Basins and bedrock: Spatial variation in ^{10}Be erosion rates and increasing relief in the southern Rocky Mountains, USA

David P. Dethier[1], Will Ouimet[2], Paul R. Bierman[3], Dylan H. Rood[4], and Greg Balco[5]
[1]Department of Geosciences, Williams College, Williamstown, Massachusetts 01267, USA
[2]Department of Geography and Center for Integrative Geosciences University of Connecticut, Storrs, Connecticut 06269, USA
[3]Department of Geology and Rubenstein School of the Environment and Natural Resources, University of Vermont, 180 Colchester Ave., Burlington, Vermont 05405, USA
[4]Scottish Universities Environmental Research Centre (SUERC), Rankine Avenue, East Kilbride G75 0QF, Scotland, UK
[5]Berkeley Geochronology Center 2455 Ridge Road, Berkeley, California 94709, USA

ABSTRACT

We used measurements of cosmogenic ^{10}Be in alluvium to estimate erosion rates on a 10^3–10^4 yr time scale for small (0.01–47 km^2), unglaciated basins in northern Colorado, southern Wyoming, and adjacent western Nebraska (western United States). Basins formed in Proterozoic cores of Laramide ranges are eroding more slowly (23 ± 7 mm k.y.$^{-1}$, n = 19) than adjacent basins draining weakly lithified Cenozoic sedimentary rocks (75 ± 36 mm k.y.$^{-1}$, n = 20). Erosion rates show a relationship to rock resistance and, for granitic rocks, to basin slope, but not to mean annual precipitation. We estimated longer-term (>10^5 yr time scale) erosion rates for the granitic core of the Front Range by measuring the concentration of ^{10}Be and ^{26}Al produced mainly by muon interactions at depths 1.7–10 m below the surface. Concentrations imply erosion rates of 9–31 mm k.y.$^{-1}$, similar to shorter-term erosion rates inferred from alluvial sediment. The spatial distribution of erosion rates and stratigraphic evidence imply that relief in the southern Rocky Mountains increased in the late Cenozoic; modern relief probably dates from post-middle Miocene time.

INTRODUCTION

Understanding topographic steepness, erosion rates, and landscape evolution in the context of tectonic forcing, climatic change, and lithological variation is a central focus of surface processes research (e.g., Whittaker, 2012; Hurst et al., 2013). Erosion rates measured using cosmogenic isotopes such as ^{10}Be correlate globally with basin slope (Portenga and Bierman, 2011), but where bedrock includes weakly lithified materials, erosion rates and the generation of relief also could depend on rock type. In this study, we report a suite of ^{10}Be erosion rates that highlight the role of rock resistance, local slope, and late Quaternary climate change in shaping the southern Rocky Mountain landscape. The landscape exposes contrasting rock types, and transient incision and dissection have created a wide range of topographic slopes.

BACKGROUND AND SETTING

The southern Rocky Mountains (western United States) were exhumed rapidly during and soon after the Laramide orogeny and a rolling surface truncated Laramide uplifts by Late Eocene time (Scott and Taylor, 1986). Apatite-fission track data demonstrate that most exposed rocks in the Laramide cores cooled below blocking temperatures by ca. 50 Ma (Karlstrom et al., 2012). Adjacent basins filled with relatively short-traveled sediment (McMillan et al., 2006), but regional transport of sediment from the region lagged orogenic activity and rapid erosion by tens of millions of years (Tucker and van der Beek, 2012). Persistent erosion of Cenozoic sedimentary rocks began before early Pliocene time, a phenomenon variously ascribed to cooling global climate, a change to snowmelt-dominated discharge, rock uplift, integration of regional drainage systems such as the Platte and upper Colorado Rivers, and headward cutting of deep canyons into Proterozoic basement (Zaprowski et al., 2005; Wobus et al., 2010; Karlstrom et al., 2012). Geomorphic evidence in Colorado and southern Wyoming (Leonard, 2002; McMillan et al., 2002) suggests that rates of rock uplift increased in Neogene time.

We focus on the Laramide ranges of Colorado and Wyoming, which rise 1000–1800 m above the High Plains and adjacent intermontane basins. With the exception of high-elevation glaciated valleys and deeply incised river canyons, most of the landscape consists of rolling, relatively gentle slopes. Temperature and mean annual precipitation (MAP) correlate strongly with elevation: average temperature ranges from –4 °C at 3800 m to nearly 12 °C in western Nebraska, and MAP ranges from 100 cm near range crests to 25 cm in southern Wyoming and western Nebraska (PRISM Climate Group data; prism.oregonstate.edu). During the latest Pleistocene, regional climate was colder and episodically wetter (Lyle et al., 2012). Valley glaciers stretched as far as 20 km from cirques to an elevation of ~2800 m, flanked by an active periglacial landscape (Madole et al., 1998). Early Holocene climate was warmer and wetter than at present, the middle Holocene mainly was warm and dry and the past 4000 yr have been relatively cool and moist (Muhs and Benedict, 2006).

We use descriptions of bedrock from regional mapping (compiled in McMillan et al., 2006), particularly lithification and grain size, as a qualitative proxy for resistance to erosion. Cores of the Laramide ranges in the study area expose resistant Proterozoic granitic and gneissic rocks; adjacent Cenozoic basins contain weakly lithified terrestrial sedimentary rocks, unconformably overlying fine-grained Mesozoic bedrock. Cenozoic rocks include sandstone and siltstone that underlie rolling hills eroded into badlands; some formations (e.g., the Ogallala) include coarser sandstones and conglomerates.

METHODS

We measured ^{10}Be concentrations in quartz in channel alluvium to estimate basin-scale erosion rates for 61 basins with areas between <0.1 and 47 km^2. These mainly included unglaciated catchments developed on low-relief surfaces in the granitic cores of the Laramide ranges, particularly the Colorado Front Range, and catchments formed in adjacent sedimentary basins (Fig. 1). Included in our granitic study catchments are: (1) five alpine sites; (2) three small basins draining isolated, weathered bedrock outcrops (tors); and (3) nine catchments developed in the inner part of Boulder Canyon or Fourmile Canyon ("canyon-edge") downstream from a knickzone. Catchments lacked significant sediment storage beneath terraces, sources of sediment from deep landslides, and anthropogenic sources such as gravel-surfaced roads. We also collected 15 bedrock samples from 1.7 m to 10 m below the surface in roadcuts and prospect pits at nine sites (Fig. 1) on and near low-relief surfaces in the Front Range. Site N (Nederland) includes a seven-sample profile that extended from soil through saprolite into fresh bedrock.

We isolated quartz from the 250–710 µm fraction of sediment and extracted and concentrated ^{10}Be and ^{26}Al (see the GSA Data Repository[1]). Isotope ratios were measured by accelerator mass spectrometry. To estimate erosion rates from ^{10}Be concentrations, we computed effective

[1]GSA Data Repository item 2014044, supplemental methods, Table DR1 (measurements and cosmogenic radionuclide parameters for individual basins), Tables DR2 (detailed ^{10}Be measurements), Table DR3 (^{10}Be laboratory blanks), and Table DR4 (detailed ^{26}Al measurements and laboratory blanks), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, February 2014; v. 42; no. 2; p. 167–170; Data Repository item 2014044 | doi:10.1130/G34922.1 | Published online 6 January 2014

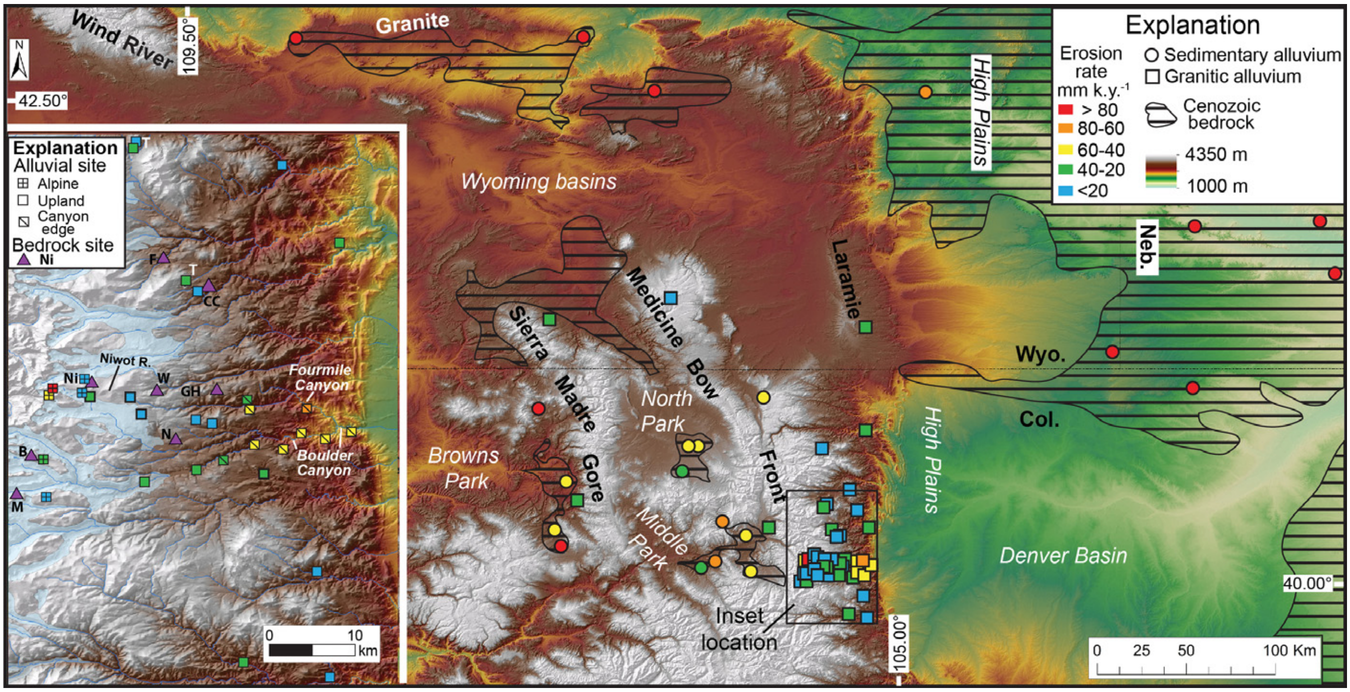

Figure 1. Map showing Laramide uplifts, adjacent Cenozoic basins (after McMillan et al., 2006) and alluvial sample sites in Colorado and Wyoming (western USA). Inset map shows selected Front Range alluvial and bedrock sites sampled for cosmogenic isotopes. Erosion rate color is the same for both parts of map. T—tor. Light-blue fill shows extent of latest Pleistocene glaciers (Madole et al., 1998).

catchment elevations and used these values as input to the online erosion rate calculator of Balco et al. (2008). We assumed an even distribution of quartz in each catchment and a rock density of 2.65 g cm^{-3}. For subsurface bedrock samples, we computed erosion rates under the assumption that nuclide concentrations reflected equilibrium between production by both neutron spallation and muon interactions and a steady erosion rate (see the Data Repository).

DATA

Erosion rates estimated from alluvial samples are related to rock type and basin slope (Fig. 2A; see the Data Repository). Erosion rates in all granitic basins range from 15 to 82 mm $k.y.^{-1}$ (Table 1). Of these, granitic basins draining rolling upland surfaces give a mean erosion rate of 23 ± 7 mm $k.y.^{-1}$ (n = 19). For equivalent slopes, most basins formed in Cenozoic rocks are eroding 2–4 times faster than the granitic basins. If we exclude extremely high rates (>2σ) measured in two basins (Fig. 2A), sedimentary rocks give erosion rates of 75 ± 36 mm $k.y.^{-1}$ (n = 20); rates are not related to basin slope ($r^2 = 0.07$; p = 0.73).

Erosion rates in the entire sample of granitic basins (Fig. 2B) are significantly lower ($p < 0.001$) than those from the Cenozoic rocks. Basin slope explains some of the variance of erosion rates in the granitic basins ($r^2 = 0.15$; $p < 0.01$), but if we exclude the steep, slow-eroding tor catchments, the relationship to slope is stronger (Fig. 2B; $r^2 = 0.56$; $p < 0.001$). Modeled erosion rates for alluvial basins in and close to the alpine zone display a range of values that may reflect different amounts of periglacial activity or local effects of snow shielding. High rates measured in steep alpine and canyon-edge catchments and at some of the sedimentary fill sites may reflect, in part, transient rates of incision related to upstream migration of knickpoints.

Erosion rates in the southern Rockies are not correlated with catchment size or MAP; observations noted by Portenga and Bierman (2011)

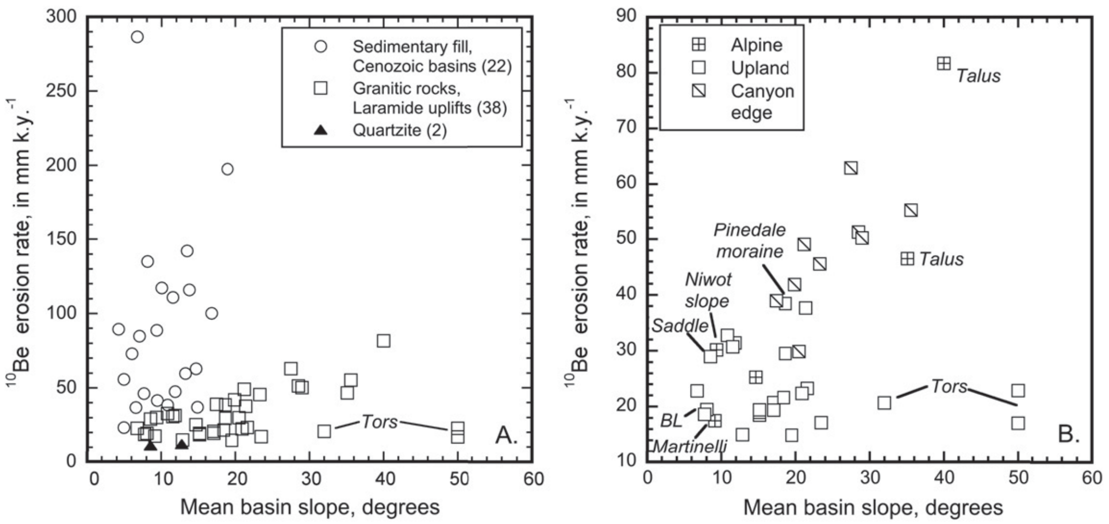

Figure 2. Relationship of erosion rate to mean basin slope. Errors (1σ) mainly are 10%–15% of measured values (see the Data Repository [see footnote 1]) and are not plotted. A: Granitic rocks, quartzite, and sedimentary fill in Cenozoic basins, southern Rocky Mountains. B: Front Range granitic rocks, including canyon-edge catchments (Boulder and Fourmile Canyons), and alpine catchments. BL is from a Bull Lake–age moraine.

TABLE 1. SUMMARY OF BASIN ATTRIBUTES AND CALCULATED EROSION RATES

Category		Number	Area (km²)	Annual precipitation* (cm)		Elevation (m)		Basin slope (°)		Calculated erosion rate (mm k.y.⁻¹)		
				Range	Mean	Range	Mean	Range	Mean	Range	Mean	±1σ
Alluvial basins												
	All granitic	37	0.001–39.5	45–93	56.6	1897–3847	2715	6.7–50	20.9	14–78.9	30.5	14.8
	Alpine	5	0.02–0.44	83–93	88.4	3518–3847	3610	9.1–40	21.6	16.5–78.9	39.3	24.7
Granitic and high-grade metamorphic	Surface of low relief	19	0.15–39.5	45–84	54.9	2024–3517	2673	6.7–23.5	15.5	14–35.9	23	6.7
	Boulder and Fourmile Canyons	9	0.12–4.31	45–45	45	1897–2536	2262	19.9–35.6	25	28.9–61.4	45.7	9.7
	Tors	3	0.001–0.01	50–57	53	2760–2910	2829	32–50	44	16.4–21.5	19.3	2.6
Cenozoic fill	All basins	22	0.3–47.3	24–70	44.2	1248–2951	2269	4.2–18.9	10.2	32.6–246.5	83.5	55.3
	Without two highest erosion rates	20	0.3–22.8	24–70	44.6	1248–2951	2320	4.2–16.7	9.9	32.6–121.4	69.3	31.3
Quartzite	All	2	0.01–3.59	45–108	76	2630–3590	n.a.	n.a.	n.a.	12.4–13.8	13.1	n.a.
Bedrock	All	15	n.a.	38–95	55.3	2480–3520	2800	n.a.	n.a.	9.0–31.2	17.9	8.1

*Data from http://prism.oregonstate.edu. n.a.—not applicable.

using a global data set. Wetter, higher elevation granitic catchments are eroding at the same rate as drier catchments and the two lowest erosion rates (12.6 and 12.0 mm k.y.⁻¹) are from quartzite basins that have MAP of 45 cm and 108 cm, respectively. The highest rates of erosion are in sparsely vegetated, semiarid badlands developed in weakly lithified, fine-grained Cenozoic rocks. High rates also may be influenced by the areal cover and rooting strength of vegetation or by effects of rainfall intensity that are not correlated with MAP.

Longer-term steady erosion rates inferred from subsurface bedrock samples are 9–31 mm k.y.⁻¹, similar to rates derived from alluvial sediment in nearby basins (Fig. 3). At Nederland, model erosion rates at intermediate depths are higher than those measured from the shallowest or deepest samples. Because cosmogenic-nuclide concentrations in deeper samples reflect a longer integration time than those in shallower samples, this variation shows that the assumption of production-erosion equilibrium used to compute erosion rates is oversimplified.

DISCUSSION

Our data and regional geologic evidence from the Rockies imply that differential erosion increases relief on time scales $>10^6$ yr where mountain ranges and adjacent sedimentary basins display sharp gradients in rock resistance. Overlap of shorter-term rates derived from alluvium with longer-term, bedrock-based rates suggests relatively steady erosion through time. Our erosion rates demonstrate that on time scales of 10^3 to $>10^4$ yr, weakly lithified rocks are eroding more rapidly than crystalline rocks in adjacent Laramide uplifts. Calculated basin-scale rates for Laramide ranges are 20–30 mm k.y.⁻¹, similar to other post-orogenic ranges (Portenga and Bierman, 2011); rates are >75 mm k.y.⁻¹ for Cenozoic rocks. Measured rates suggest that nearly 1 km of basin fill can be cleared in 12 m.y., while erosion strips a few hundred meters from adjacent ranges. Erosion data provide useful inputs to regional models that focus on how Laramide ranges and basins responded isostatically to differential exhumation and local glacial deepening.

Channel incision initiates landscape-scale erosion, which may lag knickpoint passage by millions of years in resistant rocks (Riihimaki et al., 2007). Incision rates on major drainages (Dethier, 2001), rates measured along the upper Colorado River, and some thermochronometric data from western Colorado (e.g., Aslan et al., 2010) show that incision has exceeded landscape erosion rates on time scales of 0.6–10 m.y. Geologic relations from the southern Rockies indicate that modern basin-to-range relief must postdate the Middle Miocene (Leonard, 2002). Zhang et al. (2001) showed that after Middle Miocene time, rates of sediment transport from the southern Rocky Mountains increased, implying a change in landscape-controlling variables. Plausible mechanisms include a shift to a

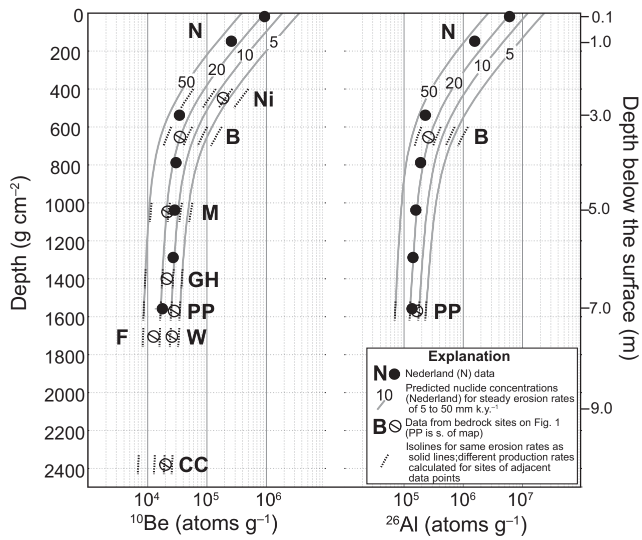

Figure 3. Relationship between sample mass depth and measured ¹⁰Be and ²⁶Al concentrations in bedrock and saprolite samples (see the Data Repository [see footnote 1]). Error bars are smaller than symbol sizes. Systematic uncertainty in erosion rate estimates is likely significantly larger than formal uncertainties computed from measurement and production rate uncertainties. Approximate scale on the right axis is nonlinear.

wetter, more seasonal climate (Pelletier, 2009) and regional drainage integration and reorientation (Zaprowski et al., 2005). Rock uplift rates and surface elevation also may have increased in response to thermal bulging associated with the Rio Grande rift in northern New Mexico and southern Colorado (McMillan et al., 2002). Neogene mantle processes may be responsible for some Neogene rock uplift in northwestern Colorado (Karlstrom et al., 2012), but geomorphic evidence is equivocal in the Front Range and to the east (Wobus et al., 2010).

The temporal snapshot provided by ^{10}Be measurements in Front Range basins suggests that channel incision and hillslope erosion increased local relief from the crest to the margins of the Front Range during late Quaternary time. Gently sloping surfaces in alpine areas are eroding at ~10 mm k.y.⁻¹ and rates are between 18 and 82 mm k.y.⁻¹ for small, steep catchments etched into alpine areas above the glacial limit (Fig. 4). Erosion of subglacial bedrock during glacial periods deepened adjacent valleys >150 mm k.y.⁻¹ (Dühnforth and Anderson, 2011), increasing relief in alpine areas. East of the glacial limit, rolling uplands are lowering at ~25 mm k.y.⁻¹, but Boulder Canyon has sliced below the surface at

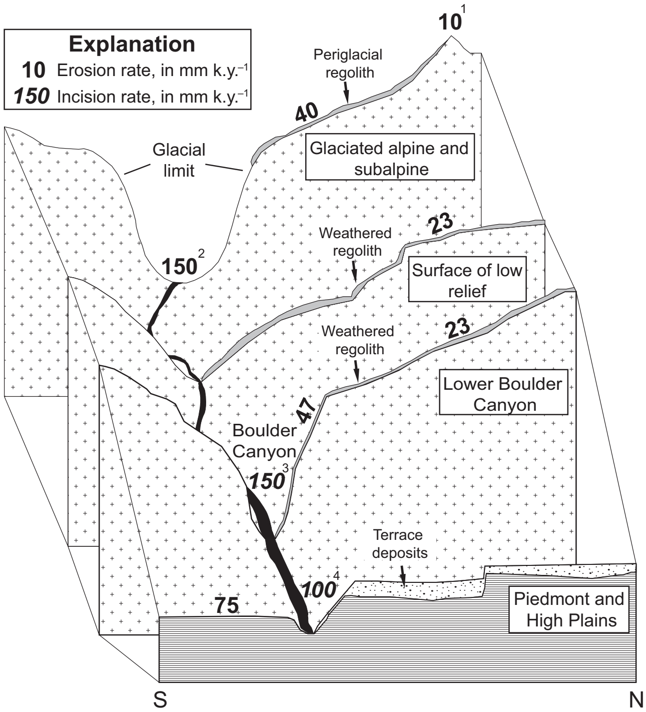

Figure 4. Sketch summarizing erosion and incision rates measured by ^{10}Be techniques for basins and bedrock in the Front Range, Colorado (USA). Values are from this study and (1) Small et al. (1997); (2) Duhnforth and Anderson (2011); (3) Schildgen et al. (2002); and (4) Duhnforth et al. (2012).

~150 mm k.y.$^{-1}$ over the past ~130 k.y. (Schildgen et al., 2002). Erosion rates between 30 and 60 mm k.y.$^{-1}$ characterize the steep catchments adjacent to Boulder Canyon. And if our regional measurements from weakly lithified rocks can be generalized, sedimentary rocks of the adjacent Denver basin likely are eroding at ~75 mm k.y.$^{-1}$, driven by higher, episodic rates of river incision (Duhnforth et al., 2012), increasing relief along the Front Range margin as well. Our erosion data highlight the significance of weak rocks, confirm the importance of basin slope for erosion rates in resistant rocks and show that local differences in MAP do not control erosion rates in the cool climate of the southern Rockies.

ACKNOWLEDGMENTS

Research in the Front Range was performed in cooperation with S. Anderson and R. Anderson (University of Colorado) and in ongoing collaboration with P. Birkeland (University of Colorado). R. Finkel supervised some of the ^{10}Be measurements. J. Frostenson, M. Jungers, and K. Remsen assisted in the field. This work was funded in part by National Science Foundation grants #072496 and #0106223, by PRF Grant #36905-B8, and the University of Connecticut Research Foundation.

REFERENCES CITED

Aslan, A., Karlstrom, K.E., Crossey, L.J., Kelley, S., Cole, R., Lazear, G., and Darling, A., 2010, Late Cenozoic evolution of the Colorado Rockies: Evidence for Neogene uplift and drainage integration, *in* Morgan, L.A., and Quane, S.L., eds., Through the generations: Geologic and anthropogenic field excursions in the Rocky Mountains from modern to ancient: Geological Society of America Field Guide 18, p. 21–54, doi:10.1130/2010.0018(02).

Balco, G., Stone, J.O., Lifton, N.A., and Dunai, T.J., 2008, A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements: Quaternary Geochronology, v. 3, p. 174–195, doi:10.1016/j.quageo.2007.12.001.

Dethier, D.P., 2001, Pleistocene incision rates in the western United States calibrated using Lava Creek B tephra: Geology, v. 29, p. 783–786, doi:10.1130/0091-7613(2001)029<0783:PIRITW>2.0.CO;2.

Dühnforth, M., and Anderson, R.S., 2011, Reconstructing the glacial history of Green Lakes Valley, North Boulder Creek, Colorado Front Range: Arctic, Antarctic, and Alpine Research, v. 43, p. 527–542, doi:10.1657/1938-4246-43.4.527.

Dühnforth, M., Anderson, R.S., Ward, D.J., and Blum, A., 2012, Unsteady late Pleistocene incision of streams bounding the Colorado Front Range from measurements of meteoric and in situ ^{10}Be: Journal of Geophysical Research, v. 117, F01023, doi:10.1029/2011JF002232.

Hurst, M.D., Mudd, S.M., Yoo, K., Attal, M., and Walcott, R., 2013, Influence of lithology on hillslope morphology and response to tectonic forcing in the northern Sierra Nevada of California: Journal of Geophysical Research, v. 118, p. 832–851, doi:10.1002/jgrf.20049.

Karlstrom, K.E., and the CREST Working Group, 2012, Mantle-driven dynamic uplift of the Rocky Mountains and Colorado Plateau and its surface response: Toward a unified hypothesis: Lithosphere, v. 4, p. 3–22, doi:10.1130/L150.1.

Leonard, E., 2002, Geomorphic and tectonic forcing of late Cenozoic warping of the Colorado piedmont: Geology, v. 30, p. 595–598, doi:10.1130/0091-7613(2002)030<0595:GATFOL>2.0.CO;2.

Lyle, M., Heusser, L., Ravelo, C., Yamamoto, M., Barron, J., Diffenbaugh, N.S., Herbert, T., and Andreasen, D., 2012, Out of the tropics: The Pacific, Great Basin Lakes, and late Pleistocene water cycle in the western United States: Science, v. 337, p. 1629–1633, doi:10.1126/science.1218390.

Madole, R.F., VanSistine, D.P., and Michael, J.A., 1998, Pleistocene glaciation in the upper Platte River drainage basin, Colorado: U.S. Geological Survey Geological Investigation Series I-2644, 1 sheet, scale 1:50,000.

McMillan, M.E., Angevine, C.L., and Heller, P.L., 2002, Postdepositional tilt of the Miocene–Pliocene Ogallala Group on the western Great Plains: Evidence of late Cenozoic uplift of the Rocky Mountains: Geology, v. 30, p. 63–66, doi:10.1130/0091-7613(2002)030<0063:PTOTMP>2.0.CO;2.

McMillan, M.E., Heller, P.L., and Wing, S.L., 2006, History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau: Geological Society of America Bulletin, v. 118, p. 393–405, doi:10.1130/B25712.1.

Muhs, D.R., and Benedict, J.B., 2006, Eolian additions to Late Quaternary alpine soils, Indian Peaks Wilderness Area, Colorado Front Range: Arctic, Antarctic, and Alpine Research, v. 38, p. 120–130, doi:10.1657/1523-0430(2006)038[0120:EATLQA]2.0.CO;2.

Pelletier, J., 2009, The impact of snowmelt on the late Cenozoic landscape of the southern Rocky Mountains, USA: GSA Today, v. 19, no. 7, p. 5, doi:10.1130/GSATG44A.1.

Portenga, E.W., and Bierman, P.R., 2011, Understanding Earth's eroding surface with ^{10}Be: GSA Today, v. 21, no. 8, p. 4–10, doi:10.1130/G111A.1.

Riihimaki, C.A., Anderson, R.S., and Safran, E.B., 2007, Impact of rock uplift on rates of late Cenozoic Rocky Mountain river incision: Journal of Geophysical Research, v. 112, F03S02, doi:10.1029/2006JF000557.

Schildgen, T., Dethier, D.P., Bierman, P., and Caffee, M., 2002, ^{26}Al and ^{10}Be dating of late Pleistocene and Holocene fill terraces: A record of fluvial deposition and incision, Colorado Front Range: Earth Surface Processes and Landforms, v. 27, p. 773–787, doi:10.1002/esp.352.

Scott, G.R., and Taylor, R.B., 1986, Map showing late Eocene erosion surface, Oligocene–Miocene paleovalleys, and Tertiary deposits in the Pueblo, Denver, and Greeley 1° × 2° quadrangles, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1626, 1 sheet, scale 1:250,000.

Small, E.E., Anderson, R.S., Repka, J.R., and Finkel, R., 1997, Erosion rates of alpine bedrock summit surfaces deduced from in situ ^{10}Be and ^{26}Al: Earth and Planetary Science Letters, v. 150, p. 413–425, doi:10.1016/S0012-821X(97)00092-7.

Tucker, G.E., and van der Beek, P., 2012, A model for post-orogenic development of a mountain range and its foreland: Basin Research, v. 12, p. 1–19, doi:10.1111/j.1365-2117.2012.00559.x.

Whittaker, A.C., 2012, How do landscapes record tectonics and climate?: Lithosphere, v. 4, p. 160–164, doi:10.1130/RF.L003.1.

Wobus, C., Tucker, G., and Anderson, R.S., 2010, Does climate change create distinctive patterns of piedmont dissection?: Journal of Geophysical Research, v. 115, F04008, doi:10.1029/2009JF001562.

Zaprowski, B.J., Pazzaglia, F.J., and Evenson, E.B., 2005, Climatic influences on profile concavity and river incision: Journal of Geophysical Research, v. 110, F03004, doi:10.1029/2004JF000138.

Zhang, P., Molnar, P., and Downs, W.R., 2001, Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates: Nature, v. 410, p. 599–604, doi:10.1038/35069099.

Manuscript received 9 July 2013
Revised manuscript received 6 November 2013
Manuscript accepted 12 November 2013

Printed in USA