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Late Quaternary Tectonics, Incision, and Landscape Evolution of the Calchaquí River Catchment, Eastern Cordillera, NW Argentina

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Key Points:

- Active tectonics and variably resistant lithologies control erosion rates
- Deformation is focused along preexisting structural heterogeneities
- Erosion rates vary over short timescales, driven by climate cyclicity

Abstract

Unravelling the relative impacts of climate, tectonics, and lithology on landscape evolution is complicated by the temporal and spatial scale over which observations are made. We use soil and desert pavement classification, analysis of longitudinal river profiles, ^{10}Be-derived catchment mean erosion rates, and paleo-erosion and vertical incision rates both from ^{10}Be depth profiles to test whether, if we restrict our analyses to a spatial scale over which climate is relatively invariant, tectonic and lithologic factors will dominate the late Quaternary landscape evolution of the Calchaquí River Catchment (CRC), NW Argentina. We find that the spatial distribution of erosion rates, normalized channel steepness indices, and concavity indices reflect active tectonics and lithologic resistance. Knickpoints are spatially coincident with tectonic and/or lithologic discontinuities, indicating local base-level control by faulting, and we find evidence for out-of-sequence shortening in the Calchaquí River Catchment. Catchment mean erosion rates, ranging from 22.5 ± 2.6 to 121.9 ± 13.7 mm kyr^{-1}, and paleo-erosion rates, ranging from 56 $^{+43}/_{-19}$ to 105 $^{+60}/_{-33}$ mm kyr^{-1}, are similar, may suggest Quaternary climate changes have not had a strong enough influence on erosion rates to be detected using cosmogenic ^{10}Be. However, ^{10}Be depth profiles document punctuated abandonment of pediment and strath terraces at 43.6 $^{+15.0}/_{-11.6}$, 91.2 $^{+54.2}/_{-22.2}$, and 151 $^{+92.7}/_{-34.1}$ ka, and disparities between vertical incision rates and catchment mean erosion rates could suggest periods of landscape transience, possibly reflecting climate cyclicity. Our results emphasize the role of tectonic uplift and lithologic contrasts in shaping the long-term erosion rates and channel morphology at the relatively local scale of the Calchaqui River Catchment, in contrast to regional-scale studies which find precipitation to exert the dominant control.

1 Introduction

Climate, tectonics, and lithology should dictate landscape evolution as expressed through the shape of the topography and the rates and patterns of erosion and sedimentation. However, unravelling the relative controls is challenging, particularly because of the chicken-or-the-egg nature of tectonic-climate coupling (Molnar and England, 1990). Compilations at a global or regional scale have demonstrated that environmental parameters such as mean annual temperature, mean annual precipitation, and vegetation, sometimes measured using elevation and latitude as proxies, can explain much of the natural variation in topography (Champagnac et al., 2012), erosion rate (Portenga and Bierman, 2011; Bookhagen and Strecker, 2012), and channel steepness (D'Arcy and Whittaker, 2014). However, a similar compilation but on a more local (range) scale points to tectonic rather than climatic control, with relief explained by vertical displacement (Ellis and Barnes, 2015).

Field based studies also find conflicting results as to whether climate or tectonics dominate landscape evolution. For example, on a regional scale, work in the Andes demonstrates a long-term latitudinal variation, linked by the authors to climatic variation, in denudation (Barnes and Pelletier, 2006; Barnes et al., 2012) and major morphologic features (Montgomery et al., 2001). Even at a very local scale, if precipitation gradients are persistent over geologic time, the impact on the exhumation and morphology of the landscape can be profound (e.g., Sobel and Strecker, 2003). In contrast, other field based studies demonstrate that tectonics exerts a major control on landscape evolution, with exhumation and erosion rate seemingly unresponsive to significant (3-5 fold increases) in precipitation (Bermudez et al., 2013; Burbank et al., 2003; Val, 2018; Wobus et al., 2006). In other examples, inherited geological contrasts such as the presence of a crustal-scale relay ramp explain regional differences in landscape evolution despite significant, persistent precipitation gradients (Whipple and Gasparini, 2014; Gasparini and Whipple, 2014), or precipitation may follow uplift patterns and enhanced exhumation (Bermudez et al., 2013; Godard et al., 2014).

The attempt to unravel tectonics, climate, and erosion is partly complicated because of temporal climate variability. For example, some studies suggest coupling between erosion rates and a long term shift toward cool conditions in the Quaternary (e.g., Molnar and England, 1990; Willenbring and von Blanckenburg, 2010; Herman et al., 2013), although these studies may suffer from spatial or temporal correlation bias (Schildgen et al., 2018; Schumer and Jerolmack, 2009). Cyclic changes in climate (Zachos et al., 2001) may complicate unravelling links between climate, tectonics, and landscape evolution as well (e.g., Braun et al., 2015). Basin-scale erosion rates are typically integrated over millennia, so the degree to which modern climate data reflect measured erosion rates is dependent on the frequency and magnitude of past climate changes (Bierman and Steig, 1996).

However, it may also be that the spatial scale of observation matters – a global or regional study may reveal one pattern, but a local study may find the dominant controls are different. If the scale of observation is small enough that one of climate, tectonics, or lithology is uniform, the others will necessarily dominate the evolution of the landscape. Less attention has been paid to this potential explanation for the conflicting interpretations of what controls long-term landscape evolution.

In this study we investigate the Late Quaternary landscape evolution of the southernmost Eastern Cordillera in the southern Central Andes (Figure 1), a region with regionally strong climatic gradients, active tectonic uplift, and significant lithologic contrasts. Bordering on the Puna Plateau to the west, the Sierras Pampeanas to the south, and the Santa Bárbara System to the east, the study area lies within the west to east transition from the high plateau to the complex retroarc foreland (Allmendinger et al., 1997; Carrapa and DeCelles, 2008). Pronounced west to east climatic gradients exist as well along the eastern margin of the central Andes due to orographic shielding of easterly moisture-bearing winds, resulting in strong differences in surface processes and erosional efficiency between the plateau and the foreland (Strecker et al., 2007; Bookhagen and Strecker, 2012). At the regional scale of the southern Central Andes, first-order spatial patterns in erosion rates can be linked to precipitation, with high precipitation corresponding to high erosion rate and low channel steepness and vice versa; variations in tectonic uplift and lithology at this scale are not significant factors (Bookhagen and Strecker, 2012). We focus on a narrower region where climate gradients are not as pronounced, the Calchaquí River Catchment (CRC) and lower Pucará Valley (Figure 1), in order to investigate whether at a more local scale tectonics and lithology play the dominant role in shaping landscape evolution.

We use a combination of longitudinal river profile analysis, ^{10}Be catchment-mean erosion rates, and estimates of paleo-erosion rates derived from ^{10}Be depth-profiles to examine the controls on erosion and topography in the Calchaquí River Catchment (CRC), within the Eastern Cordillera. At an even more narrow scale, we focus our field studies in the lower Pucará Valley, an intramontane basin within the CRC (Figure 1), mapping geomorphologic and geologic features as well as dating abandoned alluvial surfaces to determine potential climatic influences on the timing and rate of incision. Fluvial channel network morphology is a sensitive indicator of both tectonic and climatic forcing (Whipple and Tucker, 1999; Kirby and Whipple, 2012). Along-channel changes in lithology, climate, uplift rate, or sediment supply via landslides generate sharp breaks (knickpoints) in the profile, separating segments with different steepness and concavity; similarly, temporal changes in uplift rate produce transient knickpoints at the basin outlet that propagate upstream as an incisional wave, separating the newly equilibrated lower reaches from upper reaches equilibrated with previous conditions (Seidl and Dietrich, 1992; Whipple and Tucker, 1999; Blum and Törnqvist, 2000; Schoenbohm et al., 2004; Walsh et al., 2012). However, in isolation, longitudinal river profile analysis cannot explicitly distinguish the relative effects of tectonics, lithology, climate and transient perturbations on profile form, but the incorporation of supporting information (e.g. tectonic, lithologic and climatic data) can help (Kirby and Whipple, 2012). In particular, the covariance of normalized channel steepness indices and ^{10}Be catchment mean erosion rates can distinguish lithologic and tectonic controls on channel steepness (Cyr et al., 2014). Together with a priori knowledge of the distribution of lithology and precipitation, integrated field and river profile analysis and measurements of erosion rate allow the evaluation of the dominant controls on landscape evolution.

Our results highlight the importance of lithologic contrasts and the presence of active faults in controlling both regional erosion rate patterns, and the specific geometry of the channel network. Although regional, persistent climate gradients seem to have little influence on the landscape at this scale, our work does demonstrate the potential impact of short-term climate variation on punctuated incision. We also identify previously unmapped faults in the Pucará Valley, interpreting these in the context of the pattern of migration of deformation through the Eastern Cordillera.

2 Geologic Setting

2.1 Structural Evolution

The southern Eastern Cordillera is a bi-vergent fold and thrust belt, characterized by basement-involved reverse faults that preferentially occur along preexisting structural heterogeneities, including inverted Cretaceous rift structures and earlier metamorphic fabrics (Grier et al., 1991; Strecker et al., 2007; Carrera and Munoz, 2008; Santimano and Riller, 2012). Basement uplifts are composed of Precambrian metasedimentary units, Paleozoic granitoids, and sedimentary rocks related to the Cretaceous Salta Rift (Grier et al., 1991; Coutand et al., 2006). Deposition of Cenozoic sedimentary rocks in intramontane basins within the CRC reflects eastward propagation of the orogenic front from late Eocene to Pliocene (Coutand et al., 2006; Carrapa et al., 2012). Pliocene to Quaternary deformation has been primarily accommodated by the Santa Barbara System to the east (Hilley and Strecker, 2005; Coutand et al., 2006; González

Bonorino and Abascal, 2012). Uplift of orographic barriers to precipitation produced a progressive onset of aridity in basins from west to east (e.g., Coutand et al., 2006; Bywater-Reyes et al., 2010; Carrapa et al., 2012; Pingel et al., 2014; 2018; Guzman et al., 2017).

The Pucará Valley, like other intramontane basins in the CRC, is defined by N-S trending contractional structures (Figure 2). On the west, the Jasimaná–Vallecito Thrust, an inverted Cretaceous normal fault, carries sedimentary rocks of the Cretaceous rift-related Pirgua Group redbeds over Holocene sediments (Coutand et al., 2006). On the east, the Sierra de Quilmes Thrust carries Precambrian basement, mostly Neoproterozoic Puncoviscana Formation, over Pirgua Group strata (Carrera and Munoz, 2008). Pirgua Group rocks are overlain unconformably by Tertiary Payogastilla Group clastics, which underlie the central Pucará Valley. Cenozoic strata of the Pucará Valley record the evolution from a distal to proximal foredeep from the Late Eocene to Middle Miocene (Carrapa et al., 2012). Eastward propagation of deformation led to the development of a wedge-top basin from approximately 14-10 Ma, and further shortening of the wedge-top after 10 Ma led to the development of the modern intramontane physiography (Coutand et al., 2006; Carrera and Munoz, 2008; Carrapa et al., 2012).

2.2 Quaternary Climate & Geomorphology

The CRC is characterized by an arid, intramontane climate, reflecting the effects of significant orographic barriers to precipitation and highly seasonal rainfall. Mean annual precipitation in the CRC is <250 mm yr^{-1}, but most rainfall occurs in the austral summer, when a seasonal low-pressure system brings humid northeasterly and easterly winds to the region (Bianchi and Yañez, 1992; Bookhagen and Strecker, 2008). Interannual variability in precipitation is significant (±75%), and driven primarily by ENSO and the Tropical Atlantic Sea-surface Temperature Variability (TAV) (Trauth et al., 2003a). Cooler and more humid periods occurred throughout the Quaternary (Bobst et al., 2001; Fritz et al., 2004), increasing landslide-frequency (Trauth et al., 2003b), expanding glacial (Haselton et al., 2002; D'Arcy et al., 2019) and periglacial (May and Soler, 2010) zones, and increasing overall catchment erosional efficiency (Bookhagen and Strecker, 2012). Glacial advances are linked to summer insolation when the South American Summer Monsoon is strongest, with local advances at ~44 ka in the Sierra de Quilmes (Zech et al., 2017) and ~40 ka in the Sierra Aconquija (D'Arcy et al., 2019).

The geomorphology of the CRC and nearby regions reflects an arid, highly seasonal climate, active tectonics, and relief >1000 m in intramontane basins. It presents a mix of detachment limited channels in uplifted bedrock ranges along transverse rivers in the majority of the landscape, but with transport limited channels in region of thicker alluvial fill along longitudinal rivers. Abundant pediment surfaces and alluvial fans throughout the CRC are incised by modern channels. For example, in the Pucará Valley, incision and base-level lowering of ~100 m have led to the abandonment of a sequence of pediments and strath terraces. Similar evidence for Quaternary incision is well documented in the Sierras Pampeanas and Santa Barbara System (Strecker et al., 1989; Hilley and Strecker, 2005; González Bonorino and Abascal, 2012). Pedogenesis is weak, and soils are dominated by carbonate (May and Soler, 2010; this study). Periglacial processes are restricted to areas over 4500 m elevation, but this limit may have been depressed by as much as 900 m during the Pleistocene, as evidenced by broad convex range crests and moraines in the Sierra de Quilmes and northwestern CRC (Haselton et al., 2002).

3 Methods

3.1 Field Studies

Field studies were focused in the lower Pucará Valley with the goal of characterizing neotectonic structures and Quaternary landscape evolution. We conducted structural and geomorphic mapping of the valley on aerial photography and ASTER 30 m digital topography. Geology was compiled from existing maps by Carrera and Muñoz (2008) and Coutand et al. (2006). We use Trimble differential GPS equipment with <10 cm vertical and ~1 cm horizontal precision to measure ~40 pediment profiles (see Supporting Information Figure S13 for locations and S14 for examples). Additionally, we described soils at 13 sites within the valley at various pediment levels, according to USDA soil taxonomy guidelines (Staff, 2010). Descriptions are solely morphological, and geochemical classification metrics (e.g. weight percent $CaCO_3$) are inferred. Reported stages of pedogenic carbonate and gypsum accumulation follow the morphological classification scheme of Gile et al. (1966). We determined desert pavement indices (PDI) according to methods developed by Al-Farraj and Harvey (2000). See Supporting Information Text S1 and Table S1 for detailed description of classification and PDI methodology. Finally, we collected five samples of modern detrital sand for determining

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catchment mean erosion rates, and collected 5 samples of sand from each of three depth profiles for determining the ages of the Q2, Q5, and Q6 terraces surfaces; details on sampling methods are described in sections 3.3.2 and 3.3.3 respectively.

3.2 Longitudinal River Profile Analysis

We rely on digital topographic data and coupled ArcGIS and Matlab scripts to derive normalized channel steepness indices (k_{sn}) and concavity indices (θ) (http://geomorphtools.geology.isu.edu/). Channel steepness index is a measure of channel gradient adjusted for upstream drainage area, a proxy for discharge in the case of uniform precipitation, and concavity index is a measure of the concavity or convexity of the channel (Whipple and Tucker, 2002). To find these values for each channel, following methods outlined by Wobus et al. (2006a), we extracted channel topographic data from 30 m ASTER topography (NASA), removed data irregularities, smoothed channel data along a 450 m moving average window, determined local slopes over a 10 m vertical interval, and set a minimum drainage area of 3000 pixels, or ~2.7 km^2. These parameters balance our desires to preserve channel topographic complexity, remove artifacts in digital topographic data associated with high relief landscapes, and exclude channel headwaters that are dominated by debris-flow processes (Wobus et al., 2006a). Channel steepness and concavity indices are determined by linear regression of local channel slope and drainage area after log transformation. We normalize steepness indices to a reference concavity of 0.45, following empirical and theoretical predictions for detachment limited systems (Whipple and Tucker, 2002).

We identify individual segments along a profile by the occurrence of major knickpoints (i.e., readily apparent in both the longitudinal profile and the slope-area plot) or downstream confluences with larger trunk streams, and regress the data from each segment to derive normalized channel steepness index and concavity. Considering the large scale of our analysis, we selected knickpoints that are conspicuous in log-slope/log-area plots and in topographic profiles. We classify knickpoints according to morphology: slope-break knickpoints, vertical step knickpoints, the base of a convex reach, and the top of a convex reach (see Kirby and Whipple, 2012). We also classify knickpoints genetically, based on their spatial coincidence with significant tectonic (e.g., faults) and/or lithologic boundaries (e.g., transition from crystalline basement to Tertiary sedimentary rock), giving rise to four knickpoint types: lithologic, tectonic, lithotectonic (arising from lithologic boundaries coincident with faults), and undefined. We specifically focus on slope-break and undefined knickpoints, because they may represent transient channel responses to an external forcing such as changes in climate or tectonic uplift rate (e.g. Harkins et al., 2007).

3.3 Terrestrial Cosmogenic Nuclide (^{10}Be) Chronology

3.3.1 Analytical Procedures

In this study we isolate and analyze *in situ* produced cosmogenic ^{10}Be in quartz to determine catchment mean erosion rates and date stable geomorphic surfaces. Samples were processed at the University of Vermont Cosmogenic Nuclide Laboratory using standard analytical methods (Corbett et al., 2016; see also Supporting Information Text S2 and Table S8 and www.uvm.edu/cosmolab for detailed methodology and data). First, quartz was purified for ^{10}Be analysis using mineral separation procedures modified from Kohl and Nishiizumi (1992). For Beryllium isolation, samples were prepared in batches that contained a full-process blank and 11 unknowns including the CRONUS N standard. We used between 11.6 and 23.0 g of purified quartz for analysis. We added ~250 µg of ^{9}Be carrier made from beryl at the University of Vermont to each sample. After isolation, Be was precipitated at pH 8 as hydroxide gel, dried, ignited to produce BeO, ground and mixed with Nb powder at 1:1 molar ratio, and packed into copper cathodes for accelerator mass spectrometry (AMS) measurements.

$^{10}Be/^{9}Be$ ratios were measured at the Scottish University Environmental Research Center (see Xu et al., 2010 for methods) and were normalized to NIST standard with an assumed ratio of $2.79 \cdot 10^{-15}$ based on a half life of 1.36 My (Nishiizumi et al., 2007). The average measured sample ratio ($^{10}Be/^{9}Be$) was 947×10^{-15} and AMS measurement precisions, including blank corrections propagated quadratically, averaged 1.9 %. The blank correction is an inconsequential part of most measured isotopic ratios (<0.7% on average, maximum 2.0%). The CRONUS N standard was run with these samples and returned a concentration of $2.31 \pm 0.06 \times 10^{5}$ atoms g^{-1}, consistent with values reported by other labs (Jull et al., 2014).

3.3.2 ^{10}Be Catchment Mean Erosion Rates

We contribute five new ^{10}Be-derived catchment mean denudation rates from the Pucará River catchment and its subcatchments (see Figure 3 for locations of samples BW1, 2, 3, 5, and

6). Detrital samples sieved to a grain size of 250 to 850 µm were collected from bars within active streams. For each sample, we determined the contributing drainage area using ArcGIS, and ^{10}Be production rates were calculated for each pixel of the DEM within the catchment at 250 m resolution. Our calculation incorporates elevation, shielding, and muonogenic production for each pixel, but relies on mean latitude for each catchment and assumes a constant production rate with time. We estimate a 10% uncertainty associated with our scaling method. We follow the scaling scheme of Lal (1991) and a sea-level high-altitude total surface production rate of 3.96 +/- 0.204 atoms g^{-1} yr^{-1} after the local HUANCANE2A Calibration data set (Borchers et al., 2015). We calculate erosion rates using a sample density of 2.6 g cm^{-3} and an attenuation length of 160 g cm^{-2} (von Blanckenburg, 2005). The uncertainties which accompany our reported erosion rates reflect the uncertainties in both AMS measurements and catchment mean production rates (see Supporting Information Text S3 for MATLAB code used in calculation). Major lithologies in the CRC are quartz rich (Sparks et al., 1985; Francis et al., 1989; Do Campo and Guevara, 2005; Marquillas et al., 2005; Coutand et al., 2006), so we make no corrections for variably distributed quartz.

In addition to our own samples, we re-analyze seven previously published catchment mean erosion rates in the CRC (Bookhagen and Strecker, 2012). Using reported sample locations and nuclide concentrations, we recalculate production rates and erosion rates using the same methods as for our own samples. We find that recalculated and reported values differ by <15%, inflated because of our use of an updated production rate (see Supporting Information Table S3). Similarly, calculating mean erosion rate with the CRONUS calculator, using mean latitude and elevation rather than considering each pixel of the DEM, produces erosion rates that differ from our results by <3% (see Supporting Information Table S3; Balco et al., 2008). For sampled catchments that contain sampled subcatchments (e.g., BW5 and M2), we calculate the differential erosion rate by area-weighting erosion rates from the contributing subcatchments (Granger et al., 1996).

3.3.3 ^{10}Be Depth Profiles

To date pediment surfaces, we hand-excavated 2 m deep pits for cosmogenic nuclide (^{10}Be) depth profiles at three locations (Figure 2). Soil pits were dug at geomorphically stable sites with minimal field evidence for erosion, bioturbation, or complex shielding histories.

However, the absence of bar and swale topography, the presence of Av horizons, and the heavily dissected nature of the pediment surfaces throughout the valley collectively suggest some surface change at all sites. We sampled ~1 kg of sand-sized grains in ~5 cm thick horizons at 0, 50, 100, 150, and 200 cm depths, across the width of the pit. All samples were field-sieved to remove the < 250 µm fractions, which made up approximately <25% of the total soil mass. We also collected 100 surface clasts from one site (Q6, sample AR13-03), extracting equal mass from each clast to combine into an amalgamated sample.

To determine a range and central tendency of surface exposure age, ^{10}Be inheritance from exposure prior to deposition, and post-deposition erosion rate for each depth profile, we employ the Monte Carlo simulator developed by Hidy et al. (2010) (version 1.2). Results are from 10^6 successful profile simulations and we report 2σ uncertainties, based on model parameters (see Supporting Information Figures S4-12 and Table S2). Although average AMS uncertainty for the data set was <2%, we assigned nuclide concentration uncertainties of 5% for all depth-profile samples, to reflect errors in sampling (e.g., sample depth and thickness), laboratory analysis (e.g., carrier and massing errors), geomorphic variability (e.g., bioturbation/cryoturbation, shielding variations), and also systematic errors (e.g., temporal variation in cosmic ray flux and scaling uncertainty) (Gosse and Phillips, 2001). Model inputs of density and associated uncertainties are based on previous field determinations in similar soil types with similar ranges of carbonate and gypsum development (Reheis, 1987; Reheis et al., 1995; Hidy et al., 2010). Soils information and terrace surface morphology were used to constrain the erosion threshold (endmember values of net surface erosion and aggradation). Specifically, the thickness of the Av horizon was used as a maximum value for net aggradation, and maximum net erosion was determined from the estimated relief of the initial bar-and-swale topography (~30 cm) and from a conservative erosion estimate derived from depth and thickness anomalies in the B horizon (if present). Finally, because the modeled exposure age depends on a time-averaged surface erosion rate, the resulting abandonment age is not very sensitive to an intermittent period of enhanced surface erosion and the age should still be adequately captured within the modeled error. The exception to this would be if there was a rapid stripping event that mostly or completely reset the ^{10}Be accumulation signal. However, because of the preservation of a broad, flat, and undissected surface morphology on the terrace treads, we consider this scenario unlikely.

3.3.4 Paleo-Erosion Rates

Meaningful, representative measurement of paleo-erosion rates is complicated by the incompleteness of the record, potential non-equilibration of samples to a changing climate, the limited resolution of sampling, and the dependence of incision rate on the measurement interval (Finnegan et al., 2014; Mason and Romans, 2018). However, as we are able to calculate erosion and incision rate in a number of ways from our data set, we seek to make what cautious inferences we can about Quaternary climate changes and erosion rates in the CRC. We calculate paleo-erosion rate in two ways.

First, we use inheritance values for each depth-profile to calculate catchment mean paleo-erosion rates; the inherited component of the profile is equivalent to the catchment mean erosion rate of the paleo-catchment at the time the pediment-capping sediments were deposited. We calculate catchment mean ^{10}Be production rates via the methods described in section 3.3.2, defining paleo-drainage basins by the contributing area upstream of the sample location in the modern topography. We find no evidence for stream captures or major drainage reorganization in the Pucará River catchment, suggesting that the use of modern topography is reasonable. For each depth profile, we calculate ^{10}Be concentrations of a “paleo-sample” using the Bayesian most probable solution for inheritance, corrected for radioactive decay of ^{10}Be (using the profile-derived depositional age). We report erosion rates for each profile by propagating 2σ uncertainties for both inheritance and depositional age. Note that these erosion rates will only reflect conditions prevailing during deposition of the gravel caps topping surfaces within the Pucará Valley.

Second, we also calculate vertical incision rates for the Pucará River by using the age of our three dated surfaces and their height above the modern river. For age, we use the Bayesian most probable ages for each depth-profile with 2σ uncertainties. We estimate vertical incision as the difference in elevation between the modern Pucará River floodplain and each dated surface, projecting the surface to the modern floodplain using a reference slope of 3.5° perpendicular to the modern channel. The reference slope reflects the results of a best fit to differential GPS surveys we conducted across pediments and strath terraces in the Pucará Valley. We do not explicitly calculate uncertainty for vertical incision because it is negligible compared to the uncertainty in the profile age. Note that non-steady-state behavior may lead these measurements

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to be biased by measurement interval, with shorter measurement interval biased towards higher incision rate estimates (e.g., Finnegan et al., 2014).

4 Results

4.1 Field Studies

The semi-arid Pucará Valley contains seven abandoned and incised geomorphic surfaces (Q1 – Q7, youngest to oldest) from 5 m to ~100 m above modern base-level (Figure 4). These abandoned pediments and thinly mantled strath terraces dominate the landscape. We find no evidence for significant depositional intervals as is common in other regional basins (e.g., Strecker et al., 2009; Schoenbohm et al., 2015), indicating that the valley has experienced pulsed incision throughout the late Quaternary. Structural mapping reveals a series of blind and emergent thrusts on the east side of the valley, active in the Quaternary (Figure 2). The Pucará Thrust offsets Q3 surfaces, although differential GPS transects across the fault measure vertical displacement <1 m (see Supporting Information Figure S13 and S14). In the southern end of the Pucará Valley (Figure 2), we observe heavily dissected surfaces, steep rivers, and deeply incised canyons spatially coincident with a N-S striking monocline, suggesting Quaternary activity along a blind thrust. However, additional differential GPS transects (see Supporting Information Figure S14) of pediment surfaces between these two areas do not reveal any clear signal of deformation (e.g. tilting, oversteepening), suggesting that late Quaternary deformation within the lower Pucará Valley is of relatively low magnitude, or is distributed broadly, making it difficult to detect and constrain.

Soils in the study area classify broadly as aridisols, and range from Ustic Haplocambids on modern surfaces to Ustic Haplocalcids, Ustic Petrocalcids, Leptic Haplogypsids, and Ustic Petrogypsids on the abandoned surfaces (Table 1). The differences between these soil taxons reflect differing degrees of pedogenic accumulation of either carbonate or gypsum. Carbonate and gypsum reach stage III and incipient stage IV morphology on the highest (Q6 – Q3) surfaces, do not exceed Stage II on lower (Q2 – Q1) surfaces, and exhibit minimal carbonate accumulation on modern surfaces (Figure 5). Similarly, desert pavements exhibit greater development on the oldest surfaces, although the differences are minimal, likely because of the effects of vegetation, surface erosion, and human modification..

4.2 River Profile Analysis

We analyzed 77 streams in the Calchaquí River catchment, giving rise to 147 separately regressed segments, separated by 75 knickpoints (Figures 6 and S15). Normalized steepness indices range from 28 to >1000, with a mean steepness index of 175 (Figure 6b). Mean concavity index is 0.9, with a maximum of 28 and minimum values <0 (i.e., convex) (Figure 6c). The main stem of the Calchaquí River is generally well-graded, with average steepness index and concavity changing from 134 and 0.53 respectively downstream of a knickpoint, to 151 and 0.34 above it in the restricted northern part of the basin.

The highest steepness indices occur in a narrow band within and between the high crystalline ranges in the western half of the study area (Figure 6b). These steep segments vary greatly in morphology; some are small tributaries to the Calchaquí River, oriented perpendicular to the structural grain and within crystalline bedrock (e.g. smaller tributaries to the trunk stream in STR13 on Figure 3). Some steep segments are parallel to the structural grain, incising sedimentary rocks in valleys bound by thrust faults (e.g. STR11 on Figure 3), while others represent a combination of those two morphologies (e.g. STR16 on Figure 3). A common feature of all steep segments (and the corresponding catchments) is that they cross one or more approximately N-striking thrust faults within the high Eastern Cordillera (Figure 6a). The lowest steepness indices are generally observed in the eastern part of the catchment along small tributaries to the Calchaquí River (Figure 6b). Many of these tributaries are segmented, with knickpoints and convexities coincident with the Cerro Negro Thrust and other west-vergent thrust faults (Figure 6a). We also observe low normalized steepness indices in the southwestern CRC. These segments are typically bound by prominent lithotectonic or lithologic kickpoints (Figure 6b; S67, S65, and S1 in Figure 7) coincident with three prominent NW striking lineaments.

Concavity indices follow an overall similar pattern to steepness indices. Concavity index is high along streams in the west and southwest parts of the study area, and is highest immediately below knickpoints (e.g., S67 and S65 in Figure 6c). Negative steepness values are found throughout the basin, including the prominent convex segment in the south (along S1 in Figure 6c). A cluster of highly concave or convex river segments is located on tributaries north of the Calchaquí River before it exits the study area.

Morphologically, we classified 27 knickpoints as vertical-step knickpoints, 10 as slope-break knickpoints, and the remaining 38 as high and low bounds on convex channel reaches (Kirby and Whipple, 2012). From a genetic standpoint we classified 9 knickpoints as lithologic, 32 as tectonic, 26 as lithotectonic, and 8 as undefined (Figure 6b). We find no clear correlation between knickpoint morphology and knickpoint genesis, and note that no undefined knickpoints also have a slope-break morphology. See Supporting Information Figures S16-93 and Tables S4 and S5 for stream profile figures, stream profile regression data, and knickpoint data.

Three new faults in the southwestern part of the CRC are identified using multiple lines of evidence (dashed lines in Figure 6). These features are marked in the DEM and satellite imagery by sharp linear traces observed to offset bedrock and Quaternary deposits. They also align with knickpoints, generally separating regions of low steepness and normal concavity upstream (to the west) from high steepness and high concavity below.

4.3 ^{10}Be Catchment Mean Erosion Rates

Catchment mean erosion rates range from 22.5 ± 2.6 mm kyr^{-1} to 121.9 ± 13.7 mm kyr^{-1} (Table 2), indicating that the apparent age of the sampled catchments range from 5 – 27 kyr, where apparent age is the time period averaged by the analyzed sediment, calculated by dividing the absorption depth scale of 615 mm by erosion rate (von Blanckenburg, 2005). Erosion rates do not correlate significantly with catchment mean annual precipitation, catchment area, or catchment mean elevation, but show a modest correlation with catchment mean slope (Table 2). Comparing catchment mean erosion rates with lithology (Figures 3 and 6a) reveals that catchments dominated by resistant lithologies (e.g. crystalline bedrock) exhibit some of the highest (e.g. STR13) and lowest (e.g. BW3) erosion rates in the study.

4.4 ^{10}Be Depth Profiles

At all three sites, surface samples exhibit low ^{10}Be concentrations compared to depth-profile attenuation curves (Figure 8). Previous work suggests that low surface concentrations reflect bioturbation or deposition of younger material (Hidy et al., 2010). Further, our field studies (see profile descriptions below) reveal a complex near-surface history of erosion (e.g., unusually shallow Bkk horizons, lowering of bar and swale surface relief) and aggradation (e.g. vesicular A horizons). Given particularly the evidence for aggradation, which means that surface samples have not been fixed in depth with respect to the rest of the profile, we exclude the surface sand and amalgamated clast samples from our depth-profile simulations, significantly increasing the range of solutions (the uncertainty), but allowing better fits of the data at depth. The depth-profile simulator yields Bayesian ages and 2σ uncertainties of 43.6 $^{+15.0}/_{-11.6}$ ka, 91.2 $^{+54.2}/_{-22.2}$ ka, and 151 $^{+92.7}/_{-34.1}$ ka for our Q2, Q5, and Q6 surfaces, respectively, therefore agreeing with geomorphic relative-age constraints including stratigraphic position, soil development, and desert pavement development (Table 1). Additionally, simple calculations using the formulations of Anderson et al. (1996), which assume no surface erosion or deposition, yield ages of 50.2 ka, 103 ka, and 169 ka, in close agreement with the Bayesian ages, suggesting that the age signal is robust. See Supporting Information Figures S1-12 for annotated pit photos, model input parameters, and frequency histograms for age, inheritance, and surface erosion rate for each depth profile.

4.4.1 Q2 Surface (Profile AR13-01)

Depth profile AR13-01 is located on a Q2 strath terrace (Figure 2), consisting of ~4 m of channel sands and lag deposits that lie in angular unconformity over Miocene age sedimentary rock (Angastaco Fm.). The soil consists of coarse desert pavement, underlain by a 7 cm thick vesicular A horizon (Av), which is underlain by a Bk horizon that diffusely transitions to a C horizon at ~75 cm depth. The 7 cm Av horizon could indicate aggradation, which we account for in our model simulations by allowing for a negative total erosion threshold (See Supporting Information Figure S4). We find only minor field evidence for bioturbation at this site, but the weak stratification and uniformity of the soil framework grains makes identification of vertical mixing difficult. Model simulations yield a most probable age of 43.6 ka and a most probable surface erosion rate of 3.9 mm ka^{-1}, suggesting that ~22 cm of erosion has occurred at this site, within the “total erosion threshold” of -7 to 30 cm that we specified in the depth profile simulator.

4.4.2 Q5 Surface (Profile AR13-02)

AR13-02 is located on a Q5 fluvial strath terrace (Figure 2) sourced dominantly from Paleozoic granitoids and Tertiary volcanic lithologies southwest of the Pucará valley. This deposit consists of couplets of fine and coarse grained layers, similar to Q2 (AR13-01), but the sedimentology is partially obscured by significant carbonate accumulation. The soil consists of a pavement layer over a shallow, weakly developed, 10-cm thick Av horizon over a massive and root-limiting 20 cm thick Bkk horizon over a Bk horizon which transitions to a C horizon at ~150 cm depth. The shallow depth to the Bkk horizon (10 cm) suggests that >20 cm erosion of the surface has occurred (Royer, 1999), while the Av horizon suggests up to 10 cm of surface inflation. This geomorphic conundrum forces us to input a wide range (-10 – 90 cm) for the "total erosion threshold" parameter (See Supporting Information Figure S7). We report a most probable age of 91.2 ka and a most probable surface erosion rate of 5.5 mm kyr^{-1}, which yield an erosion estimate of ~57 cm, consistent with surface degradation at this site.

4.4.3 Q6 Surface (Profile AR13-03)

AR13-03 is located on a Q6 pediment surface (Figure 2) and is notable for its coarse sediment and pedogenic gypsum content. The lower portion of the alluvial deposit (>50 cm depth) is a clast-supported pebble to cobble conglomerate, with moderate internal stratification and moderate sorting within individual strata, suggesting deposition by sheetflood processes (Blair and McPherson, 1994). The upper part of the pit, a matrix-supported, poorly sorted conglomerate with no internal stratification, appears to be a storm deposit that scoured a channel into the existing alluvial surface. We argue that this storm deposit is most likely of similar depositional age to the underlying material, given similar degrees of soil development. The soil consists of a 10 cm thick Av horizon over a 20 cm thick Byy horizon over a Byk horizon that transitions to a C horizon at ~130 cm depth. Similar to Q5 (AR13-02), we place large bounds on the "total erosion threshold" parameter for AR13-03 (See Supporting Information Figure S10). Depth profile simulations yield a most probable age of 151 ka and a most probable erosion rate of 2.8 mm kyr^{-1}, suggesting that ~47 cm of erosion has occurred on this surface.

4.5 Paleo-Erosion Rates

Vertical incision estimates based on the projected height above the river for the Q2, Q5, and Q6 depth profiles are 11, 70, and 76 m, respectively, yielding vertical incision rates of 252 $^{+87}/_{-67}$ mm ka^{-1} since ~44 ka, 768 $^{+456}/_{-187}$ mm ka^{-1} since ~91 ka, and 503 $^{+309}/_{-114}$ mm ka^{-1} since ~151 ka when most probable ages and 2σ uncertainties are used (Table 3). We do not observe slower incision rates over longer time intervals, as has been noted in other studies (e.g., Finnegan et al., 2014).

Catchment mean paleo-erosion rates derived from most probable inheritance values of the three profiles are 105 $^{+60}/_{-33}$ mm ka^{-1} at ~44 ka, 56 $^{+43}/_{-19}$ mm ka^{-1} at ~91 ka, and 67 $^{+600}/_{-34}$ mm kyr^{-1} at ~151 ka (2σ) respectively (Table 3). The high positive uncertainty associated with the catchment mean paleo-erosion rate for the Q6 surface (AR13-03) reflects an extremely low 2σ solution for inheritance.

Vertical incision rates are higher than catchment mean paleo-erosion rates at each site (Table 3). The inferred paleo-drainage for the Q2 depth profile (AR13-01) reaches the edge of the Puna Plateau. At this site, best-fit values suggest that the vertical incision rate is ~2.4 times higher than the catchment mean paleo-erosion rate. The paleo-drainage for the Q5 depth profile (AR13-02) is nearly identical in extent to catchment BW3, and yields a vertical incision rate ~14 times the catchment mean paleo-erosion rate at this site. The paleo-drainage for the Q6 depth profile (AR13-03) is a local tributary to the Pucará River, similar to the modern BW1 catchment. The best fit vertical incision rate is ~7.5 times higher than the catchment mean paleo-erosion rate at this site. The large discrepancies between vertical incision rates and catchment mean paleo-erosion rates at all three sites could indicate that, since the formation of these pediments, channels within the lower Pucará Valley have lowered more rapidly than the landscape as a whole, although this interpretation is complicated by an incomplete record, climate change at a frequency too high to be detected by our data, and inconsistent measurement intervals.

5 Discussion

Here we interpret our results with respect to the distribution of lithology, faults, and precipitation in the CRC, testing our hypothesis that in contrast to previous regional scale work that found climate to exert the dominant influence on erosion rates and landscape evolution in this part of the Andes (Bookhagen and Strecker, 2012), at the smaller spatial scale of the Calchaquí River Catchment, with relatively uniform modern precipitation, tectonics and lithology will prevail. We find that the spatial distribution of steepness indices and catchment mean erosion rates indicate strong lithologic and tectonic control on erosion and topography throughout the catchment. If a combination of high steepness indices and high erosion rates can be taken to indicate sustained high tectonic uplift rates, then we also find evidence for active tectonics, particularly in the western CRC. The distribution of relatively high concavity indices also supports active faulting, as does our analysis of knickpoints. Paleo-erosion rates indicate uplift across major faults in the CRC and are similar to modern rates, possibly implying long-term continuity in erosion. In contrast, vertical incision rates are higher than basin scale erosion rates, potentially pointing to transient landscape adjustment or variable lithologic resistance. Lastly, we consider the tectonic implications of out-of-sequence deformation in the retroarc foreland.

5.1 Local-scale Controls on River Morphology within the Calchaquí River Catchment

5.1.1 Channel Steepness and Erosion Rate

In the eastern part of the catchment, normalized steepness indices are controlled, at least in part, by lithology. For example, in catchment M2, where less resistant sedimentary rocks and Quaternary alluvium dominate (Figures 3 and 6a), we observe low steepness indices (<200; Figure 6b), but a high catchment erosion rate (100 ± 11 mm kyr^{-1}; Figure 3). STR3, a small eastern catchment that has its headwaters in more resistant crystalline rock (Figure 6a), has a similarly low steepness index (Figure 6b), but a significantly lower erosion rate than M2 (34 ± 4 mm kyr^{-1}; Figure 3). The variation of erosion rate with lithology and the relatively low steepness indices indicate that erosion rates in the eastern CRC are therefore strongly influenced by lithologic resistance.

In the western CRC, high steepness values and variable erosion rates are measured in crystalline rocks within the ranges bordering the plateau. The differing erosion rates despite relatively uniform lithology suggest that in the western CRC, spatially variable uplift may instead strongly control erosion rate. For example, tributaries to the Calchaquí (STR13) and Luracatao (STR11) rivers, which principally travel over crystalline bedrock, exhibit high (>200) steepness values (Figure 6b), and the catchments erode at a high rate (121 ± 14 mm kyr^{-1} and 82 ± 9 mm kyr^{-1} respectively; Figure 3), suggesting that uplift rates are higher here than in other parts of the CRC with similar lithology (e.g. catchment STR3).

In contrast, we measure low erosion rates (<30 mm kyr^{-1}) in catchments BW2 and BW3 (Figure 3). In these two catchments, low steepness indices occur above and to the west of prominent lithotectonic knickpoints that coincide with two major NNW striking lineaments; we also observe small, ponded Quaternary basins to the west of these lineaments (Figure 6a and b).

Below and to the east of these knickpoints we observe steep segments with anomalously high concavity indices (see below for discussion of channel concavities). These observations suggest that BW2 and BW3 exhibit such low erosion rates because in each catchment the majority of the drainage area lies above two major NNW-SSE striking faults that separate areas of low and high uplift rates. The western of these two structures was previously mapped along its southern end within BW2, BW3, and part of BW5 (Schoenbohm and Strecker, 2009), but is obscured to the north by Tertiary ignimbrites. However, we use knickpoint distribution and form, dividing two zones of differing uplift rate, to trace it to the north (dashed lines in Figure 6). We suspect that the upper reaches of catchment BW5 (e.g. S67; Figure 7), would exhibit similarly low catchment mean erosion rates if sampled at or above the prominent lithotectonic knickpoints along the fault. Catchment STR16 also records a low catchment mean erosion rate, which suggests tectonic isolation similar to catchments BW2 and BW3 above a third major lineament we identified, this time striking NNE-SSW (Figure 6). The dip of these faults is unknown, but they all have an up to the east sense of displacement based on our analysis of catchment erosion rate and channel concavity; they could be west-dipping normal faults related to gravitational spreading, as inferred by Schoenbohm and Strecker (2009), or they could be east-dipping thrust faults, similar to other mapped structures in the lower Pucará Valley.

In contrast to the dominant tectonic and lithologic controls, climate likely only exerts minor control on channel steepness in the CRC. Bookhagen and Strecker (2012) demonstrated that correcting for the effect of spatially variable precipitation derived from TRMM satellite data on discharge significantly influences the distribution of specific stream power, related to channel slope, on the regional scale. However, climatic corrections would not significantly affect our interpretations at the smaller scale of the Pucará basin; precipitation is relatively uniform across the CRC compared to the steep precipitation gradient across their broader study region (Bookhagen and Strecker, 2012). We find that our systematic investigation of river profiles, which uses a significantly shorter channel-smoothing window (450 m vs. 5 km used in Bookhagen and Strecker, 2012), allows for analysis of more spatially discrete (e.g. lithologic and tectonic) controls on channel morphology.

5.1.2 Concavity Indices and Non-Uniform River Profile Morphology

A key assumption in tectonic interpretations of normalized steepness indices in bedrock channels is that lithology, climate, and uplift rate are uniform along a given channel reach, and that abrupt changes are marked by knickpoints. When this is true, concavity indices typically fall into a relatively narrow range (0.4 – 0.7) (Kirby and Whipple, 2012). However, when uplift or climate gradients exist, concavity indices can vary widely (Whipple, 2004). In addition, in gravel-bedded alluvial channels, higher uplift rate (or base-level lowering) results in lower concavity, and vice versa (Wickert and Schildgen, 2019). Our results for all streams (n = 147) yield a high mean concavity of 0.9 which rises further to >2 when we exclude convex segments (e.g. $\theta < 0$) (Figure 6c). Here, we address the spatial distribution of concavity indices in the CRC, and the factors promoting such high channel concavities.

The Calchaquí River itself displays a well-graded profile (S4, Figure 7), except for a small change across a vertical step knickpoint within a restricted part of the basin in the north. The lower segment exhibits a concavity index within the expected range for river profiles in tectonically active orogens (0.53), while the upper segment has a slightly low concavity index (0.34), likely reflecting the influence of debris-flows and/or high sediment flux in the upper most part of the catchment (Whipple, 2004). The Calchaquí River flows through and actively incises sedimentary rock and Quaternary alluvium, and also crosses the Cerro Negro Thrust, but we note no major breaks across lithologic or tectonic boundaries. The narrow range of concavity and the well graded profile suggests that the Calchaquí River is equilibrated to the prevailing climatic and tectonic conditions and thus is in steady-state (Whipple et al., 2013).

Many small tributaries to the Calchaquí River have concavities between 0.3 and 2, within the normal range of incising rivers (Figure 6c). Low concavities (<0.4) likely reflect the effects of debris-flow processes and incision thresholds, especially for smaller catchments which undergo periglacial processes in their headwaters. Higher concavities ($0.7<\theta<2$) likely reflect downstream reductions in both lithologic resistance and uplift rate, as well as transitions to alluvial conditions at the range front (Whipple, 2004 and references therein). In the CRC all three of these conditions are common, as rivers typically originate in fault-bounded crystalline ranges that are bordered by Tertiary-Quaternary intramontane basins.

Extreme concavities (>2) occur along segments that are in the hanging walls of major thrust faults, just downstream of lithotectonic knickpoints (Figure 6c). Downstream lithologic changes commonly occur along these segments; the transition from harder to softer rock could explain the high concavity (e.g., segment with θ = 3.9 in tributary S67, Figure 7). However, in some cases lithology is uniform (e.g. segment with θ = 23 in tributary S65; Figure 7), suggesting that the faults which bound these segments are active, and gradual downstream reductions in uplift rates drive the high concavities (Whipple, 2004). Although downstream increases in precipitation could also cause these extreme concavities, the magnitude of increase is likely too small (<500 mm yr^{-1}) to have a significant effect (Figure 6c; Schlunegger et al., 2011; Bookhagen and Strecker, 2012). Although most transverse rivers in the CRC are detachment limited, ponding of sediment means that rivers transition for short segments to alluvial; these transitions could potentially explain some of the concavity differences we observe as well (Wickert and Schildgen, 2019).

Channel convexities ($\theta<0$) are also closely associated with tectonic features in the CRC (Figure 6c). In most cases channel convexities are short (<10 km) and occur across faults. However, some convex reaches are as long as 50 km, and tend to run sub-parallel or at low angles to faults in the study area (e.g. S1; Figure 7). Steepness indices are usually low above convex reaches and higher below, providing evidence that these convexities represent transitions from zones of low to high uplift rate (Whipple et al., 2013).

Overall we find that deviations from the expected range of concavity indices in erosive landscapes ($0.4<\theta<0.7$) can be reasonably well explained by the structurally controlled distribution of lithology in the CRC; resistant crystalline ranges, bounded by faults, are the headwaters for streams, and lower reaches flow through less resistant (and potentially more slowly uplifting) sedimentary rocks and alluvium, leading to high concavities. Channel convexities are associated with discrete tectonic features, and may separate regions of low and high uplift rate. In particular, we argue that deformation is most active in the western half of the CRC, along a narrow band of NNW-SSE striking reverse faults.

5.1.3 Knickpoint Genesis, Form, and Distribution

The majority of knickpoints (67 of 75) in the study area are spatially coincident with tectonic and/or lithologic discontinuities along channels, providing further evidence that channel morphology in the CRC primarily reflects structurally-controlled, lithologic heterogeneity. We identify 8 knickpoints of undefined genesis (i.e., not associated with discrete lithologic and/or tectonic discontinuities), which could reflect transient channel responses in a landscape.

However, none of these knickpoints are classified as slope-break knickpoints, nor are they at a uniform elevation, such as would be expected if they reflected a transient channel response. (e.g. Schoenbohm et al., 2004; Crosby and Whipple, 2006; Wobus et al., 2006b Harkins et al., 2007).

This approach also assumes detachment-limited conditions throughout channel reaches; in transport-limited erosional systems, transient responses are characterized by a gradual change in channel gradient along the entire reach, making transient and steady-state morphologies difficult to distinguish (Whipple and Tucker, 2002), in the absence of detailed field data (Hobley et al., 2011). Although our field observations support detachment-limited conditions along steep channel reaches in the CRC, transport-limited conditions are likely dominant in the intramontane Pucará Valley (evidenced by mixed bedrock-alluvial channel morphology and >3 m thick sedimentary cover on abandoned strath terraces) (Whipple and Tucker, 2002). Further, this approach assumes that concavity indices do not respond to rock uplift rates. Our analysis suggests that concavity indices in the CRC do indeed reflect changes in uplift rates, so the migration of transient knickpoints in our study area may not produce uniform elevations.

Given these complexities, we find little evidence for transience in our analysis of knickpoint distribution and form. Undefined knickpoints are observed across a wide range of elevations (Figure 9 and Table S11), and do not exhibit physical relationships that predict transient knickpoint behavior, such as the power law relationship between knickpoint contributing drainage area and knickpoint distance upstream of tributary mouths (i.e horizontal celerity) (Harkins et al., 2007). Nor is there a clear spatial (map-view) trend to the undefined knickpoints.

5.2 Controls on Landscape Evolution of the Pucará Valley

In the Pucará Valley, vertical incision rates are local measurements, recording incision since 44, 91, and 151 ka at sites Q2, Q5, and Q6 respectively, while catchment mean paleo-erosion rates integrate over much larger areas, and likely longer (<20 kyr) periods, recording incision at 44, 91, and 151 ka upstream of the same sites. As a result, discrepancies between vertical incision rates and paleo-erosion rates may reflect spatiotemporal variations in tectonic and climatic controls on erosion in different areas of the catchment, but interpretation will be complicated by differences in the integration time and how climatic variation is captured by each measurement.

Our analyses of the Q2 and Q5 depth profiles reveal that the lower Pucará Valley has vertical incision rates 2.4 to 13.7 times higher than catchment mean paleo-erosion rates (Table 3), suggesting that the lower Pucará Valley has eroded at a higher rate than its headwaters for the last 91 kyr (the age of the Q5 surface). We acknowledge the difficulty in comparing vertical incision and catchment mean denudation (Harkins et al., 2007), or interpreting each individually (Finnegan et al., 2014; Mason and Romans, 2018), but this observation is also supported by our analysis of modern denudation rates and channel steepness indices, which are lower in the headwaters and higher in the Pucará Valley (Figures 3 and 6b). The Q6 depth profile, excavated on a pediment surface derived from a smaller catchment area (5.8 km^2), provides a more local estimate of catchment-mean paleo-erosion rate than do the Q2 (2,064 km^2) and Q5 (345 km^2) depth profiles. Vertical incision and paleo-erosion rates may therefore be expected to agree. However, at this site, as at our other sites, best-fit vertical incision rate is significantly higher (7.5x) than catchment mean paleo-erosion rates, suggesting that non-steady state or dynamic equilibrium conditions characterize this landscape.

The correlations between relative landform age and degrees of pedogenic salt and pavement development indicate that arid or semi-arid conditions in the study area are long-lived and that past humid phases, at least locally, were not significant enough (>750 mm Mean Annual Precipitation) to cause major dissolution of soil carbonate or gypsum (Gile et al., 1966; Royer, 1999; Buck and Van Hoesen, 2002). Despite this observation of relative climatic stability, the sequence of heavily dissected pediments in the Pucará Valley indicates that periods of pediment formation are punctuated by potentially more vigorous erosional events. Observations from a nearby landslide-dammed paleo-lake that existed during the humid Minchin Phase (25 to 40 ka) (Bookhagen et al., 2001) yield catchment mean erosion rates an order of magnitude higher than modern rates in the CRC (Bookhagen and Strecker, 2012), similar to our finding of high, local paleo vertical incision rates. Bookhagen and Strecker (2012) argue that short-lived humid phases would result in vigorous erosional events on steep streams that were previously equilibrated to dry climates. In this complex geological landscape, with frequent transitions between detachment-limited and transport-limited conditions, topographic expression of such landscape transience would be muted. Further, ^{10}Be catchment mean erosion rates and paleo-erosion rates are averaged over 5 – 27 kyr timescales in this study, and thus may integrate across multiple

x

shorter duration (i.e., millennial-scale) climate phases, and thus may not capture punctuated incision (Bierman and Steig, 1996).

5.3 Tectonic Implications

Our analysis of longitudinal river profiles, catchment mean erosion rates, and paleo-erosion rates provide strong evidence that Quaternary tectonic deformation and the distribution of lithology influences the rate and style of landscape evolution in the Eastern Cordillera. Coupled steepness indices (Figure 6b) and catchment mean erosion rates (Figure 3), high concavity indices (Figure 6c), and linearly-aligned litho-tectonic knickpoints below ponded Quaternary sediment (Figure 6a) all point to differential uplift across a band of approximately N-S trending faults in the western CRC. The orientation of faults within this band reflects preexisting structural anisotropies within the crystalline bedrock, and is parallel to nearby Cretaceous rift structures (Grier et al., 1991; Hongn et al., 2007; Santimano and Riller, 2012; Carrapa et al., 2014). Field investigations in the lower Pucará valley reveal an active reverse fault, an active blind thrust, and locally deeply incised (~100 m) pediment surfaces (Supporting Information Figure S13 and 14). In the southeastern CRC, lithotectonic knickpoints, high channel concavities, and channel convexities suggest that the Cerro Negro Thrust and other west-vergent thrusts, some newly identified, are also active (Figure 6). Therefore, we argue that Quaternary shortening is active along most major faults in the CRC. This assertion is supported by field evidence for shortening in subcatchments within the CRC and in adjacent areas (Strecker et al., 1989; Hilley and Strecker, 2005; Carrera and Munoz, 2008; Hain et al., 2011; Santimano and Riller, 2012).

We also present new evidence for active faulting in the southwestern CRC. In the upper reaches of the Pucará River catchment, we identify previously unmapped NNW- and NNE-striking faults (dashed lines in Figure 6) with an up to the east sense of displacement. We did not observe these fault in the field, and so cannot constrain their dip. They could be east-dipping thrust or reverse faults, consistent with the kinematics and orientation of other structures in the basin. Alternatively, these faults are parallel to strike-slip and extensional faults on the Puna Plateau mapped by Schoenbohm and Strecker (2009), to minor Quaternary strike-slip faults in the Cachi Range (Pearson et al., 2012), and to a major fault zone immediately north of the study area, which records Quaternary strike-slip faulting and extension on the Puna Plateau (Lanza et al., 2013). Plio-Quaternary strike-slip and extensional tectonics in NW Argentina have been attributed to gravitational spreading on the Puna Plateau, potentially in response to lithospheric foundering (Schoenbohm and Strecker, 2009; Zhou et al., 2013). Regardless of the morphology of these newly mapped faults, continued displacement in the current arid climate could lead to upstream channel defeat and basin isolation, and ultimately morphologic incorporation into the Puna Plateau (Humphrey and Konrad, 2000; Sobel et al., 2003).

Quaternary shortening in the CRC has implications for tectonic and kinematic models of the Eastern Cordillera. Increased erosional efficiency could reduce surface slopes across the southern Puna within the thick-skinned orogenic wedge, driving active shortening in the wedge interior (Davis et al., 1983; Whipple, 2009; DeCelles et al., 2011). Although there have likely been changes in humidity in the CRC at millennial and 100 kyr frequencies (e.g., Bookhagen et al., 2001; Tofelde et al., 2017; D'Arcy et al., 2019), the overall trend in the interior of the Eastern Cordillera has been towards orographically-driven aridity (e.g., Bywater-Reyes et al., 2010), and the Pucará basin has been arid enough to sustain aridisols and pavement development for at least the last ~151 ka. Increases in erosional efficiency therefore do not provide a sufficient explanation for internal, out-of-sequence deformation. This suggests that localized shortening in the Eastern Cordillera is driven by kinematic (e.g. changing slab geometry) or geodynamic (e.g. gravitational spreading, lithospheric foundering) processes (Schoenbohm and Strecker, 2009; DeCelles et al., 2009) rather than climatic changes.

6 Conclusions

In this study we use field investigations, systematic analysis of longitudinal river profiles, ^{10}Be-derived catchment mean erosion rates, and paleo-erosion rates and vertical incision rates both from ^{10}Be depth profiles to examine the late Quaternary landscape evolution of the Calchaquí River Catchment. Most of our analyses point to the importance of tectonic and lithologic controls on long-term landscape evolution, rather than climatic factors such as precipitation. The distribution of high normalized steepness indices, abrupt lithotectonic knickpoints, and variable catchment mean erosion rates demonstrate that incision in this landscape is controlled by active tectonics and the structural juxtaposition of variably resistant lithologies. Anomalously high channel concavities, typically observed in the hanging walls of thrust faults, reflect some combination of downstream decreases in uplift rate, decreases in bedrock resistance, and transitions from bedrock to alluvial channel reaches. Knickpoints reveal that previously unidentified faults – subparallel to the dominant structural grain – provide important base-level controls on the uppermost reaches of the western CRC. Aggradation behind these uplifting blocks occurs to keep pace with deformation, but continued tectonic isolation of base-level and low precipitation rates could lead to channel defeat, internal drainage, and incorporation into the Puna Plateau.

Despite dominant tectonic and lithologic controls, disparities between catchment-mean denudation rates and vertical incision rates may suggest that erosion rates vary significantly over relatively short timescales, perhaps driven by climate cyclicity. Our findings indicate that, in regions characterized by structural, lithologic, and geomorphic complexity, the coupled analysis of longitudinal river profiles and catchment mean denudation rates may not detect short-term landscape transience. Therefore, we emphasize the importance of field investigations in the examination of controls on landscape evolution, as digital topographic analysis may be insufficient to detect the dynamics of natural landscapes. Future kinematic analyses may elucidate the controls on active shortening in the CRC, and Quaternary paleoclimatic analyses may better evaluate the coupling of climate and tectonics in the Central Andean retroarc foreland, but the results of this study suggest that a catchment scale understanding of the controls on erosion is a prerequisite to regional analyses of tectonic and climatic interactions.

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Figure Captions

Figure 1. Composite digital elevation model and shaded relief map of the south central Andes indicating major tectonomorphic provinces. Thick black line delineates internally drained Puna Plateau from the externally drained Eastern Cordillera and Sierras Pampeanas. Black box shows the extent of Figure 2, the Pucará Valley, where field studies were focused. Blue line outlines the Calchaqui River catchment (CRC), as shown in Figures 3 and 6. Inset: digital elevation model indicating location of large map with black box.

Figure 2. Quaternary strath terraces and pediment surfaces in the Pucará Valley. Depositional ages derived from cosmogenic ^{10}Be depth profiles. Numbered soil pits are described in Table 1. JVT = Jasimaná-Vallecito Thrust. SQT = Sierra de Quilmes Thrust. PT = Pucará Thrust. See Supporting Information Figure S94 for complete geologic map. Fault nomenclature and structure modified from Carrera and Muñoz, 2008. Location shown by black box in Figure 1.

Figure 3. Shaded relief map of the CRC, ^{10}Be catchment mean erosion rates, in mm kyr^{-1}, and corresponding subcatchments (labeled) from this study and Bookhagen and Strecker (2012). Basin extent shown by blue line in Figure 1.

Figure 4. Photograph taken from the site of the Q5 depth profile in Figure 2, looking approximately northeast. Foreground shows Q5 strath terrace beveled into sedimentary rocks of the Tertiary Payogastilla Group, which rest in angular unconformity over Cretaceous Pirgua (Kp) Group redbeds. Across the river, Q2, Q3, Q4, Q6 and Q7 surfaces are beveled into both Tertiary Payogastilla (Tp) and Cretaceous sedimentary units. Rio Pucará flows from right (south) to left (north). Note sloping beds marking monocline within Cretaceous units beneath the Q7 surface, indicated by angled arrows. High ranges are composed of the Neoproterozoic Puncoviscana Formation.

Figure 5. Field photographs of representative pedogenic carbonate development on shallow soil mantled pediment surfaces in the study area. Carbonate stages according to classification scheme of Gile et al. (1966).

Figure 6. (a) Lithologic divisions, major faults, and knickpoints in the CRC. Knickpoints according to legend in (b). Newly identified faults marked by heavy dashed lines outlined in red, with sense of displacement indicated (U = Up, D = Down). CNT = Cerro Negro Thrust (Carrapa et al., 2011). (b) Normalized channel steepness indices and knickpoints in the CRC. Labeled streams are displayed in profile in Figure 7. (c) Concavity indices and mean annual rainfall in the CRC. Knickpoints according to legend in (b). TRMM precipitation data from Bookhagen and Strecker (2008). See text for description of knickpoint typology and channel regression parameters. Basin extent shown by blue line in Figure 1.

Figure 7. Selected longitudinal river profiles and corresponding local slope/drainage area regressions. Individual segments are bound by knickpoints or confluences with trunk streams. In slope-area space light blue lines represent best-fit regressions, from which concavity (θ) is determined, and red lines represent regressions with a fixed slope (θ_{ref} = 0.45), from which steepness index (k_{sn}) is determined. Dashed lines outlined in red mark newly mapped faults with unknown dip. See Figure 6b for stream locations. CNT = Cerro Negro Thrust; PT = Pucara Thrust; JVT = Jasimaná-Vallecito Thrust; see Figure 2 for locations of these structures.

Figure 8. In situ ^{10}Be depth profiles and monte carlo simulator results for age, inheritance, and surface erosion rates when run for 10^6 solutions at 2 sigma uncertainty, according to parameters described in the text and Supporting Information. Black line is the best fit. Gray lines are all other model solutions. White circles with black outlines are subsurface samples used in the model simulations. White circles with grey outlines are surface sediment samples that were analyzed, but not used in model simulations due to evidence of bioturbation. White square with grey outline represents a quartz cobble amalgamation (n=85) sample that was similarly excluded from model simulations.

Figure 9. Vertical distribution of knickpoints in the CRC. See Figure 6 for plan view.

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Table 1. Soil pit descriptions from the Pucará Valley

*Pit #	Pit Type	Pit Depth, cm	Surface level	Soil Type	Pedogenic Salt Stage	PDI
1	Soil	100	Q0	Ustic Haplocambid	0	n/a
2	Soil	50	Q1	Ustic Haplocambid	1.5	2.2
3	Cosmo	200	Q2	Ustic Haplocalcid	2	1.9
4	Soil	20	Q3	Ustic Haplocalcid	1.5	2.0
5	Soil	50	Q3	Ustic Petrocalcid	3.5	2.3
6	Soil	50	Q3	Ustic Haplocalcid	2.5	2.2
7	Pavement	0	Q4	n/a	n/a	2.2
8	Soil	25	Q4	Ustic Haplocambid	1	2.7
9	Cosmo	200	Q5	Ustic Petrocalcid	3.5	2.4
10	Cosmo	195	Q6	Leptic Haplogypsid	3	2.4
11	Pavement	0	Q6	n/a	n/a	2.7
12	Soil	25	Q6	Ustic Petrocalcid	3.5	2.4
13	Soil	80	Q6	Ustic Petrogypsid	3.5	n/a

*Pit locations indicated in Figure 2.

Table 2. Catchment mean erosion rates and corresponding topographic and climatic characteristics

Sample Name	Sample Latitude (South)	Sample Longitude (West)	Sample Elevation (m)	^{10}Be Concentration (10^5 atoms/g)	^{10}Be Concentration 1σ (10^5 atoms/g)	Mean Production Rate, atoms/g/yr	Mean Production rate 1σ , atoms/g/yr	Erosion Rate, mm kyr	Erosion Rate 1σ, mm kyr
BW1	-25.8137	-66.28566	2266	1.83	0.047	22.6	2.5	76.2	8.4
BW2	-25.9744	-66.28309	2860	11.1	0.147	46.8	5.3	26.1	3.0
BW3	-25.9364	-66.30455	2730	9.39	0.145	34.3	3.9	22.5	2.6
BW5	-25.7725	-66.24303	2206	4.83	0.113	38.0	4.3	48.4	5.5
BW5 *	-25.7725	-66.24303	2206	4.83	0.113	N/A	N/A	71.8	8.1
BW6	-25.8467	-66.35731	2472	3.67	0.0709	24.0	2.7	40.3	4.5
M2	-25.999	-65.855	1548	2.42	0.0556	32.1	3.6	81.8	9.2
M2*	-25.999	-65.855	1548	2.42	0.0556	N/A	N/A	100.0	11.2
STR2	-25.8314	-65.9677	1692	1.64	0.0221	13.1	1.5	49.2	5.6
STR3	-25.0105	-66.09571	2496	5.14	0.152	28.8	3.2	33.8	3.8
STR11	-25.4359	-66.30796	2048	3.29	0.0754	43.7	4.9	81.7	9.2
STR13	-24.9342	-66.1408	2566	2.33	0.0391	46.1	5.2	121.9	13.7
STR16	-25.4359	-66.3101	2045	5.85	0.142	34.7	3.9	36.5	4.1
STR19	-25.7949	-65.97427	1726	1.17	0.0240	22.8	2.6	120.4	13.7

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Sample Name	Apparent Age (kyr)	Centroid Latitude (South)	Centroid Longitude (West)	Mean elevation (m)	Mean Precipitation (mm/yr)	Drainage Area (km^2)	Mean Slope (degrees)	Mean 1km radius relief (m)	Mean 5km radius relief (m)
BW1	8.1	-25.8403	-66.2404	2846	332	8.83	17.2	304	N/A
BW2	23.6	-26.1920	-66.4224	4204	239	1006	14.1	329	897
BW3	27.4	-26.0134	-66.4273	3597	209	323	14.9	330	951
BW5	12.7	-25.9209	-66.5193	3745	262	2701	16.4	392	1124
BW5 *	8.6	-25.8506	-66.5137	3462	285	1319.98	18.4	423	1190
BW6	15.3	-25.8170	-66.3863	2967	483	43.2	17.5	448	N/A
M2	7.5	-25.4333	-66.2565	3339	236	12858.4	16.7	400	1157
M2*	6.2	-25.3834	-66.0718	2727	241	5335.7	13.9	313	934
STR2	12.5	-25.8434	-66.0323	2004	695	19.06	10.9	142	N/A
STR3	18.2	-24.9908	-65.9768	3273	196	326.65	14.2	317	1009
STR11	7.5	-25.1507	-66.4897	4000	203	1392.32	20.3	491	1403
STR13	5.0	-24.7254	-66.2536	4124	193	1451.89	23	575	1591
STR16	16.9	-25.5606	-66.5376	3565	230	1359.39	18.1	415	1128
STR19	5.1	-25.8494	-66.1221	2801	353	271.985	18.3	368	1027

* contribution of sub-basins removed

Table 3. Vertical incision and catchment mean paleo-erosion rates

	Surface Age	*Vertical Incision Rate**		*Inherited Catchment Mean Erosion Rate***		*Modern Catchment Mean Erosion Rate*
Depth Profile	(ka)	Total Incision (m)	Most Probable Rate (mm kyr^{-1} 2σ)	Most Probable Rate (mm kyr^{-1} 2σ)	Vertical Incision/ Inherited Catchment Mean	Most Probable Rate (mm kyr^{-1} 2σ)
AR13-01 (Q2)	43.6 $^{+15.0}/_{-11.6}$	11	252 $^{+87}/_{-67}$	105 $^{+60}/_{-33}$	2.4	-
AR13-02 (Q5)	91.2 $^{+54.2}/_{-22.2}$	70	768 $^{+456}/_{-187}$	56 $^{+43}/_{-19}$	13.7	23 +/- 3 (BW3)
AR13-03 (Q6)	151 $^{+92.7}/_{-34.1}$	76	503 $^{+309}/_{-114}$	67 $^{+600}/_{-34}$	7.5	76 +/- 9 (BW1)

*Rates derived from ^{10}Be profile ages and surface height

** Rates derived from ^{10}Be inheritance