The effects of precipitation gradients on river profile evolution on the Big Island of Hawai‘i

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ABSTRACT

To better understand how climate affects bedrock river incision and long-term landscape evolution in the absence of tectonic forcing, we quantify differences in the longitudinal profiles of eroding bedrock channels across the Kohala peninsula on the northern tip of the Big Island of Hawai‘i. An orographic rainfall gradient causes mean annual precipitation rates to vary by over an order of magnitude, from greater than 4000 mm/yr on the wet side to less than 250 mm/yr on the dry side of the peninsula. Channels on the wet side are relatively deeply incised into the surrounding landscape and have developed profiles in which slope increases downstream in upstream reaches (convex form) and decreases downstream in downstream reaches (concave form). Wet-side river channels have relatively large (10–30 m) vertical steps, or knickpoints, in the convex zone. In contrast, channels on the dry side of the peninsula are more shallowly incised, have developed nearly straight longitudinal profiles in which channel slope does not significantly change from upstream to downstream, and have smaller knickpoints. Channel profile form changes from straight to convex-concave at a watershed-averaged mean annual precipitation rate of between ~1300 and 1750 mm/yr, suggesting a climatic threshold in this landscape, above which bedrock incision rates are enhanced. Valley depth (used as a proxy for the magnitude of channel incision) increases with increasing mean annual precipitation and is consistent with a similar fluvial-incision threshold. While the lithology is entirely basalt, incision patterns also appear to be affected by spatial differences in bedrock weathering due to both local climate and basalt flow age. The older and more weathered Pololū basals (260–450 ka) are capped by the younger Hawai basalt series (120–260 ka), and we interpret that heterogeneous weathering of these units influences channel form, relief, sediment production, and knickpoint development.

INTRODUCTION

The strength of coupling between local climate and landscape erosion rate may control the sensitivity of tectonic deformation to climate. Studies concluding that climate can strongly affect deep crustal deformation have assumed a strong coupling between local climate and local exhumation rate (e.g., Beaumont et al., 2001; FinneGAN et al., 2008; Stolar et al., 2006, 2007; Willett, 1999; Zeitler et al., 2001). For example, Willett (1999) and Beaumont et al. (2001) both presented numerical simulations in which asymmetric orographic precipitation focused erosion entirely on the windward side of mountain ranges, with zero erosion on leeward slopes, leading to profound effects on the shape of a mountain belt. Although chosen to be simple end-member cases for numerical modeling, the assumption that erosion is focused on the wet side of a mountain range is also consistent with a threshold precipitation rate, below which the erosion rate is minimal. The earth science community may only be able to validate inferred links between climate and tectonics when effects of climate on erosion are better understood.

Field studies of the sensitivity of erosion and weathering to climate in tectonically active areas have produced inconsistent results. In a study that suggested erosion and rainfall patterns are decoupled, Burbank et al. (2003) found that erosion rates (averaged over >107 yr) in the Greater Himalaya, Nepal, did not vary over a region in which present-day rainfall rates vary by more than a factor of five. In contrast, Reiners et al. (2003) observed that in the Washington Cascades, patterns in erosion rates (averaged over >106 to 107 yr) follow the current spatial pattern of precipitation. Studies on the sensitivity of bedrock weathering to climate have also produced contrasting findings. The availability of water is tightly linked with chemical weathering processes, and some studies observe a link between precipitation and weathering rates (Dixon et al., 2009a, 2009b). Others have found climate to be less of a control on weathering rates than local topography and ultimately tectonic forcing (Riebe et al., 2001, 2004). These conflicting studies suggest that precipitation affects landscape evolution in multiple and contrasting ways, and that process-dependent feedbacks may lead to different landscape morphologies. However, in all of these highlighted studies, both climate and tectonics affect erosion rates, making it difficult to isolate the relative importance of either.

Our study seeks to quantify and understand how local precipitation rate influences bedrock incision patterns across a landscape without complicated uplift patterns, base-level signals, or rock-type variability. Further, we explore...
whether the precipitation-incision relation is linear or suggests threshold behavior. Studies that quantify the links between climate and erosion in landscapes that are not driven by complicated tectonics can be used to deconvolve the links among climate, erosion, and tectonics in other settings, such as mountain ranges evolving at convergent plate boundaries.

We focus on erosion patterns in the Kohala peninsula in the northernmost part of the Big Island of Hawai‘i. The peninsula has a dramatic orographic rainfall gradient, with the wet, windward side of the peninsula receiving over an order of magnitude more mean annual precipitation than the dry, leeward side. We used field observations and digital elevation model (DEM) analyses to explore differences between the style of evolution and degree of incision in bedrock channels on the wet and dry sides of the peninsula. We first introduce the field setting and describe the methods used to quantify channel form in each watershed. Our analysis quantifies how topographic patterns in nine wet-side watersheds and 11 dry-side watersheds vary with the spatially averaged mean annual precipitation in the watersheds. Finally, we interpret that a threshold precipitation rate controls the nature of bedrock incision processes and the resulting channel form between the wet and dry side of the peninsula. Our precipitation threshold is similar to an ~1400 mm/yr threshold found previously on Kohala for chemical weathering and soil production in places with minimal physical erosion (Chadwick et al., 2003; Porder et al., 2007), suggesting that fluvial incision processes are coupled to bedrock weathering in this landscape. Weathering likely affects both bedrock strength along channels and sediment production on hillslopes, which in turn influence incision.

**FIELD SETTING**

Consistent basalt lithology, relatively uniform subsidence, ocean-controlled base level around the peninsula, and a sharp orographic precipitation gradient make the Kohala peninsula an ideal location to study the relationship between climate and fluvial bedrock incision. The Kohala region is underlain by the oldest bedrock of Hawai‘i Island, and it features the most weathered and fluvially eroded land surface on the island. The Kohala peninsula consists of two basalt formations, the older Pololū series (260–450 ka) and the younger Hawī series (120–260 ka) (Fig. 1) (McDougall and Swanson, 1972; Sherrod et al., 2007; Spengler and García, 1988). The Hawī series constitutes only 1% of the subaerial volume of Kohala and generally consists of strong individual basalt flows with cooling fractures, bounded by layers of discrete basalt fragments at the upper and lower margins of individual flows (Chadwick et al., 2003). The Hawī series is ~150 m thick at the top of Kohala mountain and thins toward the coasts (Spengler and García, 1988). Geochronological evidence indicates that the period between the two episodes of volcanism was brief but distinct (Chadwick et al., 2003; Sherrod et al., 2007; Spengler and García, 1988). Our field observations and those of Sherrod et al. (2007) suggest that Hawī flows draped preexisting valley walls and at least partially filled preexisting river valleys.

Because Hawai‘i is subsiding, all channels on the island are by definition in a transient state of adjustment, as they cannot reach a steady-state condition in which long-term erosion balances uplift. U-series ages of drowned coral reefs to the west of the Kohala peninsula imply that the region has been subsiding for the last 475 k.y. at an average rate of ~2.5–2.7 mm/yr (Ludwig et al., 1991; Szabo and Moore, 1986). The 234U/238U ages of corals from the Haleakala Ridge to the northeast of Kohala peninsula suggest maximum subsidence rates of 2.9–3.0 mm/yr (Moore et al., 1990). Data are available from only these two locations, making it difficult to discern whether there is a weak but systematic pattern in subsidence rates across the region.

Base level of the channels we focus on is controlled by the ocean. Although sea level has changed over Quaternary time, we assume that the base-level control has been consistent among the channels. The study channels do not show extensive alluvial deposits near their mouths, indicating that sediment eroded away from the landscape is efficiently flushed into the submarine environment. Isolated wet-side alluviated valley reaches near the coast are the result of the dumping of sugar cane waste (J. Trump, land manager at Sweet Water LLC, 2009, oral commun.). These short coastal reaches were not included in our analysis.

Our analysis does not include the dramatic valleys along the Kohala sea cliffs, to the south of our study area (Fig. 1), because an abrupt change in base level likely dominated the evolution of these channels. The Kohala sea cliffs were likely formed by an enormous coastal landslide (the Pololū slump, evident in bathymetric data) that occurred ca. 250 ka (Lamb

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**Figure 1.** Geology and topography of the Kohala peninsula, Big Island, Hawai‘i (data overlain on hillshade map). The inset shows the Hawaiian Island chain and the location on the Big Island of the detailed map. Elevation on the detailed map is contoured every 150 m. The studied channels, or gulches, are shown in white. We use the term gulch when referring to a specific channel because that is the term used by locals in the study area. Only the rock units for the Kohala peninsula are shown.
et al., 2007). Subsequently, river incision and knickpoint propagation have carved steep-sided canyons headed by natural amphitheaters with relief up to ~700 m in the area of the Kohala sea cliffs.

Atmospheric moisture is brought to the island by easterly trade winds, and precipitation rates vary dramatically across the Kohala peninsula. Some areas on the wet side of the peninsula receive over 4000 mm of rainfall annually, while on the dry side rainfall rates can be as little as 250 mm annually (Fig. 2). Mean annual rainfall isohyets were determined from the 2012 Rainfall Atlas of Hawaii (Giambellucca et al., 2012), described in the Methods section. The highest precipitation is found on the northeastern side of the peninsula below the topographic divide, as a result of moisture-filled trade winds being pushed upslope. Another gradient exists along the northwest-southeast axis of the peninsula as mean annual precipitation decreases with decreasing elevation northwest of the summit.

Although discharge is intermittent in channels on both sides of the peninsula, flow events are much more common on the wet, northeastern side. High-flow events (floods) usually occur in wet-side channels only after multiple days of rainfall when the ground is well saturated (J. Trump, land manager at Sweet Water LLC, 2009, oral commun.). The southwestern side of the peninsula remains dry except for occasional winter cyclones known as “Kona storms” that last for days or weeks at a time and are known to cause flooding (Chu, 1995; Chu et al., 1993; Stock et al., 2003). According to one local landowner, the dry-side channels sometimes go 4 or 5 yr without significant flow (P. von Holt, owner of Ponoholo Ranch, 2009, oral commun.).

We only consider the present-day climate, assuming that it is sufficiently representative of the past across this field site. Constraints on the paleoclimate of the Kohala peninsula come primarily from pollen preserved in cinder cones (Hotchkiss et al., 2000). Hotchkiss et al. (2000) presented a model for high-elevation precipitation and temperature on the dry side of the peninsula over the last ~150 k.y. that suggests the Kohala paleoclimate may have been up to 50% drier than present conditions. The dry side has consistently remained drier than the wet side, even though the difference may have been less pronounced in the past (Chadwick et al., 2003, 2007).

Although land-use changes and deforestation by humans have been extensive, we assume that the form of our study channels instead reflects their evolution over hundreds of thousands of years. Human inhabitation of our field area has significantly altered the natural vegetation, which likely affects how water is stored and moves through the landscape. Human settlement of the Kohala peninsula occurred as early as ca. A.D. 1300, and an extensive agricultural system was developed on the leeward side of the peninsula that persisted through the eighteenth century (Field et al., 2011; Kirch et al., 2012). Paleohydrological studies on the island of Maui suggest that deforestation of agricultural land may have significantly reduced the rates of groundwater recharge due to fog drip, effectively lowering the water table below perennial seepage locations and increasing rates of surface water runoff (Stock et al., 2003). Presently, much of the dry side is used as rangeland. While clearing of vegetation has occurred for agriculture on the wet side (currently there are numerous macadamia nut groves), dense rain forest is still extensive in many places, including in the relatively deep and steep valleys of the channels we study (Homer et al., 2004).

METHODS

To explore the relationship between landscape evolution and climate, we performed topographic analyses of 26 channels in 20 different watersheds in our study area. Channel profiles and drainage areas were extracted from the 10 m National Elevation Data Set DEM using customized ArcMap and MATLAB scripts (available at www.geomorphtools.org) (Fig. 3). We quantified longitudinal channel profile concavity and local relief and explored the relationship between these landscape parameters and local mean annual precipitation.

Channel Concavity

We used channel profile concavity as a metric to compare channels, in part because previous work suggests that it may vary with precipitation patterns in both steady and non-steady-state landscapes (e.g., Roe et al., 2002; Schlunegger et al., 2011; Zaprowski et al., 2005). Following these studies, our goal was to link changes in profile concavity to precipitation patterns. We derived concavity from the commonly used stream power bedrock incision model that expresses fluvial incision as a function of discharge, local channel slope, and environmental factors such as rock type (e.g., Howard, 1994; Howard et al., 1994; Rosenbloom and Anderson, 1994; Stock...

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Figure 2. Isohyets (mm/yr) from the 2012 Rainfall Atlas of Hawaii (Giambellucca et al., 2012). The background map is the same hillshade model illustrated in Figure 1. The locations of the rain gauges that were used to create the rainfall atlas are also shown. We note that the rainfall atlas uses gridded data, but we only illustrate the isohyets. The interval between isohyets is not uniform.
and Montgomery, 1999; Tucker and Whipple, 2002; Whipple and Tucker, 1999, 2002). The stream-power model describes both steady- and non-steady-state bedrock incision:

\[ I = KQ^mS^n, \]

(1)

where \( I \) is incision rate; \( K \) is a constant that accounts for rock type; \( Q \) is the effective fluvial discharge (which can be thought of as bankfull flow); \( S \) is channel slope; and \( m \) and \( n \) are non-universal, positive exponents (e.g., Gasparini and Brandon, 2011). Discharge is modeled by the relationship

\[ Q = k_qA^c, \]

(2)

where \( A \) is drainage area, \( k_q \) is a coefficient that accounts for the precipitation rate, and \( c \) is a positive exponent typically assumed to be between 0.7 and 1 (e.g., Whipple and Tucker, 1999). Assuming spatially uniform precipitation and runoff generation, \( c \) is frequently set to 1 (e.g., Snyder et al., 2000).

A relationship between channel slope and drainage area is derived by combining Equations 1 and 2 and solving for channel slope,

\[ k_q = \left( \frac{I}{K} \right)^{1/m} \left( k_q A^c \right)^{-m/n}. \]

(3)

If \( c, k_q, I, \) and \( K \) are uniform, Equation 3 predicts a power-law relationship between \( S \) and \( A \).

Equation 3 can be recast in the form

\[ S = k_sA^{\theta}, \]

(4)

where

\[ k_s = \left( \frac{I}{K} \right)^{1/m} \left( k_q A^c \right)^{-m/n}. \]

(5)

and

\[ \theta = \frac{cm}{m}. \]

(6)

Here, \( \theta \) is the profile concavity, or the concavity index (Flint, 1974), and \( k_s \) is commonly referred to as the channel steepness (Wobus et al., 2006b) and can be thought of as the slope value at unit area (Sklar and Dietrich, 1998). Smooth, graded, equilibrium channel profiles are thought to have a nearly uniform value of \( \theta \) and \( k_s \) (Flint, 1974). A recent review article by Kirby and Whipple (2012) suggested that deviations from equilibrium channel form, that is, deviations in channel concavity, can be used to interpret how local forcings are driving patterns in erosion rates under non-steady-state conditions.

Equation 4 shows that \( \theta \) is a topographic metric that describes the scaling of channel reach slope with drainage area, independent of any assumptions of steady or non-steady landscape condition, and independent of any theory predicting its dependence on variables such as precipitation gradients. The concavity data we present in the results section can be interpreted in this way. In addition, the simple theory of Equations 1–3 and 5–6 also predicts that concavity should be sensitive to downstream changes in discharge (\( c, m \) in Eq. 6; Whipple and Tucker, 1999; Roe et al., 2002), potentially making concavity changes interpretable in terms of precipitation variations along a channel. In the simplest case of uniform precipitation and erosion rates, \( c, k_q, m, n, \) and \( I \) are uniform across a landscape, leading to a single concavity value. Spatial precipitation gradients should modify concavity. Roe et al. (2002) incorporated orographic precipitation gradients into their study of channel concavity by imposing spatial gradients in \( k_q \). For steady-state landscapes (i.e., uniform erosion rates), they found that profile concavity should increase if precipitation rates increase from the head of the watershed to the outlet, but decrease if the precipitation rate monotonically increases upstream. Although not explored by Roe et al. (2002), profile concavity would also be affected if \( c \) varied in space.

In addition to concavity, we also measured channel steepness across our field area channels (using a reference concavity of \( q_{ref} = 0.45 \); Wobus et al., 2006b). We do not present this data because we found no significant trends with climate. It is worth noting that Equations 1–3 and 5–6 predict that steepness should be influenced by precipitation gradients, and not just uplift and incision rates (e.g., Cyr et al., 2010; Duvall et al., 2004; Lague and Davy, 2003; Snyder et al., 2000; Wobus et al., 2003, 2006b). Assuming uniform incision rates, channel steepness should decrease as precipitation rate (\( k_q \) in Eq. 5) increases, all else held equal (Whipple et al., 1999).

**Relief and Valley Depth**

In addition to the topographic metric of concavity, we also calculated local relief across the Kohala peninsula, to discern patterns in channel incision and to compare differences in the surrounding landscape morphology. Relief has been used as a constraint on channel incision and as a proxy for erosion rates (e.g., Brocklehurst and Whipple, 2002; Montgomery and Brandon, 2002; Small and Anderson, 1998). We calculated relief at every landscape grid cell as the difference between the maximum and minimum elevations within a circle of 200 m radius. The 200 m window ensures that the elevations from points both at the base of a valley...
Precipitation

We used precipitation data from the 2012 Rainfall Atlas of Hawaii (Giambelluca et al., 2012). The Rainfall Atlas includes gridded mean rainfall data (spatial resolution of 8.1 arc-seconds) based on a 30 yr study period (1978–2007) for all the major Hawaiian Islands. It is the most comprehensive rainfall data source currently available for Hawaii. The atlas was formed by combining rainfall data based on five different sources: rain gauge data (from over 1000 stations across the state; see Fig. 2 for gauge locations in the study area); the Parameter-elevation Regressions on Independent Slopes Model (PRISM) rainfall observations; numerical model data from the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) simulations (http://www.mmm.ucar.edu/mm5/); and rainfall data inferred from vegetation patterns. PRISM uses point measurements of climate factors such as precipitation, as well as a DEM, to generate a spatially continuous climate data set. MM5 is a regional mesoscale meteorological model used for climate projections and weather forecasts. The 2012 Rainfall Atlas of Hawaii is formed by combining each of the individual rainfall data sources, with component weighting based on the local uncertainty in the individual data source (Giambelluca et al., 2012).

For each study watershed, we calculated the spatially averaged mean annual rainfall across the entire drainage area, as a simple way to quantify climate variation among channels. Although comparing climatic differences in terms of watershed-averaged mean annual precipitation does not account for differences in precipitation gradients along the channels, we used this approach because it is simple, and also because channels act as integrators of upstream hydrology and sediment supply. Incision at any given point along a channel likely depends on the total discharge and sediment load from the entire drainage area upstream, suggesting that watershed-averaged climate is appropriate for comparing channel-averaged topographic metrics of concavity and along-channel relief.

RESULTS

Field Measurements and Observations

In the field, we surveyed longitudinal profiles of two complete channels, Wainaia gulch on the wet side, and an unnamed channel on the dry side, which we refer to as Ponoholo gulch (based on the ranch through which the gulch runs), although some maps also refer to it as Puanui (Fig. 1). Field surveys used a TruPulse 360 laser range finder (range accuracy ±30 cm, inclination accuracy ±0.25°). Consistency between the field-derived longitudinal profiles and the DEM-derived profiles gives us confidence that the DEM data accurately capture channel form on both the densely vegetated wet side and topographically subtle dry side (Fig. 3).

Field observations of fluvial fluting, potholes, and boulder plucking indicate that fluvial erosion is active in both the wet- and dry-side channels (Fig. 5). These observations extend beyond just the Wainaia and Ponoholo gulches. These features were observed even at relatively small drainage areas in the convex upper portions of the wet-side channels. We did not observe any evidence of debris flows in these channels.

Knickpoints occur in channels on both sides of the peninsula, but they are taller and more abundant along wet-side channels (Fig. 6). Wet-side knickpoints can be as tall as ~30 m. The upper reaches of wet-side channels tend to have relatively closely spaced knickpoints, which account for a substantial fraction of the elevation drop and influence channel shape. Along the upstream reaches of Wainaia gulch, the

Figure 4. Illustration of the method used for calculation of valley depth, using Wainaia gulch as an example. (A) The white lines are the perpendicular transects (1000 m length, centered on the channel) that cross the channel (black line) every 500 m. (B–C) Examples of the transect data and identification of the valley height on either side of the channel.
Figure 5. Photos showing signs of fluvial incision on the wet side (left) and dry side (right). Note the boot (12 cm width) for scale in both photos.

Figure 6. Photos showing knickpoints in Kohala channels. Each photo shows a different knickpoint. (A) Photo of tall, wet-side knickpoint (20–25 m). (B) Photo of smaller, dry-side knickpoint (2–3 m). (C) In this photo, ferns growing on the lower portion of the knickpoint indicate the groundwater seepage line in the wet-side valley wall (dotted line); the waterfall is out of view to the left.
field survey indicated that large knickpoints occur approximately every kilometer, with many smaller steps as well (Fig. 7). Knickpoints are much less common in the lower concave portion of the wet-side channels. We use the term “transition knickpoint” to refer to the knickpoint that separates the upper convex profile from the lower concave profile. Knickpoints in dry-side channels are smaller (~1–10 m; Fig. 6), less numerous, and are not spatially concentrated in any area along the channel profile, although the taller knickpoints tend to be found in downstream reaches.

Our field observations indicate that bedrock heterogeneities, including fractures, individual lava flows, and associated a‘a and pahoehoe lava textures, play a major role in the degree of local weathering and erodibility. Heterogeneities due to individual basalt flows create variability in the fracture density of the local rock and are present on both sides of the peninsula. On the dry side, larger fracture-bound blocks tend to appear strong and relatively unweathered, particularly in the Hawī unit. Many of the dry-side knickpoints occur when a channel steps down through an individual basalt flow, with the upper and lower flow margins nearly parallel to the local longitudinal channel profile.

Particularly on the wet side, highly fractured rock is generally more intensely weathered than massive, unfractured blocks that are exposed on channel beds and valley sidewalls. Fractures and weak layers offer conduits for water flow, both within and between the mapped basalt units. On the wet side, the most weathered rock (determined qualitatively based on field observations such as scratching and hitting the rock) in the vicinity of the channels was found where intensely weathered bedrock is often exposed on the knickpoint face beneath. Importantly, but unsurprisingly, the older Pololū unit generally appears more deeply weathered than the younger Hawī flows.

Coarse sediment is much more abundant in wet-side channels than dry-side channels (Fig. 8). Rounded gravel- to boulder-sized clasts are

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Figure 7. Profile derived from laser range-finder survey showing the upper convex portion of Waināia gulch. The arrows indicate knickpoint locations. Distance downstream on the x axis indicates the distance from where the survey began. Abbreviation: a.s.l.—above sea level.

Figure 8. (A) Photograph of sediment covering the channel bedrock on the wet side. The large boulder in the center measures ~1 m across. (B) Photograph of sediment accumulating at the base of a small knickpoint (channel width ~1–2 m) on the dry side.
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Analysis of Topography and Climate

Channel profile form differs between the wet and dry sides of the peninsula. To determine if there are trends in concavity across the Kohala channels, we calculated $\theta$ by fitting Equation 4 to channel slope-area data, following the methods described by Wobus et al. (2006b). In order for the regressions to be sufficiently constrained, we only considered channels with outlet drainage areas greater than $1 \times 10^6$ m$^2$. The dry-side channel profiles are straight to slightly concave ($0 < \theta < 0.3$ in Eq. 4), with the exception of the wettest dry-side channel, Honokoa gulch (Fig. 9). All of the wet-side channel profiles have a convex upper reach ($\theta < 0$) and a concave lower reach ($\theta > 0.3$) (Fig. 9).

To explore whether channel form varies with rainfall, we compared the concavity indices of Kohala channels to the spatially averaged annual precipitation of each watershed (Fig. 10). The wet-side watersheds receive between ~1700 and 2700 mm of annual rainfall. Watersheds on the wet side of the peninsula are drained by river channels with concavity indices ($\theta$ in Eq. 4) ranging from 0.6 to 2.4 in the lower concave portions and -0.1 to -2.1 in the upper convex portions. The dry-side, low-concavity channels are in watersheds that receive less than ~1400 mm of annual rainfall. We did not fit a trend line between concavity and watershed-averaged annual precipitation because no single trend is evident across the entire data set. In the Discussion section, we interpret these data to suggest a potential threshold rainfall beyond which fluvial processes change or are accelerated.

Elevation transects near the coast illustrate that the wet-side channels are more deeply incised than the dry-side channels (Fig. 11). On the wet side, river valleys are areas of higher relief that are easily identifiable in the elevation transects. The highest wet-side relief generally occurs several kilometers upstream from the coast in the general vicinity of the Hawai‘i-Polōlū contact (Fig. 12). On the dry side, relief along channels is often no greater than the relief of the surrounding landscape. The dry-side relief is largely determined by the hummocky hillslope topography that still reflects individual lava flows (Figs. 12 and 13).

Maximum valley depth and average valley depth both increase with watershed-averaged annual precipitation (Fig. 14A). We fit linear trends between the two valley depth measurements (maximum and average) and watershed-averaged annual precipitation. Our fits include...
Figure 10. River channel concavity ($\theta$) for wet- and dry-side channels versus watershed-averaged precipitation calculated from the 2012 Rainfall Atlas of Hawaii (Giambelluca et al., 2012). Channels that have only one trend in profile shape (dry side only) are plotted with the dry, downstream marker (solid circle), and no upstream reach is plotted because there is only one trend in the profile. In channels that exhibit convex to concave profiles, the fit in the upstream part of the channel is shown with an open symbol (labeled upstream in the legend), and the downstream part of the channel is shown with a solid symbol. The concavity values in convex-to-concave channels are plotted against the spatially averaged mean annual precipitation of the entire watershed. The error bars indicate the 95% confidence interval for the fit concavity. The gray region in the plot illustrates the rainfall range over which a potential threshold in fluvial processes may be occurring. Figure 9 shows the channels from which these data were calculated.

Figure 11. Elevation data from dry- and wet-side transects trending roughly parallel to the coast. The river channels are approximated by the small, V-shaped troughs on the dry side and the larger, V-shaped troughs on the wet side. River incision is noticeably greater across the wet transect, as indicated by the deeper valleys. The locations of the transects are indicated on the map. Wainaia gulch and Ponoholo gulch are labeled as WG and PG, respectively, on both plots. Abbreviation: a.s.l.—above sea level.
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Figure 12. Map of relief calculated over a 200 m radius window. The relief map is overlain on the hillshade map. High relief is represented by dark gray, and low relief is represented by light gray. Streams with straight to low concavity profiles are represented by dashed lines, convex streams are represented by dotted lines, and concave streams are represented by solid lines.

data from both the wet and dry sides of the peninsula but exclude Honokoa gulch, the dry-side channel that has the highest mean valley depth (63 m) of all the study channels. Honokoa is clearly an outlier, and it is discussed further in the Discussion section. The fit between the average valley depth and watershed-averaged annual precipitation has a higher goodness of fit ($r^2 = 0.69$) than the fit between the maximum valley depth and watershed-averaged annual precipitation ($r^2 = 0.47$). We also calculated the Pearson correlation coefficient (a measure of the linear correlation between two variables) between the two valley depth measurements and watershed-averaged annual precipitation (Table 1). The correlations between the average valley depth and watershed-averaged annual precipitation and between the maximum valley depth and watershed-averaged annual precipitation for the entire data set (both wet and dry sides) are both significant ($p < 0.05$). However, when considering just the wet or dry side alone, the correlations are not significant ($p > 0.05$). Because we consider valley depth to be a proxy for the amount of fluvial incision, the data set as a whole (the wet- and dry-side data together) indicates that wet-side channels are generally more deeply incised than dry-side channels. We note that the dry-side channels have greater valley depth than the dry-side channels. We also calculated the Pearson correlation coefficients between the two valley depth measurements and average landscape slope (Table 1). The correlation is significant ($p < 0.05$) only when considering the dry-side data.

DISCUSSION

In this section, we first interpret that differences in concavity and valley depth between the wet and dry sides of the peninsula suggest a climate threshold to initiate substantial fluvial incision in this landscape. The climate threshold based on topography appears to be consistent with a threshold for chemical leaching and soil production (Chadwick et al., 2003; Porder et al., 2007). Although we only have qualitative field observations, climate-dependent bedrock weathering may explain the threshold incision behavior both through physically weakening bedrock along channels and also by influencing sediment production and availability. Knickpoints also affect channel profile form and evolution, and lithologic weathering contrasts and rock heterogeneities likely affect knickpoint formation and migration rate as well.
Climate Threshold for Fluvial Incision?

Changes in profile concavity with mean annual precipitation suggest a threshold for landscape response to climate. Watersheds that receive less than ~1300 mm of annual rainfall have a low, uniform profile concavity (Fig. 10). These dry-side channels appear to be minimally incised into the surrounding bedrock (Fig. 11), even though relief on the broad hummocky land surface (away from channels) does increase along the dry side to the southeast (Fig. 12). Wet-side watersheds have convex-concave profiles reflecting more deeply incised channels that have incised well-defined valleys (Fig. 10). The change in profile form in watersheds receiving more than between ~1300 and ~1750 mm/yr suggests that key processes controlling fluvial incision in Kohala channels become activated by climate in wet-side channels but remain largely dormant in most dry-side channels.

Differences in valley depths between the dry- and wet-side channels are also consistent with a climatic threshold for substantial incision, although these data can also be interpreted to indicate a more gradual climate sensitivity (Fig. 14A). Linear regressions of the data in Figure 14A show that valley depth increases significantly with mean annual precipitation when both sides of the peninsula are considered together (p < 0.05; Table 1). However, when the wet and dry sides are regressed separately, correlations between mean annual precipitation and valley depth are not statistically significant (r² values of 0.12 and 0.00034, respectively, regressions not shown; p > 0.05; Table 1). For a given landscape slope, wet-side channels are more deeply incised than dry-side channels (Fig. 14B). Overall, a threshold change in incision between ~1300 and 1750 mm/yr mean annual precipitation is consistent with the valley depth

Figure 14. (A) Average and maximum valley depth (VD) along wet- and dry-side channels versus watershed-averaged mean annual precipitation (mm/yr). (B) Average and maximum valley depth along wet- and dry-side channels versus average landscape slope (m/m). The legend for both figures is shown in the upper right corner of A. Best-fit linear relationships for the maximum and average valley depth as a function of watershed-averaged rainfall rate and average landscape slope, and the corresponding coefficient of determination, are shown in each figure. Honokoa gulch on the dry side has anomalously high valley depth and is not included in the best-fit relationships.
data as well as the channel concavities (Figs. 10 and 14).

The climate difference between the wet side and dry side does not allow for a precise determination of a threshold precipitation value for incision. Honokaa gulch, the wettest and southeasternmost channel on the dry side, is an outlier in terms of relief, and was excluded from all of the regressions (Fig. 14). It has a convex-concave profile similar to all of the wet-side channels, and it is the wettest of the dry-side channels. It is possible that Honokaa gulch may be just wet enough that fluvial incision is able to surpass a threshold, allowing for accelerated erosion. This suggests that the convex-concave channel form does not only reflect the transition from the wet to dry side of the peninsula. If Honokaa gulch is included as a constraint, the incision threshold would be restricted more narrowly to between 1300 and 1400 mm/yr mean annual precipitation. However, Honokaa gulch drains an area with the steepest landscape slope, which may have enhanced its rate of downcutting (Fig. 14B). Like many of the wet-side channels, the convex to concave transition along Honokaa gulch also occurs near the contact between Hawi and Pololū lava flows, suggesting that the lithologic contrast may also influence the profile form (discussed further in the following).

Climate Thresholds and Bedrock Weathering

Qualitative field observations suggest that bedrock weathering is sensitive to climate variations across the peninsula and may explain the interpreted incision threshold. Chemical weathering can physically weaken basalt, making it more erodible (e.g., Moon and Jayawardane, 2004; Sklar and Dietrich, 2001). Our topographically inferred bedrock incision threshold of 1300–1750 mm/yr appears to be consistent with a previously identified chemical weathering threshold for Hawi basalts at a median annual rainfall of ~1400 mm (e.g., Chadwick et al., 2003; Porder et al., 2007). This threshold rainfall rate approximately corresponds to the point where annual precipitation exceeds average evapotranspiration (Chadwick et al., 2003). Mobile elements were almost completely leached from soils above this precipitation threshold. Expanding on this work, Porder et al. (2007) quantified total mass loss due to chemical weathering in both Hawi and Pololū lava flows. They again found a weathering threshold at ~1400 mm/yr for Hawi, and a lower precipitation-leaching threshold at ~1000 mm/yr for older Pololū flows. Above the threshold values, there was minimal variation in the mass loss due to chemical weathering, and in humid Hawaiian environments, the leaching process at the surface tends to occur rapidly over time scales of less than ~20 k.y. (e.g., Vitousek et al., 1997).

We interpret the apparent correspondence in precipitation threshold behavior between bedrock weathering (~1400 mm/yr; Chadwick et al., 2003; Porder et al., 2007) and our independent channel concavity and valley depth–based estimates (mean annual precipitation 1300–1750 mm/yr) to suggest that the extent of near-surface bedrock weathering influences fluvial incision. Several methodological details of Chadwick et al. (2003) and Porder et al. (2007) are relevant for comparing their weathering constraints to our interpretations of the sensitivity of fluvial erosion to climate. To understand soil development, they intentionally quantified chemical weathering only at sites that had no indication of erosion by physical processes, and were therefore assumed to have had only chemical mass removal. Previous work demonstrates the strong sensitivity of chemical weathering rate to physical erosion rate (e.g., Riebe et al., 2001, 2004), making it challenging to directly apply their weathering results from stable areas to regions around downcutting channels. In addition, Chadwick et al. (2003) and Porder et al. (2007) tended to measure weathering in highly fractured and porous a’a lava flow textures. Porder et al. (2007) indicated that there is significant heterogeneity in the degree of weathering controlled by lava texture; they described an unweathered pahoehoe flow of the older Pololū unit, directly adjacent to an intensely leached a’a flow. Strong weathering heterogeneities in the shallow and deeper subsurface are likely an important control on local coarse sediment production.

Lithologic and Sediment Supply Controls on Channel Form and Knickpoint Formation

The size distribution and abundance of sediment supplied to channels from surrounding hillslopes appear to be highly influenced by weathering rates, and this likely affects fluvial incision rates and channel form. As described in the Results section, we qualitatively observe that wet-side channels contain abundant coarse sediment but also have some bedrock exposed on the channel beds, while dry-side channels tend to contain less sediment and have extensive bedrock exposure. An apparent bedrock incision threshold could occur, based on tools- and cover-limited incision predicted by sediment flux–dependent incision models (e.g., Sklar and Dietrich, 2004). Under this interpretation, the dry side would be severely tools-limited, because weathering has been insufficient to decrease the sizes of most fracture-bound blocks in either the channel bed or valley sidewalls to the point that they can be mobilized by the discharges in those channels. In contrast, on the wet-side, preferential weathering (e.g., localized along fractures and other heterogeneities) appears to leave essentially unweathered core stones in valley sidewalls. On the wet side, we have observed cobble- to boulder-sized blocks that appear to weather directly out of the Pololū channel sidewalls. Wet-side channel incision may now be limited by alluvial cover, but it has still been more effective over time than dry-side incision. At present, we do not have data on bedrock strength, bedrock exposure, or sediment supply to test these mechanistic hypotheses.

The overall form of wet-side longitudinal profiles is influenced by knickpoints, particularly in the transition zone from concave to convex and in the upper convex reach. Our field observations and interpretations suggest that the form of individual knickpoints depends on the interplay among (1) surface flow and plunge pool
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abrasion, (2) groundwater seepage, which appears to strongly influence local bedrock weathering, and (3) lithologic heterogeneities, including fractures and boundaries between individual lava flows and differences in weathering between flows and the Hawai‘i and Pololū units.

Sediment supply may also influence the formation and possible migration of knickpoints observed most prominently in wet-side channels. Sediment flux–dependent bedrock incision models suggest that knickpoints may form autogenically along channels, due to feedbacks between erosional efficiency, sediment flux, and channel slope (e.g., Chatanantavet and Parker, 2006; Crosby et al., 2007; Wobus et al., 2006a). Chatanantavet and Parker (2006) used a sediment flux–dependent erosion rule to model longitudinal profiles on Kaua‘i (a much older Hawaiian Island) that have a similar form as the Hawaiian Island) that have a similar form as the Kohala convex-concave channels. It is plausible that local climate has affected local sediment production through heterogeneous bedrock weathering, which in turn may have caused the development of and influenced the form of autogenic knickpoints. At present, we do not have data to quantify or constrain the relative importance of these factors.

In many wet-side Kohala channels, the tallest knickpoints are found at or near the Hawai‘i-Pololū contact, and the inflection point between convex and concave reaches is similarly near the contact in many but not all channels. We refer to the knickpoint at the inflection point between the convex and concave reaches as the “transition knickpoint.” The transition knickpoints may have formed at the toe of the Hawi flows or at other points along the channel and subsequently propagated upstream to their present locations. The location of many of the knickpoints at the Hawai‘i-Pololū contact suggests that knickpoint form, and potentially the convex-concave form of the wet-side channels, may largely be controlled by the strength contrast between generally less weathered Hawi and more deeply weathered Pololū basalts (Fig. 9). However, this interpretation of lithologic control may not be so clear-cut: There are several wet-side channels in which the transition knickpoint does not lie at the lithologic contact. The northwesternmost wet channel, Waikaulapala gulch, lies completely within the Pololū series and still shows a convex-concave channel profile. In the three southeasternmost wet-side channels, the transition knickpoint is located within the Hawai basalt (Fig. 9).

Although far from conclusive, our preferred interpretation is that the convex-concave form develops because of the climate gradient and climate-related sediment supply effects, and does not require the Hawai‘i-Pololū lithologic contact to occur. However, this form is enhanced by the present-day spatial correspondence of the Hawai‘i-Pololū contact along many of the wet-side channels and Honokoa on the dry side, where vertical knickpoints occur.

There are also several anomalous channels on the dry side of the peninsula. Honokoa gulch exhibits a convex-concave profile similar to the wet-side channel profiles, and it has a transition knickpoint at the lithologic contact (Fig. 9), suggesting lithologic controls on knickpoint formation. The eight central dry-side channels lie mostly in the Hawai basalt, although some channels have incised through the Hawi cap near the mouth to expose the Pololū basalts. However, the two northernmost dry-side channels are entirely in Pololū basalts. These channels are no more concave or deeply incised than dry-side channels incising into Hawi bedrock, despite the fact that they have had more time to incise into the older and presumably more weathered Pololū bedrock. These northernmost outlying channels support the notion that dry-side channels do not receive enough precipitation to cause significant channel downcutting.

Controls of Precipitation Patterns on Channel Concavity

We next compare our observation of distinctly different channel concavity patterns on the wet and dry sides of the Kohala peninsula to previous studies of concavity-climate relations, to gain potential insights into the influence of precipitation gradients on profile form. Using relatively simple numerical models of an uplifting landscape at steady state, Roe et al. (2002, 2003) and Wu et al. (2006) found that profile concavity is larger when precipitation increases downstream due to a more rapid downstream decrease in slopes driven by a rapid downstream increase in discharge. In contrast, profile concavity is smaller when precipitation decreases downstream due to a less rapid downstream decrease in slopes driven by a less rapid downstream increase in discharge. On the dry side of Kohala, precipitation decreases downstream, and channel concavities are lower than is typical for well-developed fluvial channels. These observations are qualitatively consistent with trends predicted by Roe et al. (2002, 2003). However, based on field observations, we interpret that concavities are very low in the dry-side channels because precipitation rates are below the climate-influenced threshold for weathering and substantial fluvial incision, leading to minimal fluvial modification of this part of the landscape. The dry-side landscape still primarily reflects the basalt flows that built it.

The overall dependence of Kohala channel concavities on climate is broadly similar to data of Zaprowski et al. (2005), who found a positive correlation between channel concavity and climate indicators, including precipitation intensity and peak annual discharge, for gauged rivers in the eastern American high plains. The tectonically stable setting of the high plains suggests that channel response time will be long (e.g., Baldwin et al., 2003), and therefore the differences in channel concavity with climate may also be influenced by the erosional evolution of these channels. Zaprowski et al. (2005) argued that the channels in the high plains may still be incising, and spatially variable patterns of incision in a single channel can result in a period of increasing channel concavity, although the concavity will likely decrease again once the channel reaches graded conditions. In both our study and Zaprowski et al. (2005), a more erosive climate appears to result in transient channels that are further evolved and more incised. Differences between the two areas do exist, though. The wet-side Kohala channels have a distinct convex to concave profile form, while the higher-precipitation American high plains channels have more concave profiles. The differences may also be influenced by the tectonic setting: subsidence in Kohala versus tectonic stability in the American high plains. Zaprowski et al. (2005) stated that knickpoints in their study channels do not significantly alter the profile form, while knickpoints likely contribute to the convex form of the upper profile in the wet-side Kohala channels, and perhaps the entire convex-concave shape. Nonetheless, both studies suggest that changes in concavity may be an indication of transient channel conditions, and the degree of evolution is likely influenced by the local climate. Numerical modeling studies of channel response to a change in climate also suggest spatial patterns in erosion and deposition, leading to changes in concavity during transient conditions (Gasparini et al., 2008; Tucker and Slingerland, 1997).

In summary, our data and the variety of plausible but somewhat conflicting interpretations highlight the complexity of feedbacks in transient (non-steady-state) landscape evolution, from climate, weathering, and sediment production. Future field work and landscape evolution modeling may allow us to further evaluate these ideas. Field measurements could include field surveys of lithologic heterogeneities and rock properties in the vicinity of knickpoints, and measurements of sediment grain-size distributions and bedrock exposure along channel beds. These data could be incorporated into a modeling framework of sediment flux–dependent incision models.
CONCLUSIONS

Longitudinal channel profiles and field observations on the Kohala peninsula, Hawai‘i, suggest that local precipitation rates influence patterns of bedrock incision and landscape evolution. Channels on the wet side of the peninsula have convex-concave profiles, with many knickpoints in the upstream, convex portion of the profiles. In contrast, dry-side channels are typically straight and have fewer and smaller knickpoints.

The relationship between channel convexity and watershed-averaged mean annual precipitation suggests a threshold precipitation for accelerated channel evolution between ~1300 and 1750 mm/yr. Below this threshold, bedrock channels have minimally incised into local landscapes. Valley depth increases with watershed-averaged mean annual precipitation and is also consistent with the climate-dependent erosion threshold. The large range of uncertainty in our threshold value reflects the differences in watershed-averaged precipitation rate between the wet and dry sides of the peninsula. Nonetheless, our topography-based threshold appears to be consistent with a previous and independent chemical and dry sides of the peninsula. Nonetheless, our topography-based threshold appears to be consistent with a previous and independent chemical

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