landscape (total depth of 1.6 m) excavated to the saprolite.

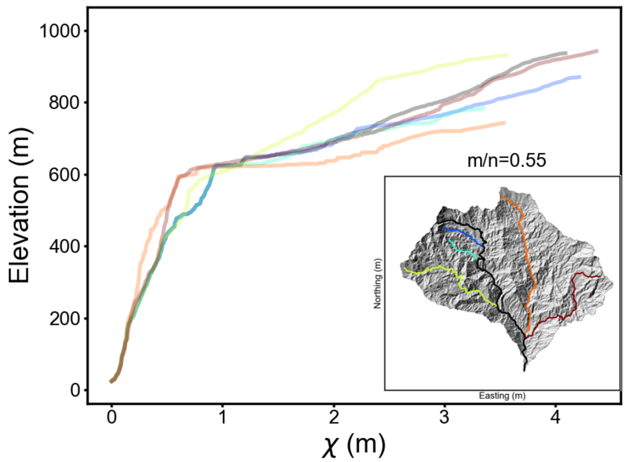

Figure 4: *Elevation-Chi plots (Perron & Royden, 2012) of 6 major tributaries in the study watershed (Harrison et al., in prep). Note that the orange channel is the Rio Icacos and it has a shallower slope in elevation-chi space upstream of the knickpoint and a steeper slope in elevation-chi space downstream of the knickpoint, in comparison with all the other channels.*

2.2. Current Understanding of Soil and River Evolution in Puerto Rico LCZO

The Luquillo mountain range experiences a tropical climate with a mean annual rainfall of 3-5 m y^{-1} and a mean annual temperature of 19-24°C, conducive to driving relatively high weathering rates for a granitoid substrate (Murphy and Stallard, 2012; Stallard, 2012). **Importantly for our proposed study, this tropical climate and elevation range is thought to have persisted for millions of years (Brocard et al., 2016).** In the upper, relict landscape headwaters of Rio Blanco, soils are thick (1-3 m) (**Fig. 3d**) and with mineral components composed of chemically-altered bedrock including secondary minerals and quartz with deep weathering front migration likely paced by albite dissolution and rindlet formation in corestones (White et al., 1998; Fletcher et al., 2006; Buss et al., 2008; Brantley et al., 2011). From preliminary field reconnaissance, we discovered that downstream of the knickzone, soils are thinner (<1m)(**Fig. 3c**) and less weathered (Brocard et al., 2015) and the weathering zone thickness decreases towards the top of the knickzone, where competent bedrock is exposed at the surface along the tributary channels of Rio Cubuy, Rio Sabana, Rio Prieto and Rio Icacos.

Importantly, the erosion rates (in soils and stream sediments) in the upper portions of the landscape are low (~50 m/My)(Brocard et al., 2015; 2016) and similar to weathering front propagation rates (~50 m/My)(White et al., 1998). Landscapes where erosion rates are low are easier to detect a transient change in soil erosion rates using *in situ*-produced cosmogenic ^{10}Be (Mudd, 2016).

Using *in situ*-produced ^{10}Be in river-borne quartz, the magnitude of the erosional difference between the relict, slowly eroding uplands and the more rapidly adjusting downstream areas was determined. Brocard et al. (2015) observed a decrease in the concentration of cosmogenic ^{10}Be across the knickpoints, confirming that a tectonic event that occurred several millions of years ago still imparts detectable differences in erosion rates in the modern landscape over the time-scale of ^{10}Be-derived measurements (typically 10^3–10^4 years). Brocard et al. (2015; 2016) have shown a doubling of the erosion rate from relict soils to soils below the knickzone in our study area, and this is thought to be a necessary condition for detecting transience in hillslopes with cosmogenic nuclides (Mudd, 2016).

By analyzing the mineral composition of the soils near the knickpoints, Brocard et al. (2015) found that this increase in erosion rate is accompanied by an increase in nutrient-bearing primary minerals. Thus, knickpoints appear to indirectly impact the biota because they separate an upland region where soils are almost completely depleted in primary nutrient-bearing minerals and where previous studies have shown that nutrients are mostly retrieved from the atmosphere and efficient recycling (e.g. Zarin and Johnson, 1995), from a downstream region where soils possess a larger stock of nutrient-bearing primary minerals and plant-available nutrients (Porder et al., 2014). This knickzone also imparts a change in the forest canopy height with average tree height downstream of the knickzone almost double the height of the trees in the relict landscape (Wolf et al., 2016).

We aim to exploit the contrast in erosion rates across the knickzone (Brocard et al., 2015; 2016) to evaluate: 1) the nature and timing of soil development; and 2) the connection between soils and the

rate and style of landscape adjustment. This research proposal is designed to test the hypothesis that **as the knickzone migrates upstream, the weathered zone immediately downstream redevelops to a new steady-state weathering profile characteristic of a higher rate of erosion.** The predicted data outcome is that soils thin from downstream to upstream approaching the knickzone, and patterns of soil production rate match patterns in rates of knickzone migration from Brocard et al. (2016). A competing hypothesis would be that the weathering front propagation predates knickzone passage and the accelerated erosion simply scrapes off the relict, thick surface soils.

3. OBJECTIVES, HYPOTHESES AND SIGNIFICANCE

3.1. Objective 1: Constrain the patterns of soil depth, grain-size and weathering with distance from the knickzones. The pace of river incision and the weathering zone response to that change is crucial to testing the link between soils and streams.

Hypothesis 1.1: **Below the knickzone, the weathered zone redevelops in response to a new steady-state weathering profile that has a higher rate of erosion.** Constraining the timing of soil production and regolith production is a crucial component of this project, and the most challenging because it requires the measurement independent isotope systems: *in situ* cosmogenic ^{14}C and ^{10}Be and uranium-series nuclide disequilibrium. Each one of these isotope systems contains an internal clock that is active inside of the soil profile. The cosmogenic ^{14}C and ^{10}Be clocks both record the amount of time that soil travels through the top few meters of the Earth's surface thorough mass loss via chemical weathering and mass loss through physical erosion. Each apparent erosion rate, or exhumation of soil grains, depends on the half-life of the radionuclide (^{14}C half-life= 5.73 ky; ^{10}Be half-life=1.4 My) because any change in the erosion rate will be recorded by the nuclide concentrations with a significant lag time that depends on the half-life of the nuclide. The uranium-series clock starts when the parent material is broken down by chemical weathering–it records the time since initiation of weathering. Taken in combination, these measurements record the changes in erosion rate and timing of chemical weathering following tectonic uplift and the subsequent timescale of response in the soil profile. The dataset is novel, and will fill an important gap in our current understanding of a possible natural acceleration, or limits, of soil production.

Prediction #1: Soils thin approaching the knickzone from downstream to upstream and the timing of weathering and rate of soil production matches knickzone migration into the relict landscape.

Hypothesis 1.2: **Different soil sizes contain information related to the flux of that sediment size to the streams.** Equal mobility/erosion of particles in soil is often tacitly assumed in conceptual models of hillslope soil erosion. However, our preliminary cosmogenic data from soil in the relict portion of the landscape in the Luquillo mountains point to different residence times for different sized particles. Amalgamations of fine sand (excluding dust) in the surface soil have resided in the landscape for >10 ky longer than the coarse sand (>500 microns). Reservoir theory for studying the geochemical evolution of soils has been considered in only one key paper (Mudd and Yoo, 2010) that has challenged the equality of the residence time distribution of particles in a soil and the residence times of particles leaving a soil. However, few such efforts have included cosmogenic nuclide production or grain-size (Anderson, 2015).

Prediction #2: Cosmogenic nuclide apparent 'ages' of different grain sizes relate to their residence times in soils and differences in diffusion constant for different sized sediments.

3.2. Objective 2: Elucidate the connection between sediment caliber and flux, climate and the rate and style of landscape adjustment.

Hypothesis 2.1. **The D_{50} of the in-stream sediment will impact the rate of landscape adjustment and channel profile morphology.**

Prediction #1: Landlab models will illustrate that the streams with coarser sediment will have knickpoints that retreat faster than the knickpoints in streams with finer sediment because coarser sediment leads to faster incision rates via abrasion by particle impact. The rate of incision will subsequently affect the channel profile morphology.

Hypothesis 2.2. **At the catchment scale, either above or below knickpoints, the discharge, slope, grain size, and sediment flux impact the channel incision rate and the time scales that different parts of the landscapes (fluvial and hillslope) respond.**

Prediction #2: Landlab models that include variability in lithology, soil depth, grain size, and discharge (via climate) will exhibit different rates and styles of knickpoint propagation, with measurable topographic signatures. It is difficult to predict exactly how different combinations of these variables will impact incision rates, which is why a numerical model is an ideal testing ground. We will do numerical experiments that are meant to capture the variability in our field area, however, the generalizable nature of landscape evolution models will allow us to test theories about preservation or destruction of topography in a range of environments, rock type, climates and tectonic forcing.

4. RESEARCH ACTIVITIES, APPROACH AND METHODS

This research addresses the above objectives by bringing together field data, topographic metrics, geochemical data, and numerical models to bear on understanding the evolution of the critical zone and its impact on the pace of landscape evolution. Expected key outcomes include: (1) quantification of rates of soil evolution and knickpoint migration in the study area; (2) increased understanding of the drivers and modulators of knickpoint retreat and soil formation and their linkages; and (3) training of graduate and undergraduate students.

4.1 Soil mapping, geochemical analyses, and topographic analyses

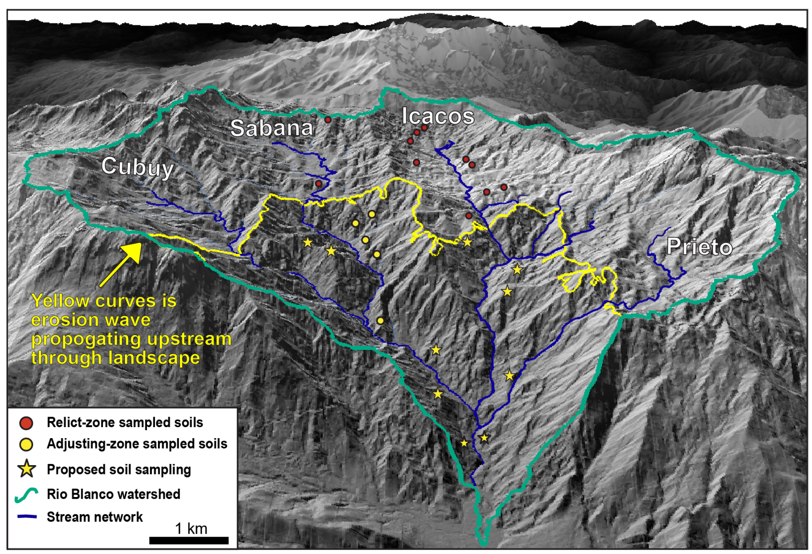

Figure 5. *Oblique shaded relief map of the Rio Blanco watershed (green line is boundary, blue lines streams). Ten new soils will be excavated and sampled (stars) and will be combined with previously sampled pits (circles) to form a unique combined dataset.*

We will map patterns in surface soil thickness from hand-dug pits, measure grain-size and organic matter content, and periodically sample for measurement of soil geochemistry. Previously measured D_{50} of bedload in the streams draining different tributaries are available to compare to sizes of soil rock fragments measured using the "*mimimum pedon volume"* concept (Marshall and Sklar, 2012; Attal et al., 2015). Measurements of porosity and soil density with depth from these pits will be used for the erosion rate calculations in §4.2. Soils will be sampled from 10 new hand-dug soil pits, dried, ground, and analyzed for bulk elemental composition using Li metaborate fusion followed by analysis with an inductively coupled plasma mass spectrometer (ICP-MS) available at Scripps Institution of Oceanography and an in house XRF to compare to composition of parent material. Soils from ridges above the knickpoint and four ridge soils below the knickpoint have already been sampled as an independent reconnaissance effort to obtain seed data for this proposal (**Fig. 5**). This proposal will support sampling of soil below the knickzone exclusively from hillslope ridges to exclude the possibility of soil transport on the measurements. Approximately 200 samples will be analyzed from depth profiles in 20 soil pits from the surface to shovel refusal within the first year of the project. A majority of the soil pits have already been sampled and processed (**Fig. 5 and 6**) during the previous two years of the UC San Diego PhD student's dissertation work. Normalized concentrations will be calculated to determine loss or gain of elements in comparison to less-soluble elements such as titanium, zirconium or niobium in the parent material and soils, following previous work (e.g., White et al., 1998; Riebe et al., 2004; Ferrier et al., 2010). We have previously concluded via collaborative measurements that colloidal transport of these immobile elements (c.f. Bern et al., 2015) is insignificant both above and below the knickzone (Carleton Bern, USGS, pers comm.). By analyzing soils and calculating normalized concentrations (White et al., 1998) and chemical depletion factors (Riebe et al., 2004), we will assess mass lost due to weathering as a function of distance from the knickpoints at LCZO.

From high resolution LiDAR data (**Fig. 5)**, we identified ridgelines to target spanning the longitudinal reach of the river system. From this high-resolution DEM, we will extract landscape morphological metrics characteristic of topographic evolution, including the hilltop curvature, hillslope length, relief, and slope (Dietrich et al., 1992; Mudd and Furbish, 2007; Hurst et al., 2013) and will use these metrics to interpret the geochemical data.

4.2. Geochemical analyses

4.2.1. Cosmogenic Nuclide-derived Basin-Wide Erosion Rates

After enough time, the bulk concentration of terrestrial cosmogenic nuclides within a sample of alluvium carried by an active stream reflects the average erosion rate of the uppermost ~meter of soil in the landscape upstream (Lal 1991; Brown et al. 1995; Granger et al. 1996). This technique has been used to determine bedrock and catchment-averaged erosion rates in Puerto Rico in the past (e.g. Brown et al. 1995; Brocard et al., 2015; 2016). **We will use previously measured basin-wide erosion rates that were supported by the LCZO and will not do additional sampling.** These data can serve as key empirical data for comparison with modeling scenarios in Landlab.

4.2.2 Soil Production rates from cosmogenic nuclides and U-series disequilibrium:

As preliminary data, we have measured soil production rates using *in situ* cosmogenic ^{10}Be concentrations measured in depth profiles, following established methods (e.g. Kohl and Nishiizumi, 1992; Heimsath et al., 1997; Dixon and Riebe, 2014) above the knickzone and **this proposal will support sampling and analysis of soils downstream of the knickpoints**. Samples were collected at depth intervals from the surface to the soil-saprolite boundary, and into the

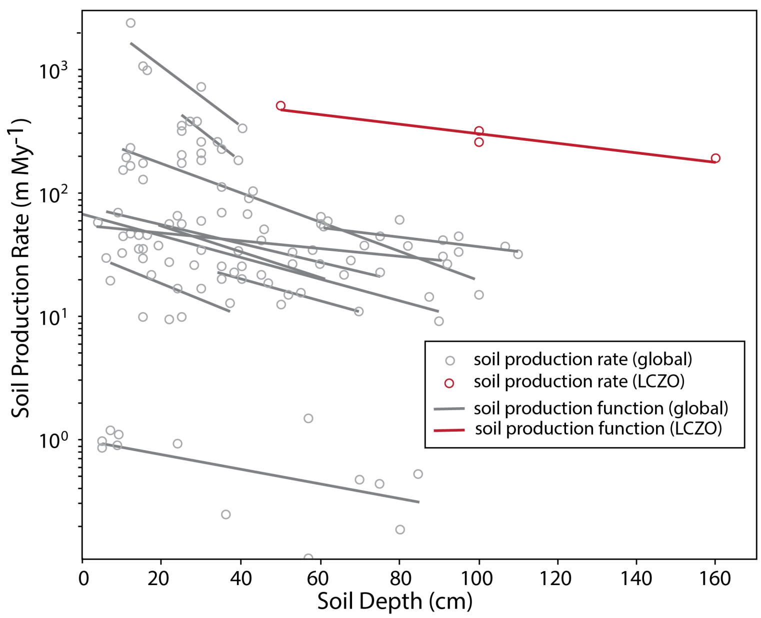

Figure 6. *Global compilation of soil production rates (gray circles) and the related soil production functions (gray lines). Preliminary data showing soil production rates (circles) and soil production function (line) in the relict portion of the LCZO, Puerto Rico are shown in red. The LCZO soil production dataset is exceptional because they mark the deepest soils ever measured and the weakest dependence on soil depth. This proposal aims to expand the dataset to soils below the knickzone, where a tectonically-driven increase in erosion rate has resulted in thinning of the soils.*

saprolite to the depth of the attenuation length of cosmic radiation (Gosse and Phillips, 2001; Dunai, 2010). The difference in age measured along the soil profile represents the time interval required to produce the soil covering, integrated over 10^3-10^4 year timescales for ^{10}Be (von Blanckenburg and Willenbring, 2014). Importantly, this work is the first to measure soil production in thick soils (>1 m) and the first to note that the site soil production function in relict landscapes deviates from the behavior of other soils with their relation to soil thickness (**Fig. 6**). This difference in soil production is not due to violation of the assumption of constant soil thickness because several independent studies have verified that the slowly eroding, relict landscape is in geomorphic equilibrium (Brown, et al., 1995; Riebe et al., 2004).

In the rapidly eroding portion of the watershed, the hypothesized change in soil thickness coincident with the passage of the knickpoints violates the assumption of steady-state soil cover that is required by the cosmogenic radionuclide measurements (Heimsath et al., 1997). Below the knickpoints, soil production and soil erosion rates must be quantified with independent methods that do not assume a time-constant soil thickness (i.e. matching rates of weathering front propagation and surface erosion). We have two strategies to address this methodological issue which will represent a new coupling of techniques.

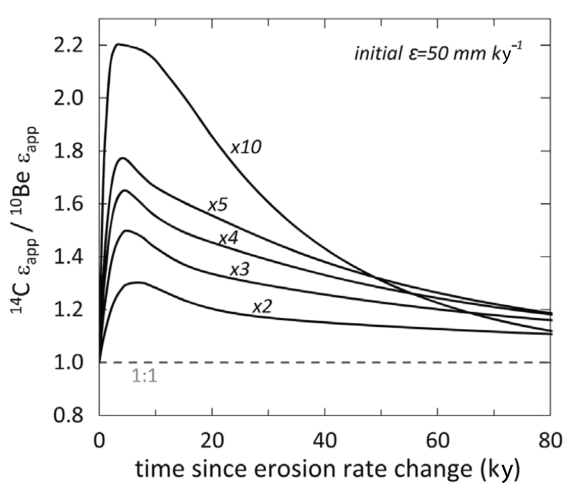

Figure 7. *Impact of a rapid change in surface erosion rates on the ratio between apparent in situ ^{14}C and ^{10}Be-derived erosion rates (^{14}C ε_{app}/^{10}Be ε_{app}) starting from an initial erosion rate of 50 mm/ky increasing by a factor of 2, 3, 4, 5, and 10 (Figure from Hippe 2017).*

One way to evaluate the temporal changes in erosion is to couple *in situ* ^{14}C apparent erosion rates to ^{10}Be apparent erosion rates measured in ridge sediments to investigate transience in actively eroding landscapes. Cosmogenic in situ ^{14}C is highly sensitive to recent, short-term changes in surface erosion and provides a method to detect erosion transience and infer the timing and magnitude of erosion rate change (Hippe et al., 2013; Mudd, 2016). The situ ^{14}C concentration more rapidly adjusts to the new erosion signal in comparison to ^{10}Be and creates a measureable offset between the apparent in situ ^{14}C and ^{10}Be erosion rates and a deviation of the ^{14}C-^{10}Be ratio (cf. Mudd, 2016)(**Fig. 7**: from Hippe, 2017). **We will couple ^{14}C and ^{10}Be apparent soil production rates at the saprolite-soil boundary and apparent erosion rates in the surface soil in 10 soil pit locations (Fig. 5). In four locations, we will measure both large (>0.5-1mm) and small grains (125-250 microns) for ^{14}C and ^{10}Be. Brent Goehring at Tulane University will measure the in situ produced ^{14}C in the soil quartz prepared by the SIO group (See letter of collaboration).**

Uranium-series isotopes have been used to successfully quantify soil residence times for weathering profiles in a variety of study areas - including in the Luquillo CZO (Dosseto et al. 2008a, 2011). This method does not require a balance between erosion and weathering front propagation. In bedrock that has been chemically unaltered for more than 1 My, all of the uranium-series nuclides will be in secular equilibrium (Bourdon et al., 2003). This condition is met in our field area where the quartz diorite was emplaced tens of millions of years ago. Weathering reactions disrupt this state, and cause disequilibrium in the activity ratios of uranium-series nuclides due to the differences in mobility of the nuclides (Chabaux et al., 2003; Dosseto et al., 2008b). The degree of disequilibrium depends on the extent and timing of weathering processes, and is used to calculate the age of weathered particles with depth in a weathering profile (Dosseto et al., 2008b; Chabaux et al., 2011). Chabaux et al. (2013) used this methodology to characterize regolith formation rates from a profile in the relict portion of this watershed, providing a ready comparison for the proposed research.

Uranium-series analyses is currently ongoing through a collaboration and international student training at the University of Wollongong, Australia. Willenbring's Ph.D. student, Emma Harrison, is working in the Wollongong Isotope Geochronology Laboratory under the supervision of Dr. Anthony Dosseto for eight weeks following the field season. She will prepare samples collected according to laboratory protocols, and measure U and Th isotopes on a laser ablation multi-collector ICP-MS following procedures described in Sims et al. (2008). These data will be analyzed with support from a SAVI grant awarded to Ph.D. student, Emma Harrison at no cost to this grant.

4.3. Numerical Model Development and Experiments:

We will use the Landlab modeling framework to link sediment production on hillslopes to sediment transport and abrasion of bedrock in fluvial channels. Landlab is an open source Python modeling library that provides the tools for building landscape evolution models. Landlab supports the building of multiple types of grids (e.g. raster, hexagonal, radial) and process components operate across a grid. The grids store data that are shared among the different process components included in a model. Landlab has built-in algorithms for importing data, standard topographic calculations (e.g. gradient, flow routing, identifying watersheds), tracking data in layers, and plotting. (Gasparini is a PI on the two NSF grants that have supported the development of Landlab.) She and a postdoctoral fellow will develop the process components necessary for this project with input from Willenbring and Sklar. None of the existing Landlab process components contain the details required for the modeling scenarios described here, but we can use the framework of other components, such as the *SPACE* component (Shobe et al., 2017) for tracking sediment transport and fluvial incision.

4.3.1. New Landlab process components*:*

Transformation of bedrock to sediment supplied to rivers: We will use the framework and geomorphic transport law developed by Sklar et al. (2017) to model the grain-size distribution resulting from the transformation of rock to soil. The primary independent variables controlling the size distribution at the top of the soil column are lithology, climate, life, and tectonics and erosion. Assumptions must be made for the form of the soil production function (exponential decline with depth, Heimsath et al. (1997)) and the size distribution of particles produced from bedrock. With these assumptions, the size distribution of sediment provided to the channel becomes a function of the fraction of soluble minerals in bedrock (F_{SM}), the chemical weathering potential (*CWP*), and the erosion rate (E). Also critical are the erosion thresholds for weathering to go from supply limited to kinetically limited (E_{SK}) and from kinetically limited to fresh rock (E_{KU}), or in other words, the erosion rate at which there is no breakdown of rock fragments in the soil column. Chemical weathering potential (*CWP*) is a function of climate (precipitation and temperature variables), although their combined behavior can be encapsulated by variation in this one variable. We do not include the details of the equations here, but for reference they are equations 17 – 21 in Sklar et al. (2017). We will implement these equations in Landlab as the new process component *Rock2RegolithConverter*.

Landlab already has four components to model hillslope sediment transport (different flavors of linear and non-linear diffusion), and we will use these to transport sediment across hillslopes and into channels.

Saltation-abrasion driven fluvial bedrock incision: We will implement at least one new fluvial incision model here generically referred to as the process component *SaltationAbrasionEroder*, which will model bedrock river incision as a function of the abrasion rate from saltating bedload. There are multiple equations to capture these dynamics (e.g. Sklar and Dietrich, 2004, 2006; Turkowski et al, 2007, Zhang et al., 2015), and we are not tied to a particular model and will likely explore more than one. We will implement the bedrock incision equation for the distribution of sediment determined from the sediment delivered from upstream and locally from the hillslopes. We will also include the breakdown of sediment grains as they are transported downstream.

4.3.2. Model experiments*:*

Our goal is to explore how climate and erosion rate impact the grain size distribution supplied to fluvial channels and how this affects the morphology of fluvial channels. Sklar et al. (2017) illustrate how climate, via variation in *CWP*, impacts the grain size distribution supplied to the channel (**Fig**. 1). How this variation in grain size distribution with climate impacts the morphology of river channels is not understood. In other words, climate will affect both fluvial shear stress and the distribution of sediment sizes in the channel. Further, changes in climate may enhance or suppress the impact of erosion rate on channel morphology. We will explore these interactions with theoretical modeling experiments and applied experiments to better understand our field area.

Theoretical experiments: We will perform two sets of theoretical steady-state experiments. The first experiments will be on hillslopes only. Once we more fully understand the sensitivity of the hillslope dynamics, we will include channels and model an entire watershed comparable in size to the Rio Blanco. In all cases, we will have uniform and steady rock uplift rate, climate, and rock type to understand how inclusion of the *Rock2RegolithConverter* and *SaltationAbrasionEroder* components impact steady-state morphology (erosion rates matched by rock uplift rates).

The parameters that we will vary in the experiments are illustrated in **Table 1**. In the hillslope-only experiments, we do not need to include stochastic rainfall or specify what causes changes in the *CWP* because these do not impact any of the hillslope transport components. However, in the experiments that include channels, we need to specify whether *CWP* changes because of temperature or precipitation, because precipitation drives changes in shear stress and fluvial incision. Further, we will explore the impact of steady vs. stochastic rainfall, and the impact of flood distributions on the fluvial incision model (e.g. Lague et al, 2005), as including multiple grain sizes and flood distributions promises some very exciting (and complicated) dynamics. In the coupled experiments we will co-vary F_{SM} with the rock strength parameters in the *SaltationAbrasionEroder* component. **Table 1** presents a large, multi-dimensional parameter space to explore even in these initial theoretical experiments. We will use DAKOTA, an open-source software for sensitivity analysis (Adams et al. 2016) to help us interpret landscape sensitivity to different parameters and drivers. We will also take advantage of the DAKOTA Python wrappers built by CSDMS to make this aspect of the project easier (see letter from G. Tucker).

	Steady-state theoretical experiments	
Parameters to explore	Hillslopes only	Hillslopes and channels
Chemical Weathering Potential, *CWP* (non-specific)	X	
Chemical Weathering Potential, *CWP* (via precipitation)		X
Chemical Weathering Potential, *CWP* (via temperature)		X
Erosion rate, *E* (via rock uplift rate)	X	X
Fraction of soluble minerals, *F_sm*	X	X
Erosion threshold from supply to kinetcialy limited, *E_sk*	X	X
Erosion threshold from kinetcialy limited to fresh rock, *E_ku*	X	X
Hillslope transport component	X	X
Fluvial rock strength parameters		X
Stochastic rainfall		X

Table 1. *Different parameters and processes that will vary among the steady-state experiments. Because each parameter has a large space that can be explored, the number of possible model realizations is very big. We will use DAKOTA to aid in understanding sensitivity to parameter space and process components.*

We will choose some subset of these steady-state landscapes, both hillslope only and coupled hillslope-channel experiments, to explore how the grain-size distribution, incision rates, and landscape morphology respond to base-level change and the generation of knickpoints. Much more simplistic modeling that did not include multiple grain sizes and the full details of the Sklar and Dietrich (2004) model suggests that many phenomenon observed in natural landscapes that are not produced with a stream power model can result when the dynamics of sediment 'tools and cover' are included in a model (e.g. Gasparini et al., 2007; Crosby et al., 2008; Hobley et al., 2016). The inclusion of multiple grain sizes adds an important step forward from previous work, and supplies an extra variable for relating model output to real landscapes. The model outcome can be used for interpreting landscapes beyond our specific study area. Although the scope of the results is hard to predict before the experiments are run, we expect to see rich dynamics and gain new insight into transient landscape dynamics.

LCZO experiments: We will begin by evolving landscapes to steady state and then perturbing them, and we will use the Icacos watershed topography, or a subdued version of it (i.e. we will take the current topography and reduce relief and smooth it, so that we will end up with roughly the same channel network organization), for the initial condition. Here, we will calibrate the *Rock2RegolithConverter* component using the data we collect in the field. We expect that the calibrated relationship will vary among the different rock types in the watershed. Modeling experiments will consider watersheds with uniform rock type, but we can vary the rock type between experiments. We will evolve the watershed to steady state with different rock uplift rates, and then perturb the landscapes to explore how sediment size distributions affect channel incision and landscape morphology using the *SaltationAbrasionEroder* component.

Field evidence suggests that knickpoint propagation rate and channel profile morphology are tightly linked to the grain size distribution supplied to the channels. We predict that both our theoretical modeling and place-based modeling will support these observations. If they do not, we will have learned something about what is missing from our models, and likely gain insight into something we do not currently understand about the real system.

5. BROADER IMPACTS

5.1 Scientific Impact

The results from this project will be applicable to interpreting other landscapes responding to changing tectonic forcing (e.g., Clark et al., 2005; Byun et al., 2015; DiBiase et al., 2015), and help elucidate potential feedbacks and linkages between lithology, climate, weathering and erosion that control the timing of whole-landscape response to baselevel fall – an area of active research (Murphy et al., 2016).

5.2 Visualizing landscapes: training beyond academia

For many non-geologists, it is difficult to understand how landscapes evolve through time. This is particularly true for the visually impaired. PI Willenbring's brother, mother, grandfather, and nine other cousins, aunts and nephews are blind through a genetic disease. As such, she understands the importance of accessibility for blind and sight-impaired people. Vision accessibility is often overlooked in preparing ADA-friendly course materials. As such, **Willenbring, Gasparini and the SIO and Tulane trainee team will develop a suite of geomorphology labs specifically for blind and sight-impaired students, which will be posted on the International Association for Geoscience Diversity Google group and other clearing-house sites for undergraduate lab materials.**

Willenbring will work with the curators of the Birch Aquarium, the public outreach arm of the Scripps Institution of Oceanography, to develop a display that discusses landscapes, how they evolve and how to derive history from them. The Birch Aquarium in San Diego hosts half a million visitors annually, including those who attend the local Braille Institute in San Diego. To aid the visually-impaired in trying to understand the diversity of landscape form, we will 3D print block models of different landscapes that all contain relict and adjusting portions – including the greater San Diego region, a landscape that resembles parts of Puerto Rico. The Scripps trainees will laser-cut models in the new SIO makerspace as part of the REU program for undergraduates, with funding for materials provided by this grant. Both ArcGIS and QGIS provide plug-ins for converting digital elevation models to a 3D-model needed for the printing. The display will feature the hands-on 3D models and will have information in both large text and in braille and will be positioned in a well-lit area (see letter from C. Peach).

Gasparini will offer two 3-credit independent study courses during the duration of this project (once annually with ~3 undergraduate students per course). Tulane requires that all undergraduates take two service learning courses, and these independent study courses will fulfill the upper tier service learning course requirement. As part of the independent study the undergraduates will learn to use 3D printers and laser cutters that are available in the Tulane MakerSpace (see letter from T. Schuler). They will print real landscapes and Landlab generated landscapes (straight forward with numpy-stl library). The students will develop course material and outreach activities for the visually impaired and other groups with special educational needs, including autistic children. The undergraduates will work with local schools to bring activities that include 3D landscapes into classrooms. Potential schools that we will work with include the Louisiana School for the Visually Impaired and two schools which serve students with Autism Spectrum Disorder: Chartwell Center and Rafael Academy. The Tulane Center for Public Service (CPS) will enable school partnerships and activities (see letter from A. Nance). Gasparini has participated in a webinar on broadening participation in science for people with disabilities, and she will work CPS to get more training for her team. **We note that because the undergraduates will receive credit, they cannot receive a salary. However, we have budgeted for supplies and printing costs.**

5.3 Undergraduate, graduate and postdoc training

This project will provide two years of postdoctoral salary. A postdoctoral researcher is necessary to successfully complete the model development and modeling proposed in a short period. Further, the earth science community almost universally requires that new faculty have some postdoc experience, therefore postdoctoral training is critical for moving scientists up the ranks, yet there are few available postdoctoral positions. The postdoc will benefit from mentoring from all the PIs. **The budget includes funds for her to travel to Montreal for one month while she is developing the *Rock2RegolithConverter* component, so that she can work closely with Sklar on this part of the project.** The postdoc will also interact with the CSDMS (see letter from G. Tucker) and Landlab teams, exposing her to a broad community of scientists and best practices in software sustainability, a skill rarely learned as part of an earth science PhD program.

Beyond working with undergraduates in the outreach program described above, Gasparini and the postdoc will mentor two more undergraduates for 10-week summer research opportunities. **Funds are requested to support these undergraduates**. The undergraduates will use Landlab models to explore how relict topography develops and work on GIS projects related to quantifying relict topography in the field area and beyond. **Funds are requested to bring the undergraduate from year 1 to a conference in year 2** (time lag because of abstract deadlines).

Willenbring will mentor one PhD student (Emma Harrison) as part of this grant. **Funds are requested to support Harrison for two years in the final years of her PhD research.** She will be trained and mentored by Willenbring, but will interact with Gasparini, Sklar and the other trainees and LCZO investigators. She is a fluent python-user but will have an opportunity to travel to Tulane to learn how to better use Landlab. **Travel for this training trip to Tulane and presentation of her research at a national conference will be included in the budget.**

The PhD student and Willenbring will co-mentor two Undergraduate Research Experience for Undergraduates (REU) (NSF Grant #1659793) students chosen from the Scripps Undergraduate Research Fellowship (SURF) REU program. **This REU program targets recruitment of students from underrepresented groups, 1st generation college students, and students that come from families with income below the poverty line.** Willenbring has mentored two previous REU students (Omar Rosales-

Cortez, UC Santa Cruz and Sarina Mazzone, SDSU) since arriving at UC San Diego in 2016. Both these students were 1st generation, underrepresented minorities (Native American/Hispanic) and both now plan to go on to graduate school in the Earth Sciences. The REU students will be funded through UC San Diego's REU award (See letter by J. Terranes). **Funds are requested to bring the undergraduate from year 1 to a conference in year 2** (time lag because of abstract deadlines).

6. TIMELINE

The following abbreviations will be used in this section. SIO: PI Willenbring, and students; TU: PI Gasparini, postdoc and students: ALL: members from all teams involved, including international collaborator Sklar. TJ = Target Journal.

Year 0: Apply for US Forest Service Soil Sampling Permit.

Year 1: <u>*Field Season 1*</u>: Timing: Summer 2019. Participants: ALL

<u>*Geochemical analyses*</u>: Send samples collected to UC San Diego with a USDA soil import permit. Process cosmogenic nuclide samples and send to AMS facility (SIO), analyze soil geochemistry.

<u>*Modeling*</u>: Develop *Rock2RegolithConverter* and *SaltationAbrasionEroder* components, including documentation, testing, and tutorials. Build models for theoretical experiments and begin theoretical modeling using DAKOTA. Postdoc works closely with Sklar, including visit.

<u>*Papers*</u>: (1 & 2) Two papers describing the new Landlab components (TJ = *Journal of Open Source Software)*, TU postdoc leads; (3 & 4) Two papers related to soil production in relict landscapes and topographic analysis of the watershed (TJ = *Earth Surface Dynamics & Geology*), SIO PhD student leads.

Year 2: <u>*Geochemical analyses*</u>: Analyze and compile data and prepare publications.

<u>*Modeling*</u>: Finish theoretical modeling. Using results from field and geochemical analyses, modeling experiments using field area are designed and carried out. SIO PhD student training at Tulane.

<u>*Papers*</u>: (1) (At least one) Paper describing theoretical modeling results (TJ = *JRG-ES*), TU postdoc leading; (2 & 3) Papers synthesizing field data, geochemical data and modeling of field area, SIO grad student leading and TU postdoc leading.

All Years: <u>*Education and Outreach*</u>: Mentoring of postdoc and PhD and undergraduate students (ALL); Development of 3D models and teaching activities that are friendly to students with different abilities (ALL); Outreach in local K-12 classrooms and museums (ALL); New Landlab code made available through CSDMS and GitHub and new components incorporated into Landlab clinics and tutorials (TU); Data uploaded to LCZO repositories (SIO); Scientific presentations given at national and local conferences and university seminars (ALL).

7. BRIDGES TO OTHER INITIATIVES

7.1 Landlab and CSDMS: We will leverage previous NSF funding by using the Landlab modeling toolkit. Landlab is an open-source Python library of code that enables users to easily build unique landscape evolution models that can address specific hypotheses (code on GitHub; Gasparini is a co-PI on the two NSF-ACI-SI2 projects). Landlab came to being and is thriving under the umbrella of another NSF-funded initiative, Community Surface Dynamics Modeling System (CSDMS) - "a diverse community of experts promoting the modeling of earth surface processes by developing, supporting, and disseminating integrated software modules". **All process components and analysis tools developed for this project will be made available in the Landlab GitHub repository and through CSDMS as soon as they are tested. Training to use these components will be given through Landlab clinics at the CSDMS annual meeting and at the CSDMS summer school (pending future CSDMS funding).**

7.2 Luquillo Critical Zone Observatory (LCZO) Willenbring is an investigator in the Luquillo Critical Zone Observatory (2014-2018), working on the fluvial erosion aspects. Our soil sampling strategy in that grant will directly benefit the LCZO, especially X. Comas's work imaging the subsurface (See letter from Bill McDowell). Any future LCZO funding would not provide tuition or stipend for the graduate student.

8. PERSONNEL

PI *Nicole Gasparini* - Gasparini will support all Landlab model development and experiments. She has helped build two landscape modeling tools, CHILD (e.g. Tucker et al. 2001) and Landlab (Hobley et al. 2017), from the ground up. She has been involved in every aspect - from code design, to coding and running code, to documentation, testing, and educating. She also has a successful track record of undergraduate mentoring. Working in a department that graduates ~6 undergraduates per year, she has advised 10 undergraduate research projects in 10 years, 6 of these students were female, and 8 of the 9 who have already graduated have gone to graduate school. She also regularly participates in pre-K through grade 8 outreach activities.

PI *Jane Willenbring* - Jane Willenbring is a field geologist who uses cosmogenic nuclide techniques, geochemistry and topographic analyses as tools to understand landscapes and quantify surface processes. She will lead on the field campaigns and analysis of the cosmogenic and geochemical data and will work with trainees and Sklar to appropriately measure grain-size in soils in the field. Willenbring has worked in Puerto Rico for almost a decade using field observations, cosmogenic nuclide-derived rates in alluvium from different grain sizes, and soil production rates metrics for similar purposes outlined in this proposal. She has a successful track record of dissemination of results from NSF-funded research and mentoring research of undergraduates (n=10) and high-school students. All of her undergraduate mentees have been from underrepresented groups and 90% have been female.

International Collaborator *Leonard Sklar* – Leonard Sklar has made many contributions to the development of the theories for channel incision and hillslope sediment size variation being tested here, and to the experimental and field evidence that supports them. Much of this work was supported by NSF grants that he received in his previous position at San Francisco State University, where he also built a strong record of mentoring undergraduate and masters-level student researchers. Sklar has recently moved to Concordia University in Montreal, Canada, where he will be seeking funding for a student.

9. RESULTS FROM PRIOR SUPPORT

<u>Nicole Gasparini:</u> (co-PI, with PI G. Tucker, UC Boulder & co-PI E. Istanbulluoglu, U Washington) *OAC-1450338, 2015-2020, $532,320. Collaborative Research: SI2-SSI: Landlab: A Flexible, Open-Source Modeling Framework for Earth-Surface Dynamics*. ***Intellectual Merit:*** Creating an open-source Python library for modeling earth surface processes, including feedbacks among hydrology, biology and erosion – see Adams et al, (2017), Hobley et al, (2017), Strauch et al, (2018), & Tucker et al, (2016). ***Broader Impacts:*** one Ph.D. dissertation (TU only), two postdocs funded (TU only), open-source teaching and research tools used well-beyond the Landlab development team - over 300 people have taken a Landlab short course (all career levels) or seen and/or used Landlab in college classrooms (undergraduate and graduate students).

<u>Jane Willenbring:</u> (sole PI) *NSF, CAREER-1651243, 2016-2021, $510,703. Meteoric Beryllium Mobility in Soil and Sedimentary Systems*. ***Intellectual merit:*** We performed laboratory experiments and took advantage of natural field experiments to understand environmental conditions necessary for beryllium mobility and retention in soil and sedimentary environments. 4 conference abstracts, 5 journal articles in print (*Boschi and Willenbring, 2016a,b*) and under review (*Valletta et al., submitted; Boschi et al., submitted; Jelinski et al., submitted*), 3 articles in preparation (*Val et al., in prep; Clow et al., in prep; Clow et al., in prep*). ***Broader impacts:*** Training of two PhD students and undergraduate research, held two "Soil Kitchen" community service events. Created and implemented "Garden to Curriculum" lessons incorporating Next Generation Science Standards (NGSS) for a local K-5 public school.