

UVM ScholarWorks

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

Item Type	article;article
Authors	McCarthy, James A.;Schoenbohm, Lindsay M.;Bierman, Paul R.;Rood, Dylan;Hidy, Alan J.
Citation	McCarthy, J. A., Schoenbohm, L. M., Bierman, P. R., Rood, D., & Hidy, A. J. (2019). Late Quaternary tectonics, incision, and landscape evolution of the Calchaquí River Catchment, Eastern Cordillera, NW Argentina. <i>Journal of Geophysical Research: Earth Surface</i> , 124, 2265– 2287. https://doi.org/10.1029/2019JF005091
DOI	10.1029/2019JF005091
Rights	©2019. American Geophysical Union. All Rights Reserved.; http://rightsstatements.org/vocab/InC/1.0/
Download date	2026-05-19 09:00:55
Link to Item	https://hdl.handle.net/20.500.14849/355



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

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

J. A. McCarthy, L. M. Schoenbohm, P. R.
Bierman, D. Rood, A. J. Hidy

February 3, 2015

Journal of Geophysical Research - Earth Surface

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

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

3
4
5 **James A. McCarthy¹, Lindsay M. Schoenbohm¹, Paul R. Bierman², Dylan Rood³,**
6 **and Alan J. Hidy⁴**

7
8 ¹Department of Earth Sciences, University of Toronto, 22 Russell Street, Toronto, ON, M5S
9 3B1, Canada

10
11 ²Department of Geology and Rubenstein School of the Environment and Natural Resources,
12 University of Vermont, Burlington, VT USA 05405

13
14 ³Department of Earth Science and Engineering, Imperial College London, South Kensington
15 Campus, London SW7 2AZ, UK

16
17 ⁴Lawrence Livermore National Laboratory, Center for Accelerator Mass Spectrometry, 7000
18 East Ave, L-397, Livermore, CA 94500, USA

19
20 Corresponding Author: L. M. Schoenbohm (lindsay.schoenbohm@utoronto.ca)

21
22 **Key Points:**

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

26 **Abstract**

27 Unravelling the relative impacts of climate, tectonics, and lithology on landscape
28 evolution is complicated by the temporal and spatial scale over which observations are made. We
29 use soil and desert pavement classification, analysis of longitudinal river profiles, ^{10}Be -derived
30 catchment mean erosion rates, and paleo-erosion and vertical incision rates both from ^{10}Be depth
31 profiles to test whether, if we restrict our analyses to a spatial scale over which climate is
32 relatively invariant, tectonic and lithologic factors will dominate the late Quaternary landscape
33 evolution of the Calchaquí River Catchment (CRC), NW Argentina. We find that the spatial
34 distribution of erosion rates, normalized channel steepness indices, and concavity indices reflect
35 active tectonics and lithologic resistance. Knickpoints are spatially coincident with tectonic
36 and/or lithologic discontinuities, indicating local base-level control by faulting, and we find
37 evidence for out-of-sequence shortening in the Calchaquí River Catchment. Catchment mean
38 erosion rates, ranging from 22.5 ± 2.6 to 121.9 ± 13.7 mm kyr $^{-1}$, and paleo-erosion rates, ranging
39 from 56^{+43}_{-19} to 105^{+60}_{-33} mm kyr $^{-1}$, are similar, may suggest Quaternary climate changes have
40 not had a strong enough influence on erosion rates to be detected using cosmogenic ^{10}Be .
41 However, ^{10}Be depth profiles document punctuated abandonment of pediment and strath terraces
42 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
43 and catchment mean erosion rates could suggest periods of landscape transience, possibly
44 reflecting climate cyclicity. Our results emphasize the role of tectonic uplift and lithologic
45 contrasts in shaping the long-term erosion rates and channel morphology at the relatively local
46 scale of the Calchaqui River Catchment, in contrast to regional-scale studies which find
47 precipitation to exert the dominant control.

48

49 **1 Introduction**

50 Climate, tectonics, and lithology should dictate landscape evolution as expressed through
51 the shape of the topography and the rates and patterns of erosion and sedimentation. However,
52 unravelling the relative controls is challenging, particularly because of the chicken-or-the-egg
53 nature of tectonic-climate coupling (Molnar and England, 1990). Compilations at a global or
54 regional scale have demonstrated that environmental parameters such as mean annual
55 temperature, mean annual precipitation, and vegetation, sometimes measured using elevation and
56 latitude as proxies, can explain much of the natural variation in topography (Champagnac et al.,

57 2012), erosion rate (Portenga and Bierman, 2011; Bookhagen and Strecker, 2012), and channel
58 steepness (D'Arcy and Whittaker, 2014). However, a similar compilation but on a more local
59 (range) scale points to tectonic rather than climatic control, with relief explained by vertical
60 displacement (Ellis and Barnes, 2015).

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

75 The attempt to unravel tectonics, climate, and erosion is partly complicated because of
76 temporal climate variability. For example, some studies suggest coupling between erosion rates
77 and a long term shift toward cool conditions in the Quaternary (e.g., Molnar and England, 1990;
78 Willenbring and von Blanckenburg, 2010; Herman et al., 2013), although these studies may
79 suffer from spatial or temporal correlation bias (Schildgen et al., 2018; Schumer and Jerolmack,
80 2009). Cyclic changes in climate (Zachos et al., 2001) may complicate unravelling links between
81 climate, tectonics, and landscape evolution as well (e.g., Braun et al., 2015). Basin-scale erosion
82 rates are typically integrated over millennia, so the degree to which modern climate data reflect
83 measured erosion rates is dependent on the frequency and magnitude of past climate changes
84 (Bierman and Steig, 1996).

85 However, it may also be that the spatial scale of observation matters – a global or
86 regional study may reveal one pattern, but a local study may find the dominant controls are
87 different. If the scale of observation is small enough that one of climate, tectonics, or lithology is

88 uniform, the others will necessarily dominate the evolution of the landscape. Less attention has
89 been paid to this potential explanation for the conflicting interpretations of what controls long-
90 term landscape evolution.

91 In this study we investigate the Late Quaternary landscape evolution of the southernmost
92 Eastern Cordillera in the southern Central Andes (Figure 1), a region with regionally strong
93 climatic gradients, active tectonic uplift, and significant lithologic contrasts. Bordering on the
94 Puna Plateau to the west, the Sierras Pampeanas to the south, and the Santa Bárbara System to
95 the east, the study area lies within the west to east transition from the high plateau to the complex
96 retroarc foreland (Allmendinger et al., 1997; Carrapa and DeCelles, 2008). Pronounced west to
97 east climatic gradients exist as well along the eastern margin of the central Andes due to
98 orographic shielding of easterly moisture-bearing winds, resulting in strong differences in
99 surface processes and erosional efficiency between the plateau and the foreland (Strecker et al.,
100 2007; Bookhagen and Strecker, 2012). At the regional scale of the southern Central Andes, first-
101 order spatial patterns in erosion rates can be linked to precipitation, with high precipitation
102 corresponding to high erosion rate and low channel steepness and vice versa; variations in
103 tectonic uplift and lithology at this scale are not significant factors (Bookhagen and Strecker,
104 2012). We focus on a narrower region where climate gradients are not as pronounced, the
105 Calchaquí River Catchment (CRC) and lower Pucará Valley (Figure 1), in order to investigate
106 whether at a more local scale tectonics and lithology play the dominant role in shaping landscape
107 evolution.

108 We use a combination of longitudinal river profile analysis, ^{10}Be catchment-mean erosion
109 rates, and estimates of paleo-erosion rates derived from ^{10}Be depth-profiles to examine the
110 controls on erosion and topography in the Calchaquí River Catchment (CRC), within the Eastern
111 Cordillera. At an even more narrow scale, we focus our field studies in the lower Pucará Valley,
112 an intramontane basin within the CRC (Figure 1), mapping geomorphologic and geologic
113 features as well as dating abandoned alluvial surfaces to determine potential climatic influences
114 on the timing and rate of incision. Fluvial channel network morphology is a sensitive indicator of
115 both tectonic and climatic forcing (Whipple and Tucker, 1999; Kirby and Whipple, 2012).
116 Along-channel changes in lithology, climate, uplift rate, or sediment supply via landslides
117 generate sharp breaks (knickpoints) in the profile, separating segments with different steepness
118 and concavity; similarly, temporal changes in uplift rate produce transient knickpoints at the

119 basin outlet that propagate upstream as an incisional wave, separating the newly equilibrated
120 lower reaches from upper reaches equilibrated with previous conditions (Seidl and Dietrich,
121 1992; Whipple and Tucker, 1999; Blum and Törnqvist, 2000; Schoenbohm et al., 2004; Walsh et
122 al., 2012). However, in isolation, longitudinal river profile analysis cannot explicitly distinguish
123 the relative effects of tectonics, lithology, climate and transient perturbations on profile form, but
124 the incorporation of supporting information (e.g. tectonic, lithologic and climatic data) can help
125 (Kirby and Whipple, 2012). In particular, the covariance of normalized channel steepness indices
126 and ^{10}Be catchment mean erosion rates can distinguish lithologic and tectonic controls on
127 channel steepness (Cyr et al., 2014). Together with a priori knowledge of the distribution of
128 lithology and precipitation, integrated field and river profile analysis and measurements of
129 erosion rate allow the evaluation of the dominant controls on landscape evolution.

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

137

138 **2 Geologic Setting**

139 **2.1 Structural Evolution**

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

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

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

165

166 **2.2 Quaternary Climate & Geomorphology**

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

180 The geomorphology of the CRC and nearby regions reflects an arid, highly seasonal
181 climate, active tectonics, and relief >1000 m in intramontane basins. It presents a mix of
182 detachment limited channels in uplifted bedrock ranges along transverse rivers in the majority of
183 the landscape, but with transport limited channels in region of thicker alluvial fill along
184 longitudinal rivers. Abundant pediment surfaces and alluvial fans throughout the CRC are
185 incised by modern channels. For example, in the Pucará Valley, incision and base-level lowering
186 of ~100 m have led to the abandonment of a sequence of pediments and strath terraces. Similar
187 evidence for Quaternary incision is well documented in the Sierras Pampeanas and Santa
188 Barbara System (Strecker et al., 1989; Hilley and Strecker, 2005; González Bonorino and
189 Abascal, 2012). Pedogenesis is weak, and soils are dominated by carbonate (May and Soler,
190 2010; this study). Periglacial processes are restricted to areas over 4500 m elevation, but this
191 limit may have been depressed by as much as 900 m during the Pleistocene, as evidenced by
192 broad convex range crests and moraines in the Sierra de Quilmes and northwestern CRC
193 (Haselton et al., 2002).

194

195 **3 Methods**

196 **3.1 Field Studies**

197 Field studies were focused in the lower Pucará Valley with the goal of characterizing
198 neotectonic structures and Quaternary landscape evolution. We conducted structural and
199 geomorphic mapping of the valley on aerial photography and ASTER 30 m digital topography.
200 Geology was compiled from existing maps by Carrera and Muñoz (2008) and Coutand et al.
201 (2006). We use Trimble differential GPS equipment with <10 cm vertical and ~1 cm horizontal
202 precision to measure ~40 pediment profiles (see Supporting Information Figure S13 for locations
203 and S14 for examples). Additionally, we described soils at 13 sites within the valley at various
204 pediment levels, according to USDA soil taxonomy guidelines (Staff, 2010). Descriptions are
205 solely morphological, and geochemical classification metrics (e.g. weight percent CaCO₃) are
206 inferred. Reported stages of pedogenic carbonate and gypsum accumulation follow the
207 morphological classification scheme of Gile et al. (1966). We determined desert pavement
208 indices (PDI) according to methods developed by Al-Farraj and Harvey (2000). See Supporting
209 Information Text S1 and Table S1 for detailed description of classification and PDI
210 methodology. Finally, we collected five samples of modern detrital sand for determining

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

214

215 **3.2 Longitudinal River Profile Analysis**

216 We rely on digital topographic data and coupled ArcGIS and Matlab scripts to derive
217 normalized channel steepness indices (k_{sn}) and concavity indices (θ)
218 (<http://geomorphtools.geology.isu.edu/>). Channel steepness index is a measure of channel
219 gradient adjusted for upstream drainage area, a proxy for discharge in the case of uniform
220 precipitation, and concavity index is a measure of the concavity or convexity of the channel
221 (Whipple and Tucker, 2002). To find these values for each channel, following methods outlined
222 by Wobus et al. (2006a), we extracted channel topographic data from 30 m ASTER topography
223 (NASA), removed data irregularities, smoothed channel data along a 450 m moving average
224 window, determined local slopes over a 10 m vertical interval, and set a minimum drainage area
225 of 3000 pixels, or ~ 2.7 km². These parameters balance our desires to preserve channel
226 topographic complexity, remove artifacts in digital topographic data associated with high relief
227 landscapes, and exclude channel headwaters that are dominated by debris-flow processes
228 (Wobus et al., 2006a). Channel steepness and concavity indices are determined by linear
229 regression of local channel slope and drainage area after log transformation. We normalize
230 steepness indices to a reference concavity of 0.45, following empirical and theoretical
231 predictions for detachment limited systems (Whipple and Tucker, 2002).

232 We identify individual segments along a profile by the occurrence of major knickpoints
233 (i.e., readily apparent in both the longitudinal profile and the slope-area plot) or downstream
234 confluences with larger trunk streams, and regress the data from each segment to derive
235 normalized channel steepness index and concavity. Considering the large scale of our analysis,
236 we selected knickpoints that are conspicuous in log-slope/log-area plots and in topographic
237 profiles. We classify knickpoints according to morphology: slope-break knickpoints, vertical step
238 knickpoints, the base of a convex reach, and the top of a convex reach (see Kirby and Whipple,
239 2012). We also classify knickpoints genetically, based on their spatial coincidence with
240 significant tectonic (e.g., faults) and/or lithologic boundaries (e.g., transition from crystalline
241 basement to Tertiary sedimentary rock), giving rise to four knickpoint types: lithologic, tectonic,

242 lithotectonic (arising from lithologic boundaries coincident with faults), and undefined. We
243 specifically focus on slope-break and undefined knickpoints, because they may represent
244 transient channel responses to an external forcing such as changes in climate or tectonic uplift
245 rate (e.g. Harkins et al., 2007).

246

247 **3.3 Terrestrial Cosmogenic Nuclide (^{10}Be) Chronology**

248 **3.3.1 Analytical Procedures**

249 In this study we isolate and analyze *in situ* produced cosmogenic ^{10}Be in quartz to
250 determine catchment mean erosion rates and date stable geomorphic surfaces. Samples were
251 processed at the University of Vermont Cosmogenic Nuclide Laboratory using standard
252 analytical methods (Corbett et al., 2016; see also Supporting Information Text S2 and Table S8
253 and www.uvm.edu/cosmolab for detailed methodology and data). First, quartz was purified for
254 ^{10}Be analysis using mineral separation procedures modified from Kohl and Nishiizumi (1992).
255 For Beryllium isolation, samples were prepared in batches that contained a full-process blank
256 and 11 unknowns including the CRONUS N standard. We used between 11.6 and 23.0 g of
257 purified quartz for analysis. We added $\sim 250\ \mu\text{g}$ of ^9Be carrier made from beryl at the University
258 of Vermont to each sample. After isolation, Be was precipitated at pH 8 as hydroxide gel, dried,
259 ignited to produce BeO , ground and mixed with Nb powder at 1:1 molar ratio, and packed into
260 copper cathodes for accelerator mass spectrometry (AMS) measurements.

261 $^{10}\text{Be}/^9\text{Be}$ ratios were measured at the Scottish University Environmental Research Center
262 (see Xu et al., 2010 for methods) and were normalized to NIST standard with an assumed ratio
263 of $2.79 \cdot 10^{-15}$ based on a half life of 1.36 My (Nishiizumi et al., 2007). The average measured
264 sample ratio ($^{10}\text{Be}/^9\text{Be}$) was 947×10^{-15} and AMS measurement precisions, including blank
265 corrections propagated quadratically, averaged 1.9 %. The blank correction is an inconsequential
266 part of most measured isotopic ratios ($<0.7\%$ on average, maximum 2.0%). The CRONUS N
267 standard was run with these samples and returned a concentration of $2.31 \pm 0.06 \times 10^5$ atoms g^{-1} ,
268 consistent with values reported by other labs (Jull et al., 2014).

269

270 **3.3.2 ^{10}Be Catchment Mean Erosion Rates**

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

273 6). Detrital samples sieved to a grain size of 250 to 850 μm were collected from bars within
274 active streams. For each sample, we determined the contributing drainage area using ArcGIS,
275 and ^{10}Be production rates were calculated for each pixel of the DEM within the catchment at 250
276 m resolution. Our calculation incorporates elevation, shielding, and muonogenic production for
277 each pixel, but relies on mean latitude for each catchment and assumes a constant production rate
278 with time. We estimate a 10% uncertainty associated with our scaling method. We follow the
279 scaling scheme of Lal (1991) and a sea-level high-altitude total surface production rate of 3.96
280 ± 0.204 atoms $\text{g}^{-1} \text{yr}^{-1}$ after the local HUANCANE2A Calibration data set (Borchers et al.,
281 2015). We calculate erosion rates using a sample density of 2.6 g cm^{-3} and an attenuation length
282 of 160 g cm^{-2} (von Blanckenburg, 2005). The uncertainties which accompany our reported
283 erosion rates reflect the uncertainties in both AMS measurements and catchment mean
284 production rates (see Supporting Information Text S3 for MATLAB code used in calculation).
285 Major lithologies in the CRC are quartz rich (Sparks et al., 1985; Francis et al., 1989; Do Campo
286 and Guevara, 2005; Marquillas et al., 2005; Coutand et al., 2006), so we make no corrections for
287 variably distributed quartz.

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

299

300 3.3.3 ^{10}Be Depth Profiles

301 To date pediment surfaces, we hand-excavated 2 m deep pits for cosmogenic nuclide
302 (^{10}Be) depth profiles at three locations (Figure 2). Soil pits were dug at geomorphically stable
303 sites with minimal field evidence for erosion, bioturbation, or complex shielding histories.

304 However, the absence of bar and swale topography, the presence of Av horizons, and the heavily
305 dissected nature of the pediment surfaces throughout the valley collectively suggest some surface
306 change at all sites. We sampled ~1 kg of sand-sized grains in ~5 cm thick horizons at 0, 50, 100,
307 150, and 200 cm depths, across the width of the pit. All samples were field-sieved to remove the
308 < 250 μm fractions, which made up approximately <25% of the total soil mass. We also
309 collected 100 surface clasts from one site (Q6, sample AR13-03), extracting equal mass from
310 each clast to combine into an amalgamated sample.

311 To determine a range and central tendency of surface exposure age, ^{10}Be inheritance from
312 exposure prior to deposition, and post-deposition erosion rate for each depth profile, we employ
313 the Monte Carlo simulator developed by Hidy et al. (2010) (version 1.2). Results are from 10^6
314 successful profile simulations and we report 2σ uncertainties, based on model parameters (see
315 Supporting Information Figures S4-12 and Table S2). Although average AMS uncertainty for the
316 data set was <2%, we assigned nuclide concentration uncertainties of 5% for all depth-profile
317 samples, to reflect errors in sampling (e.g., sample depth and thickness), laboratory analysis
318 (e.g., carrier and massing errors), geomorphic variability (e.g., bioturbation/cryoturbation,
319 shielding variations), and also systematic errors (e.g., temporal variation in cosmic ray flux and
320 scaling uncertainty) (Gosse and Phillips, 2001). Model inputs of density and associated
321 uncertainties are based on previous field determinations in similar soil types with similar ranges
322 of carbonate and gypsum development (Reheis, 1987; Reheis et al., 1995; Hidy et al., 2010).
323 Soils information and terrace surface morphology were used to constrain the erosion threshold
324 (endmember values of net surface erosion and aggradation). Specifically, the thickness of the Av
325 horizon was used as a maximum value for net aggradation, and maximum net erosion was
326 determined from the estimated relief of the initial bar-and-swale topography (~30 cm) and from a
327 conservative erosion estimate derived from depth and thickness anomalies in the B horizon (if
328 present). Finally, because the modeled exposure age depends on a time-averaged surface erosion
329 rate, the resulting abandonment age is not very sensitive to an intermittent period of enhanced
330 surface erosion and the age should still be adequately captured within the modeled error. The
331 exception to this would be if there was a rapid stripping event that mostly or completely reset the
332 ^{10}Be accumulation signal. However, because of the preservation of a broad, flat, and undissected
333 surface morphology on the terrace treads, we consider this scenario unlikely.

334

335 3.3.4 Paleo-Erosion Rates

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

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

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

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

367

368 **4 Results**

369 **4.1 Field Studies**

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

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

395

396 4.2 River Profile Analysis

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

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

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

426 Morphologically, we classified 27 knickpoints as vertical-step knickpoints, 10 as slope-
427 break knickpoints, and the remaining 38 as high and low bounds on convex channel reaches
428 (Kirby and Whipple, 2012). From a genetic standpoint we classified 9 knickpoints as lithologic,
429 32 as tectonic, 26 as lithotectonic, and 8 as undefined (Figure 6b). We find no clear correlation
430 between knickpoint morphology and knickpoint genesis, and note that no undefined knickpoints
431 also have a slope-break morphology. See Supporting Information Figures S16-93 and Tables S4
432 and S5 for stream profile figures, stream profile regression data, and knickpoint data.

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

438

439 **4.3 ^{10}Be Catchment Mean Erosion Rates**

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

449

450 **4.4 ^{10}Be Depth Profiles**

451 At all three sites, surface samples exhibit low ^{10}Be concentrations compared to depth-
452 profile attenuation curves (Figure 8). Previous work suggests that low surface concentrations
453 reflect bioturbation or deposition of younger material (Hidy et al., 2010). Further, our field
454 studies (see profile descriptions below) reveal a complex near-surface history of erosion (e.g.,
455 unusually shallow Bkk horizons, lowering of bar and swale surface relief) and aggradation (e.g.
456 vesicular A horizons). Given particularly the evidence for aggradation, which means that surface

457 samples have not been fixed in depth with respect to the rest of the profile, we exclude the
458 surface sand and amalgamated clast samples from our depth-profile simulations, significantly
459 increasing the range of solutions (the uncertainty), but allowing better fits of the data at depth.
460 The depth-profile simulator yields Bayesian ages and 2σ uncertainties of $43.6^{+15.0/-11.6}$ ka, 91.2
461 $^{+54.2/-22.2}$ ka, and $151^{+92.7/-34.1}$ ka for our Q2, Q5, and Q6 surfaces, respectively, therefore agreeing
462 with geomorphic relative-age constraints including stratigraphic position, soil development, and
463 desert pavement development (Table 1). Additionally, simple calculations using the formulations
464 of Anderson et al. (1996), which assume no surface erosion or deposition, yield ages of 50.2 ka,
465 103 ka, and 169 ka, in close agreement with the Bayesian ages, suggesting that the age signal is
466 robust. See Supporting Information Figures S1-12 for annotated pit photos, model input
467 parameters, and frequency histograms for age, inheritance, and surface erosion rate for each
468 depth profile.

469

470 **4.4.1 Q2 Surface (Profile AR13-01)**

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

483

484 **4.4.2 Q5 Surface (Profile AR13-02)**

485 AR13-02 is located on a Q5 fluvial strath terrace (Figure 2) sourced dominantly from
486 Paleozoic granitoids and Tertiary volcanic lithologies southwest of the Pucará valley. This
487 deposit consists of couplets of fine and coarse grained layers, similar to Q2 (AR13-01), but the

488 sedimentology is partially obscured by significant carbonate accumulation. The soil consists of a
 489 pavement layer over a shallow, weakly developed, 10-cm thick Av horizon over a massive and
 490 root-limiting 20 cm thick Bkk horizon over a Bk horizon which transitions to a C horizon at
 491 ~150 cm depth. The shallow depth to the Bkk horizon (10 cm) suggests that >20 cm erosion of
 492 the surface has occurred (Royer, 1999), while the Av horizon suggests up to 10 cm of surface
 493 inflation. This geomorphic conundrum forces us to input a wide range (-10 – 90 cm) for the
 494 “total erosion threshold” parameter (See Supporting Information Figure S7). We report a most
 495 probable age of 91.2 ka and a most probable surface erosion rate of 5.5 mm kyr⁻¹, which yield an
 496 erosion estimate of ~57 cm, consistent with surface degradation at this site.

497

498 **4.4.3 Q6 Surface (Profile AR13-03)**

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

512

513 **4.5 Paleo-Erosion Rates**

514 Vertical incision estimates based on the projected height above the river for the Q2, Q5,
 515 and Q6 depth profiles are 11, 70, and 76 m, respectively, yielding vertical incision rates of 252
 516 ⁺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
 517 ~151 ka when most probable ages and 2σ uncertainties are used (Table 3). We do not observe

518 slower incision rates over longer time intervals, as has been noted in other studies (e.g., Finnegan
519 et al., 2014).

520 Catchment mean paleo-erosion rates derived from most probable inheritance values of
521 the three profiles are $105^{+60/-33}$ mm ka⁻¹ at ~44 ka, $56^{+43/-19}$ mm ka⁻¹ at ~91 ka, and $67^{+600/-34}$
522 mm kyr⁻¹ at ~151 ka (2σ) respectively (Table 3). The high positive uncertainty associated with
523 the catchment mean paleo-erosion rate for the Q6 surface (AR13-03) reflects an extremely low
524 2σ solution for inheritance.

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

538

539 **5 Discussion**

540 Here we interpret our results with respect to the distribution of lithology, faults, and
541 precipitation in the CRC, testing our hypothesis that in contrast to previous regional scale work
542 that found climate to exert the dominant influence on erosion rates and landscape evolution in
543 this part of the Andes (Bookhagen and Strecker, 2012), at the smaller spatial scale of the
544 Calchaquí River Catchment, with relatively uniform modern precipitation, tectonics and
545 lithology will prevail. We find that the spatial distribution of steepness indices and catchment
546 mean erosion rates indicate strong lithologic and tectonic control on erosion and topography
547 throughout the catchment. If a combination of high steepness indices and high erosion rates can
548 be taken to indicate sustained high tectonic uplift rates, then we also find evidence for active

549 tectonics, particularly in the western CRC. The distribution of relatively high concavity indices
550 also supports active faulting, as does our analysis of knickpoints. Paleo-erosion rates indicate
551 uplift across major faults in the CRC and are similar to modern rates, possibly implying long-
552 term continuity in erosion. In contrast, vertical incision rates are higher than basin scale erosion
553 rates, potentially pointing to transient landscape adjustment or variable lithologic resistance.
554 Lastly, we consider the tectonic implications of out-of-sequence deformation in the retroarc
555 foreland.

556

557 **5.1 Local-scale Controls on River Morphology within the Calchaquí River Catchment**

558 **5.1.1 Channel Steepness and Erosion Rate**

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

568 In the western CRC, high steepness values and variable erosion rates are measured in
569 crystalline rocks within the ranges bordering the plateau. The differing erosion rates despite
570 relatively uniform lithology suggest that in the western CRC, spatially variable uplift may
571 instead strongly control erosion rate. For example, tributaries to the Calchaquí (STR13) and
572 Luracatao (STR11) rivers, which principally travel over crystalline bedrock, exhibit high (>200)
573 steepness values (Figure 6b), and the catchments erode at a high rate ($121 \pm 14 \text{ mm kyr}^{-1}$ and 82
574 $\pm 9 \text{ mm kyr}^{-1}$ respectively; Figure 3), suggesting that uplift rates are higher here than in other
575 parts of the CRC with similar lithology (e.g. catchment STR3).

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

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

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

608

609 **5.1.2 Concavity Indices and Non-Uniform River Profile Morphology**

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

620 The Calchaquí River itself displays a well-graded profile (S4, Figure 7), except for a
621 small change across a vertical step knickpoint within a restricted part of the basin in the north.
622 The lower segment exhibits a concavity index within the expected range for river profiles in
623 tectonically active orogens (0.53), while the upper segment has a slightly low concavity index
624 (0.34), likely reflecting the influence of debris-flows and/or high sediment flux in the upper most
625 part of the catchment (Whipple, 2004). The Calchaquí River flows through and actively incises
626 sedimentary rock and Quaternary alluvium, and also crosses the Cerro Negro Thrust, but we note
627 no major breaks across lithologic or tectonic boundaries. The narrow range of concavity and the
628 well graded profile suggests that the Calchaquí River is equilibrated to the prevailing climatic
629 and tectonic conditions and thus is in steady-state (Whipple et al., 2013).

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

638 Extreme concavities (>2) occur along segments that are in the hanging walls of major
639 thrust faults, just downstream of lithotectonic knickpoints (Figure 6c). Downstream lithologic
640 changes commonly occur along these segments; the transition from harder to softer rock could

641 explain the high concavity (e.g., segment with $\theta = 3.9$ in tributary S67, Figure 7). However, in
642 some cases lithology is uniform (e.g. segment with $\theta = 23$ in tributary S65; Figure 7), suggesting
643 that the faults which bound these segments are active, and gradual downstream reductions in
644 uplift rates drive the high concavities (Whipple, 2004). Although downstream increases in
645 precipitation could also cause these extreme concavities, the magnitude of increase is likely too
646 small ($<500 \text{ mm yr}^{-1}$) to have a significant effect (Figure 6c; Schlunegger et al., 2011;
647 Bookhagen and Strecker, 2012). Although most transverse rivers in the CRC are detachment
648 limited, ponding of sediment means that rivers transition for short segments to alluvial; these
649 transitions could potentially explain some of the concavity differences we observe as well
650 (Wickert and Schildgen, 2019).

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

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

665

666 **5.1.3 Knickpoint Genesis, Form, and Distribution**

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

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

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

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

693

694 **5.2 Controls on Landscape Evolution of the Pucará Valley**

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

703 Our analyses of the Q2 and Q5 depth profiles reveal that the lower Pucará Valley has
704 vertical incision rates 2.4 to 13.7 times higher than catchment mean paleo-erosion rates (Table
705 3), suggesting that the lower Pucará Valley has eroded at a higher rate than its headwaters for the
706 last 91 kyr (the age of the Q5 surface). We acknowledge the difficulty in comparing vertical
707 incision and catchment mean denudation (Harkins et al., 2007), or interpreting each individually
708 (Finnegan et al., 2014; Mason and Romans, 2018), but this observation is also supported by our
709 analysis of modern denudation rates and channel steepness indices, which are lower in the
710 headwaters and higher in the Pucará Valley (Figures 3 and 6b). The Q6 depth profile, excavated
711 on a pediment surface derived from a smaller catchment area (5.8 km²), provides a more local
712 estimate of catchment-mean paleo-erosion rate than do the Q2 (2,064 km²) and Q5 (345 km²)
713 depth profiles. Vertical incision and paleo-erosion rates may therefore be expected to agree.
714 However, at this site, as at our other sites, best-fit vertical incision rate is significantly higher
715 (7.5x) than catchment mean paleo-erosion rates, suggesting that non-steady state or dynamic
716 equilibrium conditions characterize this landscape.

717 The correlations between relative landform age and degrees of pedogenic salt and
718 pavement development indicate that arid or semi-arid conditions in the study area are long-lived
719 and that past humid phases, at least locally, were not significant enough (>750 mm Mean Annual
720 Precipitation) to cause major dissolution of soil carbonate or gypsum (Gile et al., 1966; Royer,
721 1999; Buck and Van Hoesen, 2002). Despite this observation of relative climatic stability, the
722 sequence of heavily dissected pediments in the Pucará Valley indicates that periods of pediment
723 formation are punctuated by potentially more vigorous erosional events. Observations from a
724 nearby landslide-dammed paleo-lake that existed during the humid Minchin Phase (25 to 40 ka)
725 (Bookhagen et al., 2001) yield catchment mean erosion rates an order of magnitude higher than
726 modern rates in the CRC (Bookhagen and Strecker, 2012), similar to our finding of high, local
727 paleo vertical incision rates. Bookhagen and Strecker (2012) argue that short-lived humid phases
728 would result in vigorous erosional events on steep streams that were previously equilibrated to
729 dry climates. In this complex geological landscape, with frequent transitions between
730 detachment-limited and transport-limited conditions, topographic expression of such landscape
731 transience would be muted. Further, ¹⁰Be catchment mean erosion rates and paleo-erosion rates
732 are averaged over 5 – 27 kyr timescales in this study, and thus may integrate across multiple

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

735

736 **5.3 Tectonic Implications**

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

755 We also present new evidence for active faulting in the southwestern CRC. In the upper
756 reaches of the Pucará River catchment, we identify previously unmapped NNW- and NNE-
757 striking faults (dashed lines in Figure 6) with an up to the east sense of displacement. We did not
758 observe these fault in the field, and so cannot constrain their dip. They could be east-dipping
759 thrust or reverse faults, consistent with the kinematics and orientation of other structures in the
760 basin. Alternatively, these faults are parallel to strike-slip and extensional faults on the Puna
761 Plateau mapped by Schoenbohm and Strecker (2009), to minor Quaternary strike-slip faults in
762 the Cachi Range (Pearson et al., 2012), and to a major fault zone immediately north of the study
763 area, which records Quaternary strike-slip faulting and extension on the Puna Plateau (Lanza et

764 al., 2013). Plio-Quaternary strike-slip and extensional tectonics in NW Argentina have been
765 attributed to gravitational spreading on the Puna Plateau, potentially in response to lithospheric
766 foundering (Schoenbohm and Strecker, 2009; Zhou et al., 2013). Regardless of the morphology
767 of these newly mapped faults, continued displacement in the current arid climate could lead to
768 upstream channel defeat and basin isolation, and ultimately morphologic incorporation into the
769 Puna Plateau (Humphrey and Konrad, 2000; Sobel et al., 2003).

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

783

784 **6 Conclusions**

785 In this study we use field investigations, systematic analysis of longitudinal river profiles,
786 ¹⁰Be-derived catchment mean erosion rates, and paleo-erosion rates and vertical incision rates
787 both from ¹⁰Be depth profiles to examine the late Quaternary landscape evolution of the
788 Calchaquí River Catchment. Most of our analyses point to the importance of tectonic and
789 lithologic controls on long-term landscape evolution, rather than climatic factors such as
790 precipitation. The distribution of high normalized steepness indices, abrupt lithotectonic
791 knickpoints, and variable catchment mean erosion rates demonstrate that incision in this
792 landscape is controlled by active tectonics and the structural juxtaposition of variably resistant
793 lithologies. Anomalously high channel concavities, typically observed in the hanging walls of
794 thrust faults, reflect some combination of downstream decreases in uplift rate, decreases in

795 bedrock resistance, and transitions from bedrock to alluvial channel reaches. Knickpoints reveal
796 that previously unidentified faults – subparallel to the dominant structural grain – provide
797 important base-level controls on the uppermost reaches of the western CRC. Aggradation behind
798 these uplifting blocks occurs to keep pace with deformation, but continued tectonic isolation of
799 base-level and low precipitation rates could lead to channel defeat, internal drainage, and
800 incorporation into the Puna Plateau.

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

813

814 **Acknowledgements**

815 The data for this paper are fully contained in the manuscript and the associated
816 supporting information files, including desert pavement classification and raw data and
817 photographs of soil carbonate development; ¹⁰Be analytical procedures and raw data,
818 photographs of profile pits, Monte Carlo input parameters and graphical and tabulated results;
819 GPS profiles; stream profiles; and a geologic map of the Pucará Valley. Catchment averaged
820 erosion rates are uploaded to the OCTOPUS: Open Cosmogenic Isotope and Luminescence
821 database (<https://earth.uow.edu.au>). Questions may be addressed to the corresponding author.
822 This work was supported by the Natural Sciences and Engineering Research Council of Canada,
823 the US National Science Foundation (NSF) Grant EAR-0911577, and a Geological Society of
824 America Graduate Student Research Grant. This work was performed in part under the auspices
825 of the U.S. Department of Energy by Lawrence Livermore Nation Laboratory under Contract

826 DE-AC52-07NA27344. This is LLNL-JRNL-666920. We thank the editors and associate editors,
 827 Jason Barnes, Taylor Schildgen, Jessica Thompson Jobe, and three anonymous reviewers for
 828 constructive comments. ASTER GDEM is a product of METI and NASA.

829

830 **References**

- 831 Ahnert, F. 1970, Functional relationships between denudation, relief, and uplift in large, mid-latitude
 832 drainage basins: *American Journal of Science*, v. 268, p. 243-263.
- 833 Al-Farraj, A., and Harvey, A. M., 2000, Desert pavement characteristics on wadi terrace and alluvial fan
 834 surfaces: *Wadi Al-Bih, UAE and Oman: Geomorphology*, v. 35, no. 3-4, p. 279-297.
- 835 Allmendinger, R. W., Jordan, T. E., Kay, S. M., and Isacks, B. L., 1997, The evolution of the Altiplano-
 836 Puna plateau of the Central Andes: *Annual review of Earth and Planetary Sciences*, v. 25, p. 139-
 837 174.
- 838 Anderson, R. S., Repka, J. L., and Dick, G. S., 1996, Explicit treatment of inheritance in dating
 839 depositional surfaces using in situ ^{10}Be and ^{26}Al : *Geology*, v. 24, p. 47-51.
- 840 Balco, G., Stone, J. O., Lifton, N. A., and Dunai, T. J., 2008, A complete and easily accessible means of
 841 calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements:
 842 *Quaternary Geochronology*, v. 3, p. 174-195.
- 843 Barnes, J.B., Ehlers, T.A., Insel, N., McQuarrie, N., and Poulsen, C.J., 2012, Linking orography, climate,
 844 and exhumation across the central Andes: *Geology*, v. 40, p. 1135-1138, doi:10.1130/G33229.1.
- 845 Barnes, J.B., and Pelletier, J.D., 2006, Latitudinal variation of denudation in the evolution of the Bolivian
 846 Andes: *American Journal of Science*, v. 306, p. 1-31.
- 847 Bermúdez, M.A., van der Beek, P.A., and Bernet, M., 2013, Strong tectonic and weak climatic control on
 848 exhumation rates in the Venezuelan Andes: *Lithosphere*, v. 5, p. 3-16, doi: 10.1130/L212.1.
- 849 Bianchi, A.R., and Yañez, C.E., 1992, Las precipitaciones en el noroeste Argentina: Slat, Argentina,
 850 Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Agropecuaria, 383 p.
- 851 Bierman, P., and Steig, E. J., 1996, Estimating rates of denudation using cosmogenic isotope abundances
 852 in sediment: *Earth Surface Processes and Landforms*, v. 21, no. 2, p. 125-139.
- 853 Blum, M.D., and Törnqvist, T.E., 2000, Fluvial responses to climate and sea-level change: a review and
 854 look forward: *Sedimentology*, v. 47, p. 2-48.
- 855 Bobst, A. L., Lowenstein, T. K., Jordan, T. E., Godfrey, L. V., Ku, T. L., and Luo, S. D., 2001, A 106 ka
 856 paleoclimate record from drill core of the Salar de Atacama, northern Chile: *Palaeogeography*
 857 *Palaeoclimatology Palaeoecology*, v. 173, no. 1-2, p. 21-42.
- 858 Bookhagen, B., Haselton, K., and Trauth, M. H., 2001, Hydrological modelling of a Pleistocene
 859 landslide-dammed lake in the Santa Maria Basin, NW Argentina: *Palaeogeography*
 860 *Palaeoclimatology Palaeoecology*, v. 169, no. 1-2, p. 113-127.
- 861 Bookhagen, B., and Strecker, M. R., 2008, Orographic barriers, high-resolution TRMM rainfall, and relief
 862 variations along the eastern Andes: *Geophysical Research Letters*, v. 35, no. 6.
- 863 Bookhagen, B., and Strecker, M.R., 2012, Spatiotemporal trends in erosion rates across a pronounced
 864 rainfall gradient: Examples from the southern Central Andes: *Earth and Planetary Science*
 865 *Letters*, v. 327, p. 97-110.
- 866 Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F.,
 867 Schaefer, J., and Stone, J., 2016, Geological calibration of spallation production rates in the
 868 CRONUS-Earth project: *Quaternary Geochronology*, v. 31, p. 188-198, doi:
 869 10.1016/j.quageo.2015.01.009.
- 870 Braun, J., Voisin, C., Gourlan, A.T., and Chauvle, C., 2015, Erosional response of an actively uplifting
 871 mountain belt to cyclic rainfall variations: *Earth Surface Dynamics*, v. 3, p. 1-14,
 872 doi:10.5194/esurf-3-1-2015.
- 873 Buck, B. J., and Van Hoesen, J. G., 2002, Snowball morphology and SEM analysis of pedogenic gypsum,
 874 southern New Mexico, USA: *Journal of Arid Environments*, v. 51, no. 4, p. 469-487.

- 875 Burbank, D.W., Blythe, A.E., Putkonen, J., Pratt-Sitaula, B., Gabet, E., Oskin, M., Barros, A., and Ojha,
876 T.P., 2003, Decoupling of erosion and precipitation in the Himalayas: *Nature*, v. 426, p. 652-655.
- 877 Bywater-Reyes, S., Carrapa, B., Clementz, M., and Schoenbohm, L., 2010, Effect of late Cenozoic
878 aridification on sedimentation in the Eastern Cordillera of northwest Argentina (Angastaco
879 basin): *Geology*, v. 38, no. 3, p. 235-238.
- 880 Carrapa, B., Bywater-Reyes, S., DeCelles, P. G., Mortimer, E., and Gehrels, G. E., 2012, Late Eocene-
881 Pliocene basin evolution in the Eastern Cordillera of northwestern Argentina (25 degrees-26
882 degrees S): regional implications for Andean orogenic wedge development: *Basin Research*, v.
883 24, no. 3, p. 249-268.
- 884 Carrapa, B., DeCelles, P.G., 2008, Eocene exhumation and basin development in the Puna of
885 northwestern Argentina: *Tectonics*, doi: 10.1029/2007TC002127.
- 886 Carrapa, B., Reyes-Bywater, S., Safipour, R., Sobel, E. R., Schoenbohm, L. M., DeCelles, P. G., Reiners,
887 P. W., and Stockli, D., 2014, The effect of inherited paleotopography on exhumation of the
888 Central Andes of NW Argentina: *Geological Society of America Bulletin*, v. 126, no. 1-2, p. 66-
889 77.
- 890 Carrera, N., and Munoz, J. A., 2008, Thrusting evolution in the southern Cordillera Oriental (northern
891 Argentine Andes): Constraints from growth strata: *Tectonophysics*, v. 459, no. 1-4, p. 107-122.
- 892 Champagnac, J.-D., Molnar, P., Sue, c., and Herman, F., 2012, Tectonics, climate, and mountain
893 topography: *Journal of Geophysical Research*, v. 117, B02403, doi: 10.1029/2011JB008348.
- 894 Corbett, L.B., Bierman, P.R., and Rood, D.H., 2016, An approach for optimizing *in situ* cosmogenic ¹⁰Be
895 sample preparation: *Quaternary Geochronology*, v. 33, p. 24-34, doi:
896 10.1016/j.quageo.2016.02.001.
- 897 Coutand, I., Carrapa, B., Deeken, A., Schmitt, A. K., Sobel, E. R., and Strecker, M. R., 2006, Propagation
898 of orographic barriers along an active range front: insights from sandstone petrography and
899 detrital apatite fission-track thermochronology in the intramontane Angastaco basin, NW
900 Argentina: *Basin Research*, v. 18, no. 1, p. 1-26.
- 901 Crosby, B. T., and Whipple, K. X., 2006, Knickpoint initiation and distribution within fluvial networks:
902 236 waterfalls in the Waipaoa River, North Island, New Zealand: *Geomorphology*, v. 82, no. 1-2,
903 p. 16-38.
- 904 Cyr, A. J., Granger, D. E., Olivetti, V., and Molin, P., 2014, Distinguishing between tectonic and
905 lithologic controls on bedrock channel longitudinal profiles using cosmogenic Be-10 erosion
906 rates and channel steepness index: *Geomorphology*, v. 209, p. 27-38.
- 907 D'Arcy, M., Schildgen, T.F., Strecker, M.R., Wittmann, H., Duesing, W., Mey, J., Tofelde, S.,
908 Weissmann, P., and Alonso, R.N., 2019, Timing of past glaciation at the Sierra de Aconquija,
909 northwestern Argentina, and throughout the Central Andes: *Quaternary Science Reviews*, v. 204,
910 p. 37-57, doi: 10.1016/j.quascirev.2018.11.022.
- 911 D'Arcy, M., and Whittaker, A.C., 2014, Geomorphic constraints on landscape sensitivity to climate in
912 tectonically active areas: *Geomorphology*, v., 204, p. 366-381, doi:
913 10.1016/j.geomorph.2013.08.019.
- 914 Davis, D., Suppe, J., and Dahlen, F. A., 1983, Mechanics of fold-and-thrust belts and accretionary
915 wedges: *Journal of Geophysical Research*, v. 88, no. NB2, p. 1153-1172.
- 916 Do Campo, M., and Guevara, S. R., 2005, Provenance analysis and tectonic setting of late Neoproterozoic
917 metasedimentary successions in NW Argentina: *Journal of South American Earth Sciences*, v. 19,
918 no. 2, p. 143-153.
- 919 Ellis, M.A., and Barnes, J.B., 2015, A global perspective on the topographic response to fault growth:
920 *Geosphere*, v. 11, p. 1008-1023, doi: 10.1130/GES01156.1.
- 921 England, P., and Molnar, P., 1990, Surface uplift, uplift of rocks, and exhumation of rocks: *Geology*, v.
922 18, p. 1173-1177.
- 923 Finnegan, N.J., Schumer, R., and Finnegan, S., 2014, A signature of transience in bedrock river incision
924 over timescales of 10⁴-10⁷ years: *Nature*, v. 505, p. 391-394, doi:10.1038/nature12913.

- 925 Francis, P. W., Sparks, R. S. J., Hawkesworth, C. J., Thorpe, R. S., Pyle, D. M., Tait, S. R., Mantovani,
 926 M. S., and McDermott, F., 1989, Petrology and geochemistry of volcanic rocks of the Cerro
 927 Galan caldera, northwest Argentina: *Geological Magazine*, v. 126, no. 5, p. 515-547.
- 928 Fritz, S. C., Baker, P. A., Lowenstein, T. K., Seltzer, G. O., Rigsby, C. A., Dwyer, G. S., Tapia, P. M.,
 929 Arnold, K. K., Ku, T. L., and Luo, S. D., 2004, Hydrologic variation during the last 170,000 years
 930 in the southern hemisphere tropics of South America: *Quaternary Research*, v. 61, no. 1, p. 95-
 931 104.
- 932 Gasparini, N.M., and Whipple, K.X., 2014, Diagnosing climatic and tectonic controls on topography:
 933 Eastern flank of the northern Bolivian Andes: *Lithosphere*, v. 6, p. 230-250, doi: 10.1130/L322.1.
- 934 Gile, L. H., Peterson, F. F., and Grossman, R. B., 1966, Morphological and genetic sequences of
 935 carbonate accumulation in desert soils: *Soil Science*, v. 101, no. 5, p. 347-&.
- 936 Godard, V., Bourles, D.L., Spinabella, F., Burbank, D.W., Boohkagen, B., Burch Fisher, G., Moulin, A.,
 937 and Leanni, L., 2014, Dominance of tectonics over climate in Himalayan denudation: *Geology*, v.
 938 42, p. 243-246, doi: 10.1130/G35342.1.
- 939 González Bonorino, G., and Abascal, L. D., 2012, Drainage and base-level adjustments during evolution
 940 of a late Pleistocene piggyback basin, Eastern Cordillera, Central Andes of northwestern
 941 Argentina: *Geological Society of America Bulletin*, v. 124, no. 11-12, p. 1858-1870.
- 942 Gosse, J. C., and Phillips, F. M., 2001, Terrestrial in situ cosmogenic nuclides: theory and application:
 943 *Quaternary Science Reviews*, v. 20, no. 14, p. 1475-1560.
- 944 Granger, D. E., Kirchner, J. W., and Finkel, R., 1996, Spatially averaged long-term erosion rates
 945 measured from in situ-produced cosmogenic nuclides in alluvial sediments: *Journal of Geology*,
 946 v. 104, no. 3, p. 249-257.
- 947 Grier, M. E., Salfity, J. A., and Allmendinger, R. W., 1991, Andean reactivation of the Cretaceous Salta
 948 rift, northwestern Argentina: *Journal of South American Earth Sciences*, v. 4, no. 4, p. 351-372.
- 949 Guzmán, S., Strecker, M.R., Martí, J., Petrinovic, I.A., Schildgen, T.F., Grosse, P., Montero-López, C.,
 950 Neri, M., Carniel, R., Hongn, F., Muruaga, C., and Sudo, M., 2017, Construction and degradation
 951 of a broad volcanic massif: The Vicuña Pampa volcanic complex, southern Central Andes, NW
 952 Argentina: *Geological Society of America Bulletin*, v. 129, p. 750-766.
- 953 Hain, M. P., Strecker, M. R., Bookhagen, B., Alonso, R. N., Pingel, H., and Schmitt, A. K., 2011,
 954 Neogene to Quaternary broken foreland formation and sedimentation dynamics in the Andes of
 955 NW Argentina (25 degrees S): *Tectonics*, v. 30.
- 956 Harkins, N., Kirby, E., Heimsath, A., Robinson, R., and Reiser, U., 2007, Transient fluvial incision in the
 957 headwaters of the Yellow River, northeastern Tibet, China: *Journal of Geophysical Research-
 958 Earth Surface*, v. 112, no. F3.
- 959 Haselton, K., Hilley, G., and Strecker, M. R., 2002, Average Pleistocene climatic patterns in the southern
 960 central Andes: Controls on mountain glaciation and paleoclimate implications: *Journal of
 961 Geology*, v. 110, no. 2, p. 211-226.
- 962 Herman, F., Seward, D., Valla, P.G., Carter, A., Kohn, B., Willet, S.D., and Ehlers, T.A., 2013,
 963 Worldwide acceleration of mountain erosion under a cooling climate: *Nature*, v. 504, p. 423-427,
 964 doi:10.1038/nature12877.
- 965 Hidy, A. J., Gosse, J. C., Pederson, J. L., Mattern, J. P., and Finkel, R. C., 2010, A geologically
 966 constrained Monte Carlo approach to modeling exposure ages from profiles of cosmogenic
 967 nuclides: An example from Lees Ferry, Arizona: *Geochemistry Geophysics Geosystems*, v. 11, p.
 968 18.
- 969 Hilley, G. E., Blisniuk, P. M., and Strecker, M. R., 2005, Mechanics and erosion of basement-cored uplift
 970 provinces: *Journal of Geophysical Research-Solid Earth*, v. 110, no. B12.
- 971 Hilley, G. E., and Coutand, I., 2010, Links between topography, erosion, rheological heterogeneity, and
 972 deformation in contractional settings: Insights from the central Andes: *Tectonophysics*, v. 495,
 973 no. 1-2, p. 78-92.

- 974 Hilley, G. E., and Strecker, M. R., 2005, Processes of oscillatory basin filling and excavation in a
 975 tectonically active orogen: Quebrada del Toro Basin, NW Argentina: *Geological Society of*
 976 *America Bulletin*, v. 117, no. 7-8, p. 887-901.
- 977 Hobley, D.E.J., Sinclair, H.D., Mudd, S.M., and Cowie, P.A., 2011, Field calibration of sediment flux
 978 dependent river incision: *Journal of Geophysical Research* v. 116, F04017, doi:
 979 10.1029/2010JF001935.
- 980 Hongn, F., Papa, C. d., Powell, J., Petrinovic, I., Mon, R., and Deraco, V., 2007, Middle Eocene
 981 deformation and sedimentation in the Puna-Eastern Cordillera transition (23°-26°S): Control by
 982 preexisting heterogeneities on the pattern of initial Andean shortening: *Geology*, v. 35, no. 3, p.
 983 271-274.
- 984 Humphrey, N. F., and Konrad, S. K., 2000, River incision or diversion in response to bedrock uplift:
 985 *Geology*, v. 28, no. 1, p. 43-46.
- 986 Jull, A. J. T., Scott, E. M., and Bierman, P., 2014, The CRONUS-Earth inter-comparison for cosmogenic
 987 isotope analysis: *Quaternary Geochronology*, doi: 10.1016/j.quageo.2013.09.003.
- 988 Kirby, E., and Whipple, K. X., 2012, Expression of active tectonics in erosional landscapes: *Journal of*
 989 *Structural Geology*, v. 44, p. 54-75.
- 990 Kohl, C., and Nishiizumi, K., 1992, Chemical isolation of quartz for measurement of in-situ-produced
 991 cosmogenic nuclides: *Geochimica et Cosmochimica Acta*, v. 56, no. 9, p. 3583-3587.
- 992 Lal, D., 1991, Cosmic ray labeling of erosion surfaces; in situ nuclide production rates and erosion
 993 models: *Earth and Planetary Science Letters*, v. 104, no. 2-4, p. 424-439.
- 994 Lanza, F., Tibaldi, A., Bonali, F. L., and Corazzato, C., 2013, Space-time variations of stresses in the
 995 Miocene-Quaternary along the Calama-Olacapato-El Toro Fault Zone, Central Andes:
 996 *Tectonophysics*, v. 593, p. 33-56.
- 997 Marquillas, R. A., del Papa, C., and Sabino, I. F., 2005, Sedimentary aspects and paleoenvironmental
 998 evolution of a rift basin: Salta Group (Cretaceous-Paleogene), northwestern Argentina:
 999 *International Journal of Earth Sciences*, v. 94, no. 1, p. 94-113.
- 1000 Mason, C.C., and Romans, B.W., Climate-driven unsteady denudation and sediment flux in a high-relief
 1001 unglaciated catchment-fan using ²⁶Al and ¹⁰Be: Panamint Valley, California: *Earth and Planetary*
 1002 *Science Letters*, v. 492, p. 130-143, doi:10.1016/j.epsl.2018.03.056.
- 1003 May, J. H., and Soler, R. D., 2010, Late Quaternary morphodynamics in the Quebrada de Purmamarca,
 1004 NW Argentina: *Quaternary Science Journal*, v. 59, no. 1-2, p. 21-35.
- 1005 Molnar, P. and England, P., 1990, Late Cenozoic uplift of mountain ranges and global climate change:
 1006 chicken or egg? *Nature*, v. 346, p. 29-34.
- 1007 Montgomery, D.R., Balco, G., Willett, S.D., 2001, Climate, tectonics, and the morphology of the Andes:
 1008 *Geology*, v. 29, p. 579-582.
- 1009 Nishiizumi, K., Imamura, M., Caffee, M. W., Southon, J. R., Finkel, R. C., and McAninch, J., 2007,
 1010 Absolute calibration of Be-10 AMS standards: *Nuclear Instruments & Methods in Physics*
 1011 *Research Section B-Beam Interactions with Materials and Atoms*, v. 258, no. 2, p. 403-413.
- 1012 Ouimet, W. B., Whipple, K. X., and Granger, D. E., 2009, Beyond threshold hillslopes: Channel
 1013 adjustment to base-level fall in tectonically active mountain ranges: *Geology*, v. 37, no. 7, p. 579-
 1014 582.
- 1015 Pearson, D. M., Kapp, P., Reiners, P. W., Gehrels, G. E., Ducea, M. N., Pullen, A., Otamendi, J. E., and
 1016 Alonso, R. N., 2012, Major Miocene exhumation by fault-propagation folding within a
 1017 metamorphosed, early Paleozoic thrust belt: Northwestern Argentina: *Tectonics*, v. 31.
- 1018 Pingel, H., Mulch, A., Alonso, R.N., Cottle, J., Hynek, S.A., Poletti, J., Rohrmann, A., Schmitt, A.K.,
 1019 Stockli, D.F., and Strecker, M.R., 2016, Surface uplift and convective rainfall along the southern
 1020 Central Andes (Angastaco Basin, NW Argentina): *Earth and Planetary Science Letters*, v. 440, p.
 1021 33-42.
- 1022 Pingel, H., Alonso, R.N., Mulch, A., Rohrmann, A., Sudo, M., and Strecker, M.R., 2014, Pliocene
 1023 orographic barrier uplift in the southern Central Andes: *Geology*, v. 42 (8), p. 691-694.

- 1024 Portenga, E. W., and Bierman, P. R., 2011, Understanding Earth's eroding surface with ^{10}Be : *GSA Today*,
 1025 v. 21, no. 8, p. 4 - 8.
- 1026 Reheis, M. C., 1987, Gypsic Soils on the Kane Alluvial Fans, Big Horn County, Wyoming: United States
 1027 Geological Survey Bulletin, v. Report 1590-C, p. C1-C39.
- 1028 Reheis, M. C., Goodmacher, J. C., Harden, J. W., McFadden, L. D., Rockwell, T. K., Shroba, R. R.,
 1029 Sowers, J. M., and Taylor, E. M., 1995, Quaternary soils and dust deposition in southern Nevada
 1030 and California: *Geological Society of America Bulletin*, v. 107, no. 9, p. 1003-1022.
- 1031 Royer, D. L., 1999, Depth to pedogenic carbonate horizon as a paleoprecipitation indicator?: *Geology*, v.
 1032 27, no. 12, p. 1123-1126.
- 1033 Santimano, T., and Riller, U., 2012, Kinematics of Tertiary to Quaternary intracontinental deformation of
 1034 upper crust in the Eastern Cordillera, southern Central Andes, NW Argentina: *Tectonics*, v. 31.
- 1035 Schildgen, T.F., van der Beek, P.A., Sinclair, H.D., and Thiede, R.C., 2018, Spatial correlation bias in
 1036 Late Cenozoic erosion histories derived from thermochronology: *Nature*, v. 559, p. 89-93,
 1037 doi:10.1038/s41586-018-0260-6.
- 1038 Schlunegger, F., Norton, K. P., and Zeilinger, G., 2011, Climatic Forcing on Channel Profiles in the
 1039 Eastern Cordillera of the Coroico Region, Bolivia: *Journal of Geology*, v. 119, no. 1, p. 97-107.
- 1040 Schumer, R., and Jerolmack, D.J., 2009, Real and apparent changes in sediment deposition rates through
 1041 time: *Journal of Geophysical Research*, v. 114, F00A06, doi:10.1029/2009JF001266.
- 1042 Schoenbohm, L.M., Carrapa, B., McPherson, H.M., Pratt, J.R., Bywater-Reyes, S., and Mortimer, E.,
 1043 2015, Climate and tectonics along the southern margin of the Puna Plateau, NW Argentina:
 1044 Origin of the late Cenozoic Puna Schotter conglomerates, *in* DeCelles, P.G., Ducea, M.N.,
 1045 Carrapa, B., and Kapp, P.A., eds., *Geodynamics of a Cordilleran Orogenic System: The Central*
 1046 *Andes of Argentina and Northern Chile: Geological Society of America Memoir 212*, p. 251-260.
- 1047 Schoenbohm, L. M., and Strecker, M. R., 2009, Normal faulting along the southern margin of the Puna
 1048 Plateau, northwest Argentina: *Tectonics*, v. 28.
- 1049 Schoenbohm, L. M., Whipple, K. X., Burchfiel, B. C., and Chen, L., 2004, Geomorphic constraints on
 1050 surface uplift, exhumation, and plateau growth in the Red River region, Yunnan Province, China:
 1051 *Geological Society of America Bulletin*, v. 116, no. 7-8, p. 895-909.
- 1052 Seidl, M.A., and Dietrich, W.E., 1992, The Problem of Channel Erosion into Bedrock: *Catena*
 1053 *Supplement*, v. 23, p. 101-124.
- 1054 Sobel, E. R., Hilley, G. E., and Strecker, M. R., 2003, Formation of internally drained contractional basins
 1055 by aridity-limited bedrock incision: *Journal of Geophysical Research-Solid Earth*, v. 108, no. B7.
- 1056 Sobel, E. R., and Strecker, M. R., 2003, Uplift, exhumation and precipitation: tectonic and climatic
 1057 control of Late Cenozoic landscape evolution in the northern Sierras Pampeanas, Argentina:
 1058 *Basin Research*, v. 15, no. 4, p. 431-451.
- 1059 Sparks, R. S. J., Francis, P. W., Hamer, R. D., Pankhurst, R. J., Ocallaghan, L. O., Thorpe, R. S., and
 1060 Page, R., 1985, Ignimbrites of the Cerro Galan Caldera, NW Argentina: *Journal of Volcanology*
 1061 *and Geothermal Research*, v. 24, no. 3-4, p. 205-248.
- 1062 Staff, S. S., 2010, Keys to Soil Taxonomy, 11th ed., *in* USDA-NRCS, ed.: Washington, DC.
- 1063 Strecker, M.R., Alonso, R.N., Bookhagen, B., Carrapa, B., Coutand, I., Hain, M.P., Hilley, G.E.,
 1064 Mortimer, E., Schoenbohm, L., and Sobel, E.R., 2009, Does the topographic distribution of the
 1065 central Andean Puna Plateau result from climatic or geodynamic processes?: *Geology*, v. 37(7),
 1066 p. 643-646.
- 1067 Strecker, M. R., Alonso, R. N., Bookhagen, B., Carrapa, B., Hilley, G. E., Sobel, E. R., and Trauth, M.
 1068 H., 2007, Tectonics and climate of the southern central Andes: *Annual review of Earth and*
 1069 *Planetary Sciences*, Volume 35: Palo Alto, Annual Reviews, p. 747-787.
- 1070 Strecker, M. R., Cervený, P., Bloom, A. L., and Malizia, D., 1989, Late Cenozoic tectonism and
 1071 landscape development in the foreland of the Andes - Northern Sierras Pampeanas (26°-28°S),
 1072 Argentina: *Tectonics*, v. 8, no. 3, p. 517-534.
- 1073 Tofelde, S., Schilden, T.F., Savi, S., Pingel, H., Wickert, A.D., Bookhagen, B., Wittmann, H., Alonso,
 1074 R.N., Cottle, J., and Strecker, M.R., 2017, 100 kyr fluvial cut-and-fill terrace cycles since the

- 1075 Middle Pleistocene in the southern Central Andes, NW Argentina: *Earth and Planetary Science*
 1076 *Letters*, v. 473, p. 141-153, doi: 10.1016/j.epsl.2017.06.001.
- 1077 Trauth, M. H., Bookhagen, B., Muller, A. B., and Strecker, M. R., 2003a, Late pleistocene climate change
 1078 and erosion in the Santa Maria Basin, NW Argentina: *Journal of Sedimentary Research*, v. 73, no.
 1079 1, p. 82-90.
- 1080 Trauth, M. H., Bookhagen, B., Marwan, N., and Strecker, M. R., 2003b, Multiple landslide clusters
 1081 record Quaternary climate changes in the northwestern Argentine Andes: *Palaeogeography*
 1082 *Palaeoclimatology Palaeoecology*, v. 194, no. 1-3, p. 109-121, doi: 10.1016/S0031-
 1083 0182(03)00273-6..
- 1084 Val, P., Venerdini, A.L., Ouimet, W., Alvarado, P., and Hoke, G.D., 2018, Tectonic control of erosion in
 1085 the southern Central Andes: *Earth and Planetary Science Letters*, v. 482, p. 160-170.
- 1086 von Blanckenburg, F., 2005, The control mechanisms of erosion and weathering at basin scale from
 1087 cosmogenic nuclides in river sediment: *Earth and Planetary Science Letters*, v. 237, no. 3-4, p.
 1088 462-479.
- 1089 Walsh, L.S., Martin, A.J., Ojha, T.P., and Fedenczuk, T., 2012, Correlations of fluvial knickzones with
 1090 landslide dams, lithologic contacts, and faults in the southwestern Annapurna Range, central
 1091 Nepalese Himalaya: *Journal of Geophysical Research*, v. 117, F01012, doi:
 1092 10.1029/2011JF001984.
- 1093 Whipple, K. X., 2004, Bedrock rivers and the geomorphology of active orogens: *Annual review of Earth*
 1094 *and Planetary Sciences*, v. 32, p. 151-185.
- 1095 Whipple, K.X., 2009, The influence of climate on the tectonic evolution of mountain belts: *Nature*
 1096 *Geoscience*, v. 2, no. 2, p. 97-104.
- 1097 Whipple, K. X., DiBiase, R. A., and Crosby, B. T., 2013, 9.28 Bedrock Rivers, *in* Shroder, J. F., ed.,
 1098 *Treatise on Geomorphology*: San Diego, Academic Press, p. 550-573.
- 1099 Whipple, K.X., and Gasparini, N.M., 2014, Tectonic control of topography, rainfall patterns, and erosion
 1100 during rapid post-12 ma uplift of the Bolivian Andes: *Lithosphere*, v. 6, p. 251-268, doi:
 1101 10.1130/L325.1.
- 1102 Whipple, K. X., and Tucker, G. E., 1999, Dynamics of the stream-power river incision model:
 1103 Implications for height limits of mountain ranges, landscape response timescales, and research
 1104 needs: *Journal of Geophysical Research-Solid Earth*, v. 104, no. B8, p. 17661-17674.
- 1105 Whipple, K.X., and Tucker, G.E., 2002, Implications of sediment-flux-dependent river incision models
 1106 for landscape evolution: *Journal of Geophysical Research-Solid Earth*, v. 107, no. B2.
- 1107 Wickert, A.D., and Schildgen, T.F., 2019, Long-profile evolution of transport-limited gravel-bed rivers:
 1108 *Earth Surface Dynamics*, v. 7, p. 17-43, doi:10.5194/esurf-7-17-2019.
- 1109 Willenbring, J.K. and von Blanckenburg, F., 2010, Long-term stability of global erosion rates and
 1110 weathering during late-Cenozoic cooling: *Nature*, v. 465, p. 211-214, doi:10.1038/nature09044.
- 1111 Willett, S. D., 1999, Orogeny and orography: The effects of erosion on the structure of mountain belts:
 1112 *Journal of Geophysical Research: Solid Earth*, v. 104, no. B12, p. 28957-28981.
- 1113 Wobus, C., Whipple, K. X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B., and Sheehan,
 1114 D., 2006a, Tectonics from topography: Procedures, promise, and pitfalls: *Tectonics, Climate, and*
 1115 *Landscape Evolution*, v. 398, p. 55-74, doi: 10.1130/2006.2398(04).
- 1116 Wobus, C. W., Crosby, B. T., and Whipple, K. X., 2006b, Hanging valleys in fluvial systems: Controls on
 1117 occurrence and implications for landscape evolution: *Journal of Geophysical Research-Earth*
 1118 *Surface*, v. 111, no. F2.
- 1119 Xu, S., Dougans, A. B., Freeman, S. P. H. T., Schnabel, C., and Wilcken, K. M., 2010, Improved ¹⁰Be
 1120 and ²⁶Al-AMS with a 5 MV spectrometer: *Nuclear Instruments & Methods in Physics Research*
 1121 *Section B-Beam Interactions with Materials and Atoms*, v. 268, p. 3.
- 1122 Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, Rhythms, and Aberrations in
 1123 *Global Climate 65 Ma to Present*: *Science*, v. 292, p. 686-693, doi:10.1126/science.1059412.

- 1124 Zech, J., Terrizzano, C., Garcia-Morabito, E., Veit, H., and Zech, R., 2017, Timing and extent of late
1125 Pleistocene glaciation in the arid Central Andes of Argentina and Chile: Geographical Research
1126 Letters, v. 43(2), p. 697-718.
- 1127 Zhou, R. J., Schoenbohm, L. M., and Cosca, M., 2013, Recent, slow normal and strike-slip faulting in the
1128 Pasto Ventura region of the southern Puna Plateau, NW Argentina: Tectonics, v. 32, no. 1, p. 19-
1129 33.
- 1130
1131

1132 **Figure Captions**

1133 **Figure 1.** Composite digital elevation model and shaded relief map of the south central Andes
 1134 indicating major tectonomorphic provinces. Thick black line delineates internally drained Puna
 1135 Plateau from the externally drained Eastern Cordillera and Sierras Pampeanas. Black box shows
 1136 the extent of Figure 2, the Pucará Valley, where field studies were focused. Blue line outlines the
 1137 Calchaqui River catchment (CRC), as shown in Figures 3 and 6. Inset: digital elevation model
 1138 indicating location of large map with black box.

1139

1140 **Figure 2.** Quaternary strath terraces and pediment surfaces in the Pucará Valley. Depositional
 1141 ages derived from cosmogenic ^{10}Be depth profiles. Numbered soil pits are described in Table 1.
 1142 JVT = Jasimaná-Vallecito Thrust. SQT = Sierra de Quilmes Thrust. PT = Pucará Thrust. See
 1143 Supporting Information Figure S94 for complete geologic map. Fault nomenclature and structure
 1144 modified from Carrera and Muñoz, 2008. Location shown by black box in Figure 1.

1145

1146 **Figure 3.** Shaded relief map of the CRC, ^{10}Be catchment mean erosion rates, in mm kyr^{-1} , and
 1147 corresponding subcatchments (labeled) from this study and Bookhagen and Strecker (2012).
 1148 Basin extent shown by blue line in Figure 1.

1149

1150 **Figure 4.** Photograph taken from the site of the Q5 depth profile in Figure 2, looking
 1151 approximately northeast. Foreground shows Q5 strath terrace beveled into sedimentary rocks of
 1152 the Tertiary Payogastilla Group, which rest in angular unconformity over Cretaceous Pirgua (Kp)
 1153 Group redbeds. Across the river, Q2, Q3, Q4, Q6 and Q7 surfaces are beveled into both Tertiary
 1154 Payogastilla (Tp) and Cretaceous sedimentary units. Rio Pucará flows from right (south) to left
 1155 (north). Note sloping beds marking monocline within Cretaceous units beneath the Q7 surface,
 1156 indicated by angled arrows. High ranges are composed of the Neoproterozoic Puncoviscana
 1157 Formation.

1158

1159 **Figure 5.** Field photographs of representative pedogenic carbonate development on shallow soil
 1160 mantled pediment surfaces in the study area. Carbonate stages according to classification scheme
 1161 of Gile et al. (1966).

1162

1163 **Figure 6.** (a) Lithologic divisions, major faults, and knickpoints in the CRC. Knickpoints
1164 according to legend in (b). Newly identified faults marked by heavy dashed lines outlined in red,
1165 with sense of displacement indicated (U = Up, D = Down). CNT = Cerro Negro Thrust (Carrapa
1166 et al., 2011). (b) Normalized channel steepness indices and knickpoints in the CRC. Labeled
1167 streams are displayed in profile in Figure 7. (c) Concavity indices and mean annual rainfall in
1168 the CRC. Knickpoints according to legend in (b). TRMM precipitation data from Bookhagen and
1169 Strecker (2008). See text for description of knickpoint typology and channel regression
1170 parameters. Basin extent shown by blue line in Figure 1.

1171

1172 **Figure 7.** Selected longitudinal river profiles and corresponding local slope/drainage area
1173 regressions. Individual segments are bound by knickpoints or confluences with trunk streams. In
1174 slope-area space light blue lines represent best-fit regressions, from which concavity (θ) is
1175 determined, and red lines represent regressions with a fixed slope ($\theta_{\text{ref}} = 0.45$), from which
1176 steepness index (k_{sn}) is determined. Dashed lines outlined in red mark newly mapped faults with
1177 unknown dip. See Figure 6b for stream locations. CNT = Cerro Negro Thrust; PT = Pucara
1178 Thrust; JVT = Jasimaná-Vallecito Thrust; see Figure 2 for locations of these structures.

1179

1180 **Figure 8.** In situ ^{10}Be depth profiles and monte carlo simulator results for age, inheritance, and
1181 surface erosion rates when run for 10^6 solutions at 2 sigma uncertainty, according to parameters
1182 described in the text and Supporting Information. Black line is the best fit. Gray lines are all
1183 other model solutions. White circles with black outlines are subsurface samples used in the
1184 model simulations. White circles with grey outlines are surface sediment samples that were
1185 analyzed, but not used in model simulations due to evidence of bioturbation. White square with
1186 grey outline represents a quartz cobble amalgamation ($n=85$) sample that was similarly excluded
1187 from model simulations.

1188

1189 **Figure 9.** Vertical distribution of knickpoints in the CRC. See Figure 6 for plan view.

1190

1191

1192

1193 **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

1194 *Pit locations indicated in Figure 2.

1195

1196 **Table 2.** Catchment mean erosion rates and corresponding topographic and climatic

1197 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

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

1198 * contribution of sub-basins removed

1199

1200

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

Depth Profile	Surface Age	Vertical Incision Rate*		Inherited Catchment Mean Erosion Rate**	Vertical Incision/ Inherited Catchment Mean	Modern Catchment Mean Erosion Rate
	(ka)	Total Incision (m)	Most Probable Rate (mm kyr ⁻¹ 2σ)	Most Probable Rate (mm kyr ⁻¹ 2σ)		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)

1201 *Rates derived from ¹⁰Be profile ages and surface height

1202 ** Rates derived from ¹⁰Be inheritance

1203