Longitudinal Profile Development into Bedrock: An Analysis of Hawaiian Channels[1]

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ABSTRACT

Analysis of topographic maps of rivers incised into dated Hawaiian lava flows shows that the long term average bedrock erosion rate along certain reaches is linearly related to stream power. Field observations suggest that two processes may control Hawaiian channel downcutting: (1) stream power-dependent erosion, including abrasion of the channel bed by transported particles, and (2) step-wise lowering caused by knickpoint propagation. Modeling results indicate that a simple stream power-dependent erosion law predicts the straight to weakly convex longitudinal profiles characteristic of Kauai channels but is insufficient to predict two other characteristic features: the upslope propagation of knickpoints and the straight 5–8° channel slopes below the knickpoints; thus more than this single transport law is apparently required to model bedrock channel incision. Field surveys also indicate that significant portions of the channel lengths below the knickpoints are mantled with large boulders. We propose that the boulder mantling of long channel reaches inhibits channel incision, reducing downcutting to a rate set by boulder weathering, breakdown and transport of the material, and perhaps by knickpoint propagation sweeping under the boulder armor. Partial boulder mantling of bedrock-dominated channels is common in mountainous regions, and a theory which takes boulder armoring into account will have broader applications than one which ignores these limiting effects.

Introduction

Bedrock channels are common in mountainous landscapes, yet no theory, supported by field data, exists to predict the development of river longitudinal profiles into bedrock. This lack of knowledge inhibits our ability to model landscape evolution. Diverse topography generally is formed by the action of water cutting channels and forming a hierarchical network of progressively larger valleys downstream. The intriguing hypothesis that late Cenozoic uplift is linked to climatically accelerated erosion (Molnar and England 1990; Burbank 1992) emphasizes the importance of understanding how the evolution of the rate and depth of river incision and subsequent canyon formation control the evolution of terrain.

Most studies of river longitudinal profile form start with the assumption that the profile in question is in an equilibrium condition, or at grade. Since the work of Gilbert (1877), geomorphologists have recognized that river longitudinal profiles are generally concave upward, and in predictions of profile evolution, profile concavity is often interpreted as confirmation that the simulations are realistic (e.g., Snow and Slingerland 1987; Slingerland and Snow 1988). However, close inspection of long profiles reveals that profile concavity is often interrupted by steep or convex reaches, commonly referred to as knickpoints, and that some profiles are convex through their entire length. Many published profiles appear to be made up of several relatively flat reaches, linked by steeper or more convex reaches. Profiles of large and small rivers in Europe, the U.S., and Africa are characterized by overall convex shapes, straight and convex reaches, and/or by sharp, local convexities that outcrop along their respective profiles (e.g., Woodford 1951; McKeown et al. 1988; Pavich et al. 1989; Brice 1964; Peters 1978; L. B. Leopold pers. comm.). Recent work by Young and McDougall (1993) documents the persistence of steep reaches through 20 m.y. of profile evolution in southeastern Australia.

Local reaches of steep gradient usually are assumed to correlate either with (1) areas of more

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resistant strata in bedrock-bedded streams (e.g., Lewis 1945; Wolman 1955; Hack 1957; Brush 1961), (2) sites where coarser load is introduced (e.g., Woodford 1951; Hack 1973), (3) loci of tectonic activity (e.g., Reed 1981; Burnett and Schumm 1983; McKeown et al. 1988), or (4) the upslope propagation of base level change (e.g., Penck 1924; Foley 1980*a*; Seidl and Dietrich 1992). Of these four knickpoint-forming mechanisms, the most controversial, and perhaps the most important, is propagation of base level change via knickpoint migration. Penck (1924), who introduced the term knickpoint, recognized that propagation of steep reaches up a river system would profoundly change landscape-forming processes and valley evolution. The controversy revolves around whether (1) knickpoints can migrate very far before they become indistinct and (2) whether or not knickpoint formation and preservation require the presence of a more resistant rock unit at the top of the knickpoint. Gilbert (1896) discussed the importance of a resistant caprock to the maintenance and retreat of Niagara Falls, while Young (1985) described retreating waterfalls which lacked a resistant caprock and discussed waterfall retreat mechanisms.

In alluvial channels, knickpoints have been shown both to propagate long distances and rejuvenate fluvial transport, and to affect channel processes only a short distance upstream (e.g., Schumm and Hadley 1957; Leopold et al. 1964; Leopold and Bull 1979; Begin et al. 1980, 1981; Gardner 1983). Foley (1980*a*) identified several knickpoints formed in glacial outwash materials on tributaries to the Dearborn River, Montana, and connected them to episodic incision on the Dearborn.

Profiles incised into bedrock are often characterized by prominent knickpoints, the locations of which appear to be related neither to lithology, tributary confluence, nor uplift (Woodford 1951). Knickpoint migration in bedrock remains poorly understood, although it has often been inferred (e.g., Jones 1924; Gardner 1983). If knickpoints propagate, they could be very important in translating base level change into bedrock channel incision (e.g., Reed 1981).

The detailed mechanisms by which rivers cut through bedrock remain poorly understood. Recent work highlights the importance of three processes shaping bedrock channels: (1) erosion of channel beds by flowing water and sediment, (2) scour by debris flow, and (3) knickpoint propagation (Seidl and Dietrich 1992). Other proposed mechanisms include solution weathering and seepage erosion (e.g., Laity and Malin 1985; Baker 1990) and cavitation at the base of waterfalls and the related retreat of waterfall walls (e.g., Barnes 1956). Little is known, however, about the relative importance of each of these mechanisms, and few field data exist that either fully support or contradict the hypothesis that propagating knickpoints may shape stream profiles.

Here we investigate longitudinal profile development on the island of Kauai where dated lava flows, well-preserved initial surfaces, and distinctly varying base level conditions provide clues to rates and controls on profile evolution. We start by assessing whether a stream power erosion law for these boulder-bedrock channels adequately represents the long-term average erosion rate of the channels. We then use a finite-difference model to assess the effects of stream power dependent erosion on profile evolution and knickpoint migration.

Stream Power Dependent Erosion

Most theories for longitudinal profile development are based on sediment continuity and alluvial sediment transport equations and therefore implicitly assume bedrock to be eroded as if it were composed of cohesionless grains (e.g., Smith and Bretherton 1972; Pickup 1977; Begin et al. 1980; Ahnert 1987; Snow and Slingerland 1987, 1990). (An exception is the work of Foley [1980*b*], who coupled sediment transport equations with abrasion models derived from the engineering literature to model bedrock erosion.) Many channels in hilly and mountainous regions, however, cut into bedrock and lack a thick alluvial mantle. The sediment transport capacities of channels in these regions can be much greater than the supply derived from either the canyon walls or upstream channel delivery. In these cases the bedrock's resistance to erosion presumably plays a dominant role in controlling long profile evolution. A field-tested theory that models bedrock erosion, rather than cohesionless sediment transport, may contribute to our understanding of profile development in mountainous regions.

Howard and Kerby (1983) described the parallels between erosion of cohesive soils in flume experiments (e.g., Akky and Shen 1973; Croad 1981) and erosion of bedrock in rivers. They argued that incision is proportional to shear stress, specifically to the shear stress exerted on the bed by the dominant discharge. To test this argument, Howard and Kerby (1983) analyzed profiles developed in a 0.13

km^2 badlands landscape. By using Manning's equation and arguments from channel geometry, they inferred that the erosion rate of a bedrock channel is proportional to the product of drainage area and slope raised to the 0.4 and 0.8 power, respectively. While Howard and Kerby's model is mechanistically based, it requires information about channel geometry and roughness that is difficult to obtain. This motivated us to take a simpler approach based on stream power. Although our approach cannot easily account for important roughness and channel scale effects, it is simpler, and thus potentially more general. Because Howard and Kerby studied a microlandscape, their measured exponents and coefficients are site-specific, and the coefficients and exponents required by Howard and Kerby's model are more readily measured in their scaled-down system than in stream basins.

Following our previous analysis (Seidl and Dietrich 1992), we hypothesize that the rate of river incision into bedrock is proportional to the power expended by the stream flow, i.e.,

$$-\frac{\partial z}{\partial t} = k(QS)^n \tag{1}$$

where z is the elevation of the channel above a datum, t is time, Q is river discharge, S is the local slope of the river, and k and n are empirical constants. Bedrock erosion is probably an infrequent event that usually occurs during high runoff. If we assume that on average these peak runoff events scale with drainage area, A, then equation (1) can be written in the more convenient form,

$$-\frac{\partial z}{\partial t} = kA^m S^n \tag{2}$$

where m is an empirical constant.

Here we examine this proposed stream power erosion law through empirical analysis and numerical modeling of Hawaiian river channels. We first show that long-term erosion rates of western Kauai rivers correlate well with stream power as represented by equation (2), despite a nearly continuous boulder mantle in some of these channels which probably inhibits local bedrock erosion. We then use equation (2) to simulate the long-term evolution of stream profiles on Kauai and test whether the profile forms, predicted using equation (2) and reasonable initial and boundary conditions for the Kauai channels, are consistent with the rivers' contemporary forms.

Field Site

Our analyses rely on observations made on rivers located on the Hawaiian islands of Kauai, Molokai, Maui, and Hawaii, with the focus placed on Kauai river longitudinal profiles incised into gently dipping basalt (figure 1). The Kauai channels have three features particularly useful for profile evolution studies, including: (1) they are runoff-dominated channels downcutting through uniform bedrock lithology of well-constrained age, (2) they have preserved initial surfaces above the present day channels, enabling us to calculate long-term downcutting rates, and (3) they have well-characterized and varied base level histories. Channels on both the Napali Coast and Mana Plain of western Kauai (figure 2) provide tests of the erosion law and examples of river profiles developed under varying base level conditions. The Napali Coast is located on northwestern Kauai. The Mana Plain is an apron of sediments that forms a broad flat surface along the southern edge of the Napali Coast. Deposition of the Plain has caused the sea cliffs that were once at the coast to be isolated by the sea (Stearns 1985). These cliffs now ring the inland boundary of the Plain.

Basin Morphology. Several authors have argued that particular Hawaiian valleys form primarily by groundwater sapping and have contended that morphologically similar Martian valleys formed by similar processes (e.g., Baker 1988; Kochel 1988; Baker 1990). This basin morphology, termed "amphitheater headed valley" by Hinds (1925), occurs on the windward sides of the Hawaiian Islands, most notably along the Kohala Coast of Hawaii, and is often located in close proximity to calderas and their associated dike complexes, which may serve as catastrophic seepage sources when breached. These amphitheater headed valleys are defined on the basis of morphology and assumed process of formation. The valleys typically have u-shaped cross-sections, steep walls that often meet the valley floor at nearly right angles, plan views that widen to a blunt shape in the upstream direction, non-dendritic drainage patterns, and short tributaries located far apart from each other (e.g., Baker 1990). Dunne (1990), however, challenges the notion that particular basin morphologies are related uniquely to seepage erosion.

In contrast, the channels we have chosen to study do not have either the morphology or structural controls proposed by Baker and his colleagues, nor have we seen any evidence in the field of seepage processes. The Napali Coast and Mana

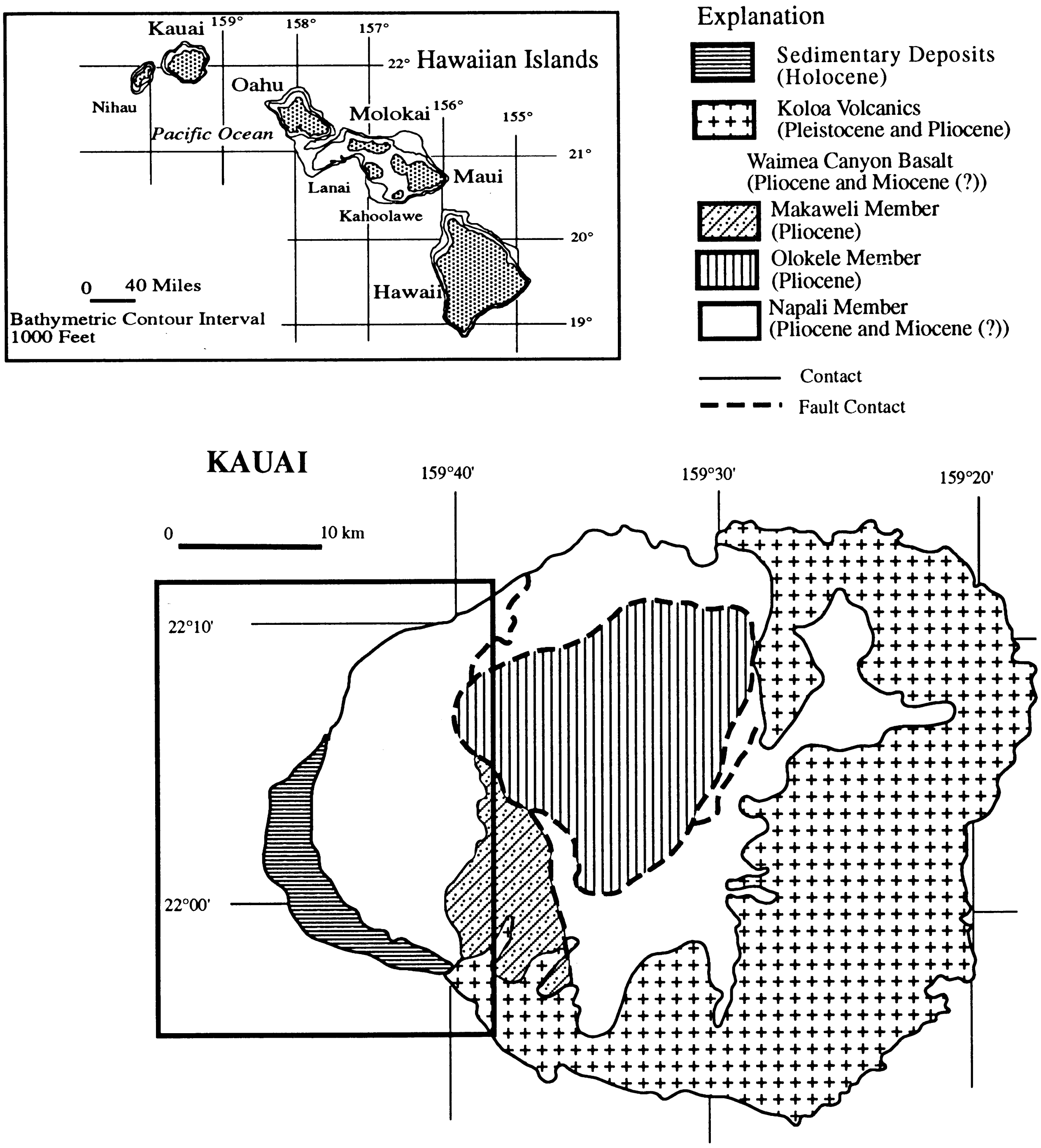

Figure 1. Location map of the Hawaiian Islands (modified from Stearns 1985) and map of Kauai showing generalized geology (modified from Langenheim and Clague 1987 and Sterans 1985).

Plain channels are located on the leeward, drier side of Kauai, with yearly precipitation ranging from 100 cm at the divide to 50 cm at the coast (Macdonald et al. 1960), and are not located near dike complexes. These channels have dendritic drainage patterns, v-shaped cross-sections, valley widths that taper regularly toward the channel head, and elongate tributaries.

Lithology. Located on the oldest portion of the Kauai shield, channels of the Napali Coast flow over the remarkably uniform and continuous Na-

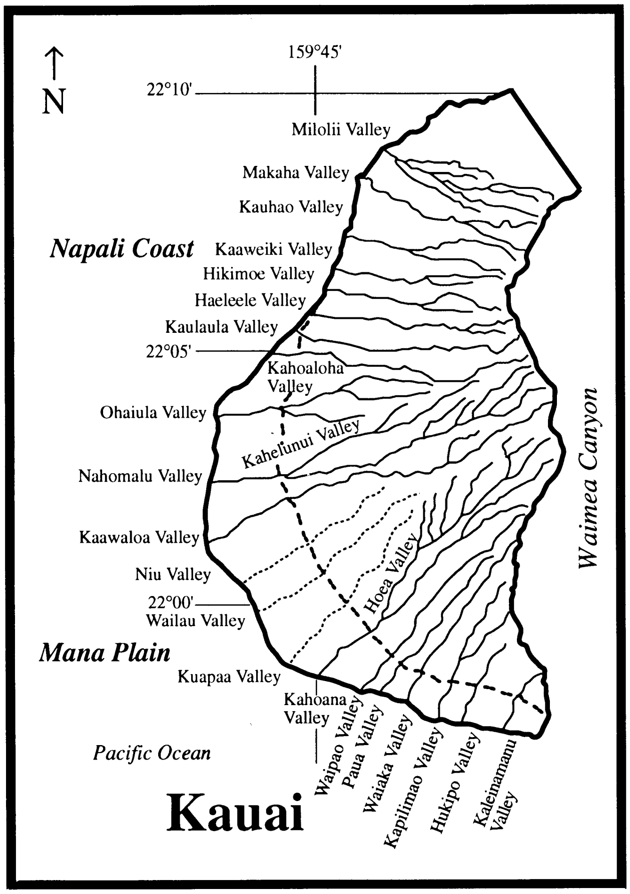

Figure 2. Location of digitized river channels on Kauai. Dashed channels were not digitized. The Mana Plain is the surface to the south bounded by the dashed line and the coast. The Napali Coast stretches to the north of the Plain. Ancient sea cliffs demarcate the inward (eastern) edge of the Mana Plain. Outline of box around figure corresponds to outline on figure 2.

pali member of the Waimea Canyon Basalt of Pliocene age (McDougall 1964; Langenheim and Clague 1987) (figure 1). Channels that flow over the Mana Plain and into the sea also originate in the Napali member (figure 1). The member consists of thin-bedded tholeiitic and pahoehoe flows of predominantly olivine basalt erupted during the shield-building stage on the island (Stearns 1985). The flows exposed in the valley walls are uniformly thin, averaging several meters in thickness and dip, on average, 6° (Macdonald et al, 1960). Individual flow units can be traced for long distances, and intercalated ash and soil beds are rare, as are erosional unconformities between flows (Macdonald et al. 1960). This continuity evidenced by the lava flows is "the characteristic result of the rapid accumulation of lavas of uniform basaltic composition on the unobstructed flanks of a highly active shield volcano" (Macdonald et al. 1960, p. 27). Pyroclastic rocks comprise <1% of the mass of the formation (Macdonald et al. 1960). On western Kauai, the Napali member flows are not overlain by other volcanic rocks and the thickness of the formation is on the order of 6500 m when measured from the seafloor (Stearns 1985). The Napali member flows are approximately 5.1 m.y. old and are the oldest rocks on Kauai (Clague and Dalrymple 1987; Langenheim and Clague 1987).

Paleosurfaces. On western Kauai the geometry of the shield volcano allows the ridges above the channels to be identified as the initial basaltic surface into which the channels have incised. The surfaces can be connected across valleys and the resultant form is representative of the original shield volcano. These paleosurfaces are considered by us to be approximately equivalent in slope and relative elevation above the channel floor to the original surface of the shield volcano. The surfaces are easily recognized as the wide, gently sloping divides between deeply incised, v-shaped canyons. The paleosurfaces traverse the distance from the valley headwaters to the sea, where their seaward edges are truncated by the sea cliffs.

Base Level Histories. Past and present fluctuations in base level must be determined clearly before we can predict longitudinal profile evolution from an erosion law. It is now recognized that the Hawaiian volcanoes subside 2–4 km, with the greater part of this subsidence occurring in the first million years after volcanism on the sea floor began (Moore 1987). The southernmost Hawaiian islands currently are subsiding actively, whereas the northwestern islands, including Kauai, Molokai, and Oahu, effectively have been stable for a long period (Moore 1987).

Comparing the Napali Coast and Mana Plain channels illustrates how boundary conditions affect longitudinal profile evolution. The Napali Coast is an area of active cliff erosion, with sea cliffs reaching upward of 600 m in height. These cliffs may have been formed by a major landslide while the island was subsiding (Moore et al. 1989) and have been modified by wave erosion over the last several million years. Similar large-scale features have been described on other volcanic landforms, and the prevalence of massive landsliding events over the course of volcanic evolution has been documented recently (Borgia et al. 1992). Whereas the Napali Coast channels have been affected by cliff retreat and sea level change through their entire history, the Mana Plain channels have been buffered from sea level changes during the Pleistocene. The Plain is an uplifted coral reef across which streams have built a large alluvial fan. The Mana Plain may have been uplifted as a result of tilting during Pleistocene volcanism that affected eastern Kauai and may be as old as 2 m.y. (D. Clague, pers. comm.). Therefore, channels in both areas flow over the same rock formation and have experienced similar early histories, yet channels of the Napali Coast have been subjected to base level changes due to glacio-eustatic fluctuations whereas channels of the Mana Plain appear to have been protected from sea level fluctuations and cliff erosion during the Quaternary.

Methods

Longitudinal Profile Analyses. The analysis presented here relies on field observations and detailed interpretation of topographic maps. We visited representative channels from both the Napali Coast and Mana Plain to confirm the accuracy of the maps and the assumptions made in the theory. To test the hypothesis that bedrock channel erosion rates are proportional to stream power, we calculated erosion rates, drainage areas, and channel slopes from topographic maps and compared the empirical relationship between these factors to the relationship predicted by equation (2). Erosion rates were calculated from the difference in elevation between the paleosurface and the adjacent channel. A polynomial was fit to the channel's digitized profile so that, for any distance along the channel, the corresponding elevation could be calculated. Similarly, a curve was fit to the paleosurface to determine the elevation of the ridge for a given distance. The distance between the paleosurface and channel was then calculated for every contour interval along the profile.

Profiles of the main channels draining the Napali Coast and Mana Plain were digitized from U.S. Geological Survey 7 1/2′ topographic maps. Elevation and distance coordinates were determined for every contour interval along river traces. Paleosurfaces for each channel were similarly digitized from the 7 1/2′ topographic maps. Elevations and distances of the paleosurfaces were digitized approximately every 200 ft. Nineteen channels that drain the Napali Coast and Mana Plain were digitized (figure 2 and table 1). Three channels that flow to the Mana Plain were not digitized because they terminate far from the Waimea Canyon divide. Three of the 12 digitized Mana Plain channels were not used in the erosion rate analysis because several nearby cinder cones obscured the paleosurfaces above these streams.

Drainage areas were determined directly from topographic maps with a digital planimeter. Between five and 18 separate determinations of drainage area were made along each of the longitudinal profiles. These contributing drainage areas and associated channel lengths were used to determine drainage area as a function of distance from the divide for each of the catchments.

Channel slope values were calculated using the digitized profile data. Measurements of local slopes

Table 1. Summary of Analyses of Kauai Channels

Basin	Channel Length (km)	Relief	Drainage Area (A) as a function of Channel Length (L)[a]	r^2	Erosion Rate[b] (ER)	+	Area-Slope[b] (AS)	r^2	n
Makaha	7.2	1.1	$20.7 \times L^{1.4}$	1.00	(4.4×10^{-6})	+	(7.5×10^{-11})	.81	66
Kauhao	7.4	1.1	$4.5 \times L^{1.6}$	.99	(3.7×10^{-5})	+	(3.7×10^{-11})	.23	53
Kaaweiki	7.3	1.0	$2.1 \times L^{1.7}$	1.00	(-1.1×10^{-5})	+	(1.1×10^{-10})	.95	55
Hikimoe	7.5	1.1	$24.3 \times L^{1.4}$	.97	(1.4×10^{-5})	+	(3.6×10^{-11})	.86	42
Haeleele	7.9	1.0	$133.2 \times L^{1.2}$	.99	(3.6×10^{-6})	+	(7.7×10^{-11})	.97	72
Kaulaula	9.4	1.0	$116.5 \times L^{1.2}$	.99	(7.3×10^{-6})	+	(4.7×10^{-11})	.59	70
Kahoaloha	10.3	1.1	$25.6 \times L^{1.4}$	1.00	(6.5×10^{-6})	+	(4.9×10^{-11})	.89	75
Ohaiula	7.3	.7	$11.4 \times L^{1.5}$	.91	(4.5×10^{-6})	+	(8.6×10^{-11})	.85	54
Kahoana	10.9	.7	$9.3 \times L^{1.5}$	.97	(1.2×10^{-5})	+	(3.8×10^{-11})	.87	57
Waipao	9.7	.7	$12.7 \times L^{1.4}$	.99	(1.1×10^{-5})	+	(3.5×10^{-11})	.84	52
Paua	5.5	.4	$190.8 \times L^{1.1}$	1.00	(5.9×10^{-6})	+	(3.6×10^{-11})	.96	31
Waiaka	7.7	.6	$36.2 \times L^{1.3}$	.99	(8.3×10^{-6})	+	(5.0×10^{-11})	.68	37
Kapilimao	6.4	.5	$3.0 \times L^{1.7}$	.99	(5.1×10^{-6})	+	(78.7×10^{-11})	.90	36
E.Kapilimao	5.4	.5	$.1 \times L^{2.1}$	.92	(6.9×10^{-6})	+	(9.0×10^{-12})	.21	24
Hukipo	4.6	.4	$5.1 \times L^{1.6}$	.98	(7.0×10^{-6})	+	(4.3×10^{-11})	.71	29
Kaleinamanu	2.8	.3	$19.8 \times L^{1.4}$	.94	(1.4×10^{-6})	+	(1.9×10^{-10})	.97	19

[a] This column is the empirically determined relationship between Drainage Area (A) in km^2 and Channel Length (L) and should be read as: $A = 20.7 \times L^{1.4}$ and so on down the column.

[b] This column represents the empirically determined relationships between Erosion Rate (ER) and the Drainage Area (A)-Slope (S) product and should be read as: $ER = [(4.4 \times 10^{-6}) + (7.5 \times 10^{-11})(AS)]$.

made in the field compared favorably with those calculated from the topographic maps. The slope used in this analysis was a spatially averaged value, because we are calculating long-term average erosion rates. For any point on a profile, the slope of the present channel bed was determined by averaging slope values over five contour intervals: two contours above and two contours below the elevation in question. Several channel profiles had short, notably steep reaches that correlated with waterfalls in the field. These reaches of nearly vertical gradient were excluded from the data set. The 100 m directly downstream from the channels' headwaters were similarly excluded from the analysis because erosion rates along these upper reaches approached zero. The slope of the paleosurface above the channel was similarly averaged, over 15 contour intervals, to generate a value representative of the initial surface. These channel and ridge slopes were combined to calculate the slope value used in the analysis.

Erosion rates were calculated assuming a 5.1 Ma age for the basalt and were plotted against the product of the measured drainage area and the computed slope for points on 16 profiles (table 1).

Empirical Analysis

Empirical Test of Erosion Law. Clear relationships exist between erosion rate, drainage area, and slope on both on an inter- and an intra-basin basis. Local river incision rates into basalt on Kauai range from 5 to 80 m/m.y., as compared to the 5 to 30 m/m.y. incision rates reported in Young and McDougall (1993) for Australian rivers carved into basalt in a similarly humid environment. Regression of the data for both the Napali Coast and Mana Plain basins indicates that

$$-\frac{\partial z}{\partial t} = (6.1 \times 10^{-6}) + [(6.3 \times 10^{-11})(A\,S)], \quad (3)$$

with an r of 0.88 (figure 3). The erosion rate was measured in meters/year and the drainage area in square meters. The measured drainage areas vary over four orders of magnitude. Regression of the data within each basin indicated that the exponent of length varied from 1.1 to 2.1 and averaged 1.5 on Kauai (table 1).

It should be noted at this point that we are comparing a time-averaged erosion rate with measurements of current drainage area. Because of this discrepancy, we analyzed several channels on two other Hawaiian islands to determine if changes in drainage area could be related to increases in age. A systematic variation in drainage area with time should manifest itself in differing area-length relationships in basins of disparate ages. We chose channels flowing over uniform rocks of younger age than the Napali member flows, in areas with precipitation gradients, paleosurface gradients, and channel lengths similar to those of western Kauai. Channels on East Maui, which flow over the relatively uniform Kula Volcanics of Pleistocene age, and channels on northwestern Hawaii, which are incising into the Hualalai Volcanics of Pleistocene and Holocene age (Langenheim and Clague 1987), were analyzed in the same manner as on Kauai. Only drainage basins that extended from the divide to the sea were examined. This analysis indicated that area-length relationships do not vary systematically from island to island; there is enough scatter in the data that no systematic variation in exponent-length relationships can be ascertained (table 2, figure 4). Although there is a 4.7 m.y. difference in their ages, drainage basins on the island of Maui appear to be well developed and similar in shape to the older Kauai valleys (figure 5). This result was unexpected, and we speculate that the nonuniform initial topography created by successive surface flows contributes to the early definition of a characteristic, but spatially variable, catchment area-draining distance relationship. Subsequent dissection leads to the creation of locally steep valley walls, much steeper than the initial surface, but not to an increase in drainage area. We assume that the catchment relationships given in table 1 apply throughout the development of the profile.

In contrast to the range in drainage area values,

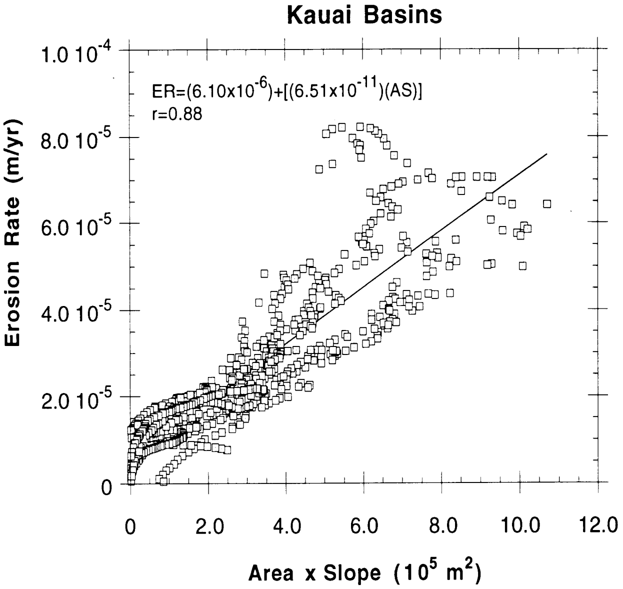

Figure 3. Calculated erosion rate as a function of the product of drainage area and slope for channels on both the Napali Coast and Mana Plain, Kauai.

Table 2. Summary of Area-Length Data for Hawaii and East Maui

Basin	Drainage Area (A) in km^2 as a function of Channel Length (L^b)			r^2
Hawaii:				
Waiaha	1.7	×	$L^{1.7}$	1.00
North Waiaha	.1	×	$L^{2.1}$	.97
Unnamed	118.9	×	$L^{1.1}$	.98
East Maui:				
Waiopai	1.5	×	$L^{1.7}$	.93
Wailaulau	341.9	×	$L^{1.1}$	.93
Pahihi	.1	×	$L^{2.1}$	.99
Manawainui	1.5	×	$L^{1.7}$	.90

the profile shapes are often straight along some portion of their length, and because the paleosurfaces are also straight, the range in calculated slope values is small, ignoring the nearly vertical sections made up of waterfalls. As such, the exponent on slope is not as tightly constrained as it would be if the slopes of the present day river profiles varied more.

Longitudinal Profiles. For the empirically derived erosion law to be applicable to longitudinal profile evolution, it should predict at least the general properties of the observed Kauai channels. Here we describe the digitized profiles to compare them with subsequent model predictions. In sharp contrast to the classic concept of a graded profile, longitudinal profiles of channels on the Mana Plain have straight to weakly convex profiles (figure 6), whereas the Napali Coast channels are characterized by straight reaches punctuated by distinct convexities, or knickpoints (figure 6). The Hawaiian knickpoints occur as both small, local features tens of meters in length and as much larger features hundreds of meters of length. Each knickpoint is either a waterfall, from 20 to 100 m in height, or a series of 2 to 10 m bedrock steps. Woodford (1951) distinguishes between sharp nicks, or knickpoints, and longer convexities, and asserts that the nicks evolve into the convex reaches. For simplicity, we will call both very local and larger-scale, strongly convex regions knickpoints. A plot of local slope against relative distance toward the sea along the profile reveals where these generally straight profiles are punctuated with convex reaches (figure 7) and shows the greater frequency and magnitude of knickpoints in the Napali Coast channels. The effects of the lower boundary condition are shown clearly as well. Whereas the Mana Plain slopes rapidly decline at about $0.7(x/L)$ (where x is distance from the divide, and L is total length to the sea) due to fan construction across the Plain, the Napali Coast channels steepen at about $0.4(x/L)$ and maintain an average slope of 0.15 to the sea. The Mana Plain channels all have about the same mean slope (0.10), and this is less steep than the 0.15 slopes of the Napali Coast channels.

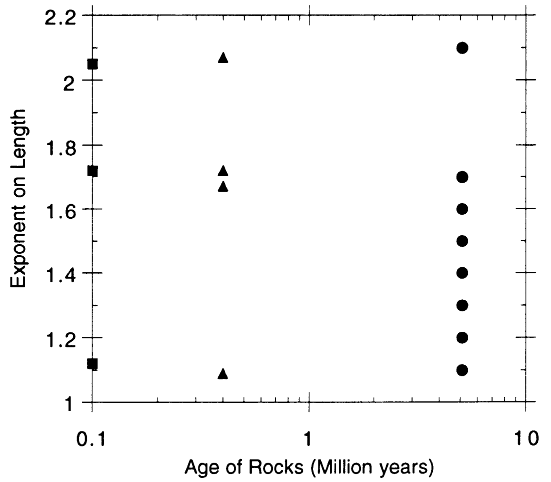

Figure 4. Drainage area-length relationships for the three Hawaiian Islands of Kauai (5.1 m.y.—dots), Maui (0.4 m.y.—triangles), and Hawaii (0.1 m.y.—squares).

Most casual impressions of waterfalls formed in volcanic terrain and elsewhere are that they originate due to some resistant unit, typically an aphanitic dike, and greatly retard channel incision. Many waterfalls in Hawaii originate this way, but in our field area this does not appear to be the case. Map traces of Mana Plain and Napali Coast channels are generally free of mapped dike localities (Macdonald et al. 1960). Six valleys do contain such mapped intrusions, including Milolii Valley, with nine dikes mapped in the lower reaches, Makaha Valley, with five dikes mapped crossing the lower valley, Hikimoe Valley, with one mapped intrusion. Nahomalu Valley, Kaawaloa Valley, and Kahoana Valley, all with several mapped locations (Macdonald et al. 1960). The accuracy of the intrusion locations has been called into question; indeed, the mapped dikes probably do not exist (D. Clague, pers. comm.) On Kahoana Valley a mapped dike locality corresponds to a channel knickpoint. This site was visited in the field, however, and no sign of an intrusion was noted. The rock constituting the knickpoints that we observed in the field is indistinguishable from the surrounding bedrock. Dikes may have been mapped on the basis of waterfalls rather than from independent data; thus dike mapping may assume that dikes cause knickpoints. On channels with both pronounced knick-

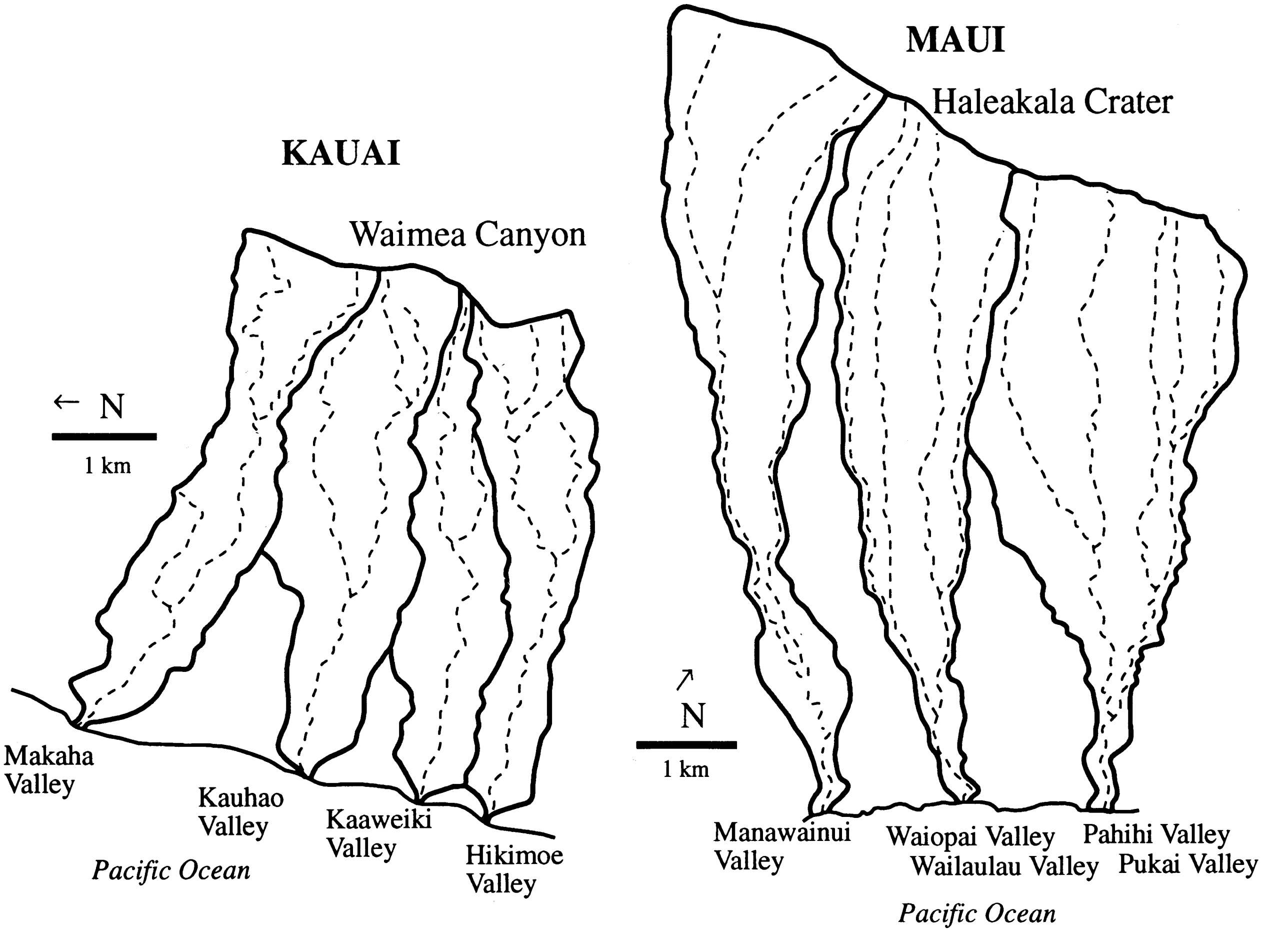

Figure 5. Outlines of drainage basins on Kauai and East Maui. Note that both drawings are at the same scale.

points and mapped intrusions, the two features occur in the same place on only one valley, Milolii Valley, which was inaccessible in the field. In two of the valleys containing mapped dikes, Makaha Valley and Hikimoe Valley, the mapped intrusions are located kilometers downstream of the digitized knickpoints. In general, the locations of the Kauai knickpoints do not correspond to sites of more resistant strata.

Channels crossing the Mana Plain have been buffered from sea level change for a long time and display singularly straight to slightly convex profiles (figure 6). Conversely, Napali Coast channels may have been subjected to sea level fluctuations and cliff retreat for several more million years and exhibit profiles characterized by marked steps (figure 6). Although knickpoints presumably formed on the Mana Plain channels at the time of sea cliff formation, knickpoints are generally not present on the profiles; channels bounded by the Mana Plain would have ceased generating knickpoints at the onset of uplift of the coral reef. These different boundary conditions under which the channels in the two areas evolved, when contrasted with their similarities, suggests that the knickpoints may be formed by base level changes, but may, without continued base level fluctuations, die out over time.

Dramatic morphologic changes occur in the valleys above and below the knickpoints. Upstream of the knickpoints the adjacent hillslopes are soil-mantled and have relatively gentle gradients. The bedrock outcropping in the channel bed and banks is extremely weathered. Downstream of the knickpoints, valley walls have steep, often nearly vertical gradients three to five times greater than those above the knickpoint and lack substantial soil cover. The digitized channel reaches below the knickpoints have remarkably uniform, straight slopes of approximately 8°. Channel incision is a boundary condition to hillslope development, and a change in the process of incision across the waterfalls, from propagating knickpoints downstream to abrasion and dissolution upstream, could explain the distinctive landscapes.

Our field surveys also revealed that significant

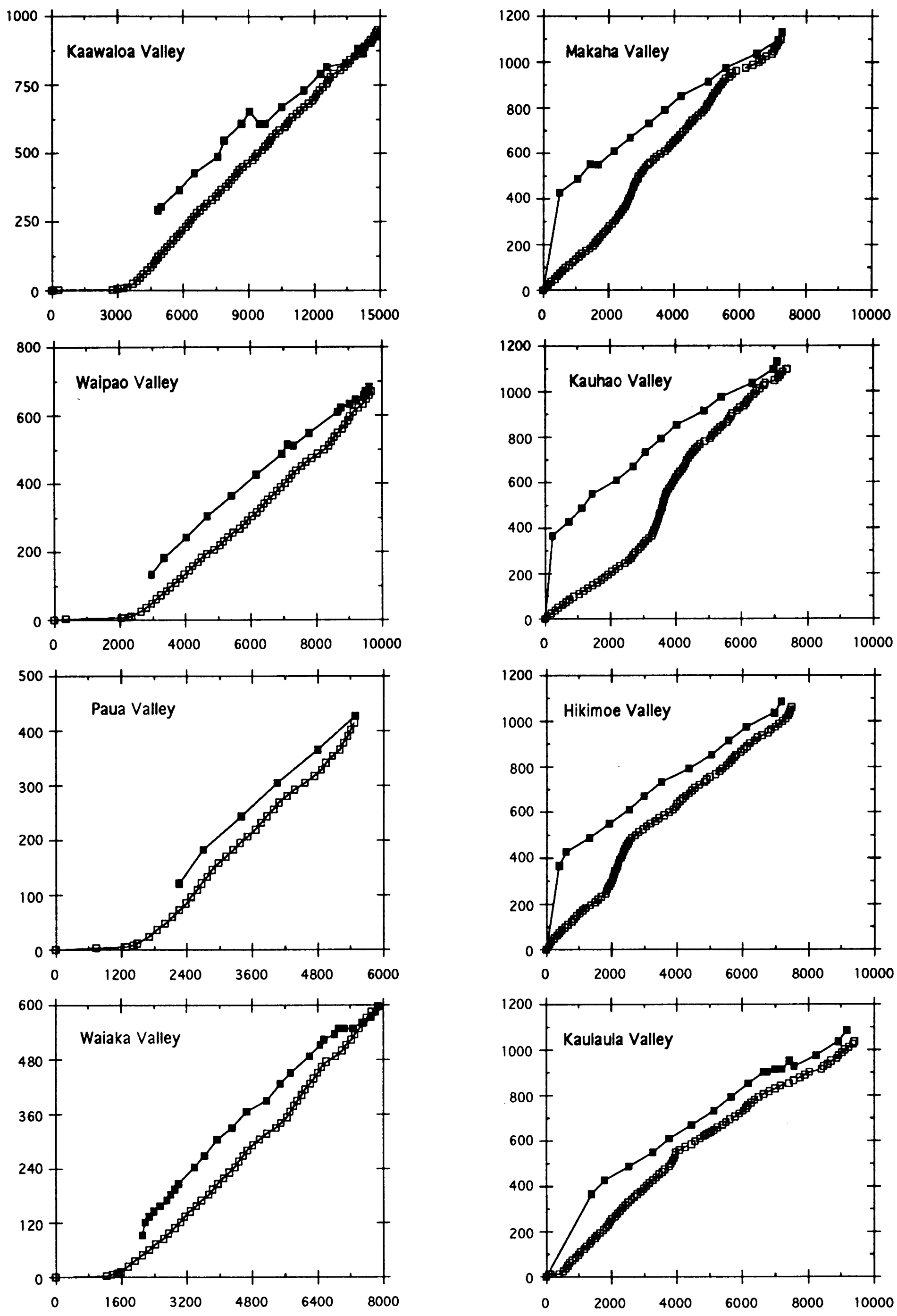

Figure 6. Representative profiles from Kauai with elevation and distance plotted in meters on the *y*- and *x*-axis, respectively. The straight to weakly convex Mana Plain profiles are shown on the left; the flat channel segments beginning at the sea correspond to the Mana Plain. Napali Coast channel profiles are shown on the right. Note the sharp knickpoints and longer convex reaches that punctuate the profiles. Open squares represent the channel profiles and solid squares represent the paleosurfaces above the channels. Note that the amount of vertical exaggeration differs from profile to profile.

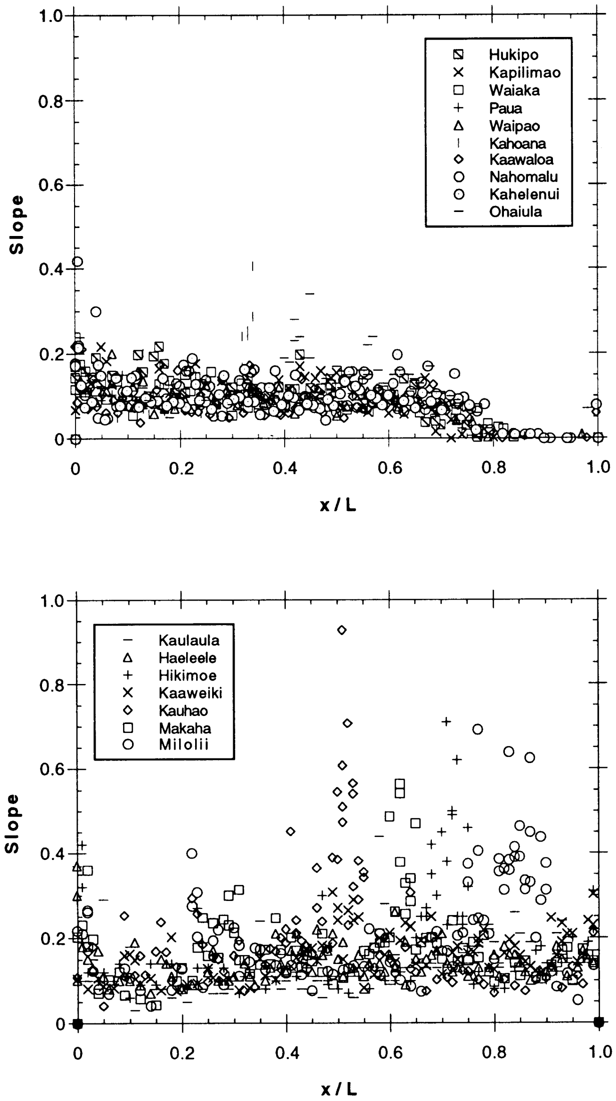

Figure 7. Plot of slope against normalized distance (*x*/*L*) for representative Mana Plain channels (top) and Napali Coast channels (bottom).

portions of the channel lengths above and below knickpoints are mantled with boulders. Below the knickpoints, the boulders are very large with an average diameter of several meters, often angular, interlocked in a fashion that shows no evidence of reworking by the stream and appear to be weathering *in situ.* Most boulders are stored in debris terraces adjacent to the channel. These terraces are angular ramps of material rising 2–8 m above the present channel. The channel itself is mantled by this material over much of its length, but the periodic outcropping of resistant bedrock in the channel bed and banks indicates the valley is not filled by a deep layer of boulders. There is no noticeable fining of sediment either in the channel or on the boulder terraces in the downstream direction. We saw no clear evidence of flood transport of large boulders. Debris flow mobilizaiton of material probably predominates on the tributaries, but the main channel gradient is close to depositional grade and so debris flow scour is less likely.

The large, apparently immobile boulders impose another constraint on the river incision process. Rivers can overcome the resistance to erosion offered by boulders and cut into the underlying bedrock by (1) moving them and breaking the boulders down during large flood flows, especially in narrow canyons where flows can be deep, or during mobilization of debris flows (e.g., Baker 1977; Pierson 1980; Baker and Pickup 1987; Benda 1990; Miller 1990; Wohl 1992), (2) eroding decay products of weathered boulders (Schumm 1977), and (3) undermining the boulder mantle by propagating knickpoints that are significantly thicker than the boulder pile size (Seidl and Dietrich 1992). None of these processes fit into a conventional cohesionless sediment transport law normally used in predicting longitudinal profile evolution. In a river that has cut progressively through bedrock, even when receiving untransportable boulders, either the boulders must be removed through weathering and breakdown, or they must be undercut by propagating knickpoints. The former process may still be crudely accounted for in a simple stream power-like erosion law if breakdown can be thought of as slowing the rate of bedrock erosion. This presumes that the weathering rate is spatially constant and that the boulder influx rate is not sufficient to inhibit eventual bedrock erosion. Cosmogenic isotope analyses of boulder olivines on one of the Napali Coast channels, Kaulaula Valley, indicate that larger boulders may lie in the valley for at elast 180,000 yr (Seidl 1993), suggesting that the rate of breakdown is relatively slow. In the modeling to follow, we will account for both the progressive downwearing and the propagating knickpoint hypotheses.

Theoretical Analysis

Model Framework. A finite-difference model was developed to predict the present general form of river profiles in western Kauai from the inferred initial conditions and our empirical erosion law (equation 2). If equation (2) is valid, it should at least predict the gross features of the longitudinal profiles from which it was derived. In our one-dimensional model, drainage area was replaced with distance from the divide using an empirical correlation and our erosion law thus becomes,

$$-\frac{\partial z}{\partial t} = -c(x)^b\left(\frac{\partial z}{\partial x}\right)^n \qquad (4)$$

in which x is distance from the divide, $(-\partial z/\partial x)$ is slope, c is 6.5×10^{-4}, b equals 1.5, and n equals 1.0, where lengths are in meters and time is in millions of years. A value of b equal to 1.5 is used because the $A \propto L^b$ relationships average roughly $A \propto L^{1.5}$ (table 1).

The initial condition in most modeled cases was similar to observed paleosurfaces and consisted of a constant slope of 0.08, relief of 1 km, and a divide positioned 12 km from the sea. The length and relief values correspond to linear projections of the digitized ridge topography downstream from the Waimea Canyon divide, across and beyond the sea cliffs, to present sea level. Because the extensions parallel the straight ridge surfaces and the offshore gradient is low, a different sea level would affect the length and relief of the initial profiles, but would have little effect on the slope. A steep offshore gradient would make such a topographic reconstruction less straightforward. Island subsidence is considered to have occurred during the shield building stage and prior to this reconstructed stage. This simple projection is therefore assumed to be a reasonable proxy for the initial volcanic surfaces. For each profile, 100 nodes were used, which is similar to the number of map contour intervals used to measure the actual channel profile. Starting from this initial condition, each node was iteratively lowered according to (4), with the coefficients specified above. This erosion process was repeated for the equivalent of 4 m.y.

In all simulations, the divide elevation and the sea level elevation remained fixed. The two dominant base level effects on the Kauai channels are the sudden formation of sea cliffs due to massive landslides and the slower shoreline retreat and sea cliff formation through wave action, chemical weathering, and mechanical failure. These two processes might be expected to affect the profile differently. Sea cliffs were therefore simulated in two different ways: (a) by altering the initial conditions and imposing a steep slope over a long reach of the paleosurface and (b) by imposing a constant rate of cliff retreat, which formed steep sea cliff-like features at the coast. Initial condition (a) effectively modeled a massive landsliding event, whereas (b) simulated the modifications wrought by more gradual erosional processes. The effects of sea level rise and fall are incorporated in (a). If the offshore gradient is steep, a drop in sea level will be accompanied by a steepening of the distal profile. Similarly, sea level rise accompanied by erosive wave action at the river-sea confluence will result in an increase in channel gradient at the confluence. The steep slope imposed on the profile in (a) acts as a proxy for both these phenomena.

Straight Initial Condition. This model represents the case of profile evolution with a fixed base level from the initial, essentially straight paleosurface created by successive lava deposition. If knickpoints formed and propagated, it is assumed to be of secondary importance. This model simulation would apply most closely to the profiles on the Mana Plain which have had a fixed base level without cliff retreat. Figure 8*a* shows the predicted profile evolution. Note that the profile consists of two distinct reaches: a straight to weakly convex portion that becomes progressively steeper through time and a reach of zero slope that extends toward the divide through time. No erosion occurs at the divide because there x equals zero, hence the profile rotates about this hinge point.

Qualitatively this result is in good agreement with the Mana Plain profiles (figure 6), which have approximately straight upper reaches showing little or no erosion at the divide and increasing incision along the profile in the downstream direction. The flat lower reaches shown in figure 8*a* correspond to the Mana Plain depositional surface and should not be equated with the reaches of zero slope predicted by the model. The upper reaches of Napali Coast channels also display notably straight profiles with little or no erosion at the divide and successively more incision downstream along the profile.

The reaches of zero slope near the sea occur in the model because base level remains fixed during simulation. Clearly such a zero slope does not occur in nature. Instead, deposition of boulder-sized material along the lower channel reaches may both restrict incision and be instrumental in setting the 5–8° channel slopes found on the profiles. The deposition of fairly uniformly sized material is likely to yield a straight slope. This process is not included in our simple model, but may be added in subsequent analyses.

In the model, the approximately straight to weakly convex reaches result from the relatively low value of the exponent m in the distance term of equation (4).

Steepened Reach Imposed on Initial Profile. This model represents profile development after a mas-

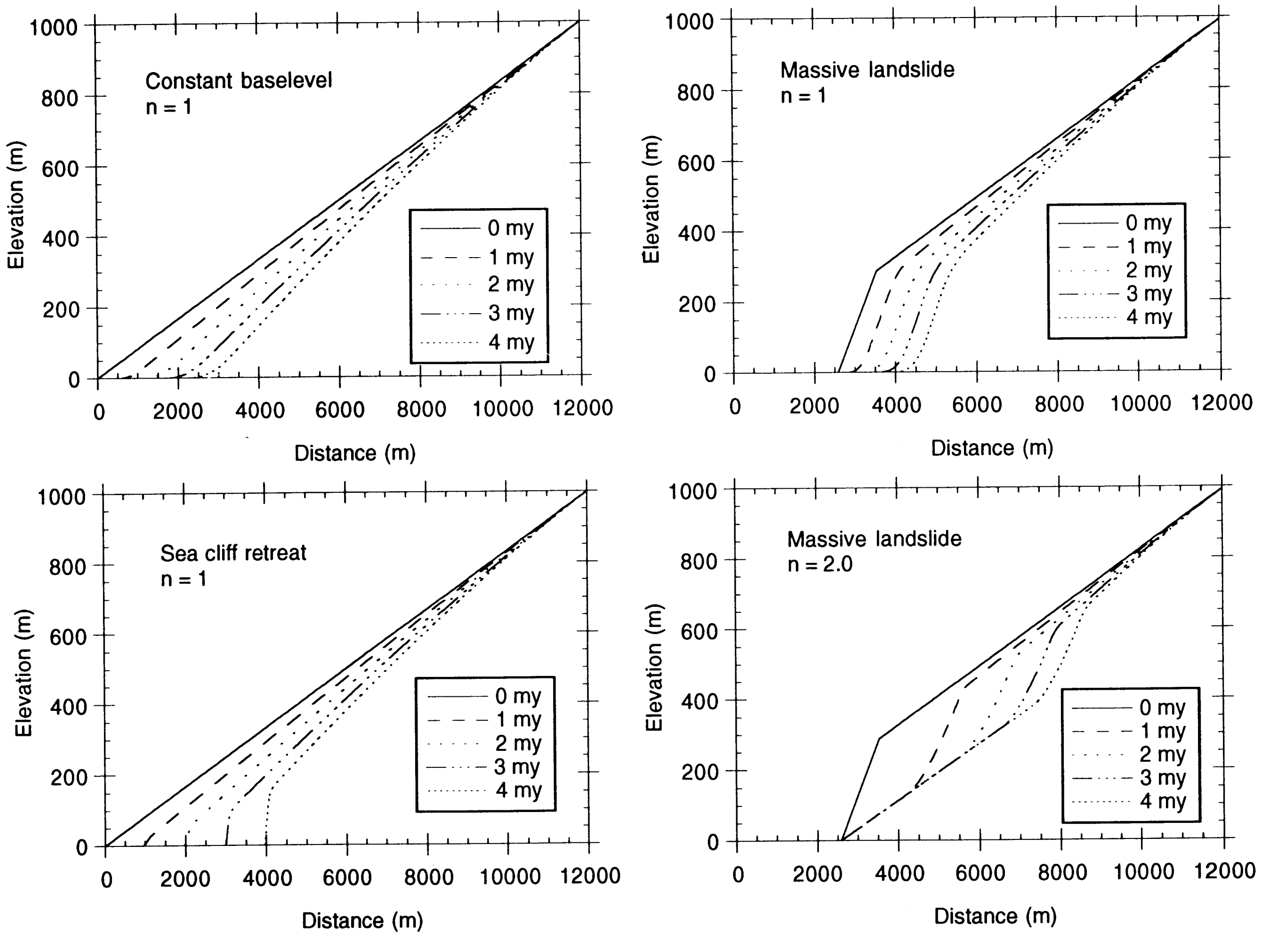

Figure 8. Longitudinal profile development predicted by numerical solutions of stream power dependent erosion law assuming *m* and *n* equal to 1.0, unless otherwise stated, and (*a* top left) a stable base level, and changing boundary conditions simulated by (*b* top right) imposition of a steep reach, (*c* bottom left) cliff retreat continuing for 4 m.y. and (*d* bottom right) imposition of a steepened reach with slope exponent changed to 2.0.

sive landslide. A steepened reach 300 m in height with a slope of 0.6 was imposed on the profile. The height and length of the step approximate the Napali Coast cliffs.

The initial profile looks very similar to the Napali Coast channels. We have hypothesized that such a change in base level will result in the formation and propagation of knickpoints. The main purpose of this model run was to see if the catastrophic generation of a 300 m high step resulted in the migration of the step headward. As shown in figure 8*b*, the height and slope of the steep feature are preserved on each successive profile; the area of steeper gradient does not appear to either wear back or migrate upstream.

Cliff Retreat Rate Imposed on Straight Initial Profile. We modeled the effect of progressive cliff retreat on profile development by shifting base level toward the divide at a rate of 1 m/1000 yr on an initially straight slope. This rate corresponds to that calculated for the western Kauai channels assuming an initial shield volcano geometry, projecting the present day paleosurfaces out to sea, and assuming a 4 m.y. time interval. In figure 8*c*, the cliff retreat function runs for the full 4 m.y. The resultant profiles are characterized by no erosion at the divide, straight to weakly convex profiles, and a steep reach that gains in height through time at the advancing shoreline. As in the case of the landsliding event, the steep reaches do not propagate upslope as knickpoints but instead gain in elevation over time, while retreating in a parallel fashion. Although the increase in height of the feature might appear at first glance to be mimicking a propagating feature, the formation of the cliffs does not result in the formation of a knickpoint that migrates faster upslope than the cliff retreat rate.

Discussion

Our empirical analysis of channels in Kauai provides the first quantitative evidence for a stream power-based erosion law for river incision into bedrock. Landscape models that use a stream power-based erosion law for channel incision (e.g., Willgoose et al. 1991*a*, 1991*b*) now have at least some field evidence to support this assumption. Nonetheless, our analysis has important limitations. The channel slope of Kauai rivers did not vary widely; hence the slope dependence of channel incision rates is poorly constrained. One data set that provides values of slope ranging over two orders of magnitude, from 2.5×10^{-2} to 5.8×10^{-4} (m/m), is that reported in Hack (1965). Hack (1965) investigated postglacial drainage patterns on rivers draining north to Lake Superior. He measured channel slope, width, depth, and bed material size, as well as valley width and depth on these rivers. The basin shapes are generally linear, as flow direction is to a large extent focused by glacial grooves. He qualitatively determined that the depth of valley incision was roughly a function of discharge. Re-plotting data on 17 of the Michigan streams reported in Hack (1965), assuming a 9000 yr age for the retreat of glaciers and onset of incision, indicate that

$$-\frac{\partial z}{\partial t} = \{(9.8 \times 10^{-4}) + [(3.5 \times 10^{-9})(A\,S)]\}, \quad (5)$$

with an r^2 of 0.87 (figure 9). Although not all of the data points are known to be on bedrock, this result lends further support to a stream power dependent erosion law. In addition, the *y*-intercept and coefficient in (5) can be compared to those in equation (3), 6.1×10^{-6} and 6.5×10^{-11}, respectively. The lower slope and intercept determined for Kauai channels indicate the lower erosion rates on the channels, relative to the Michigan streams. The smaller coefficient in equation (3) presumably documents the more resistant material through which the channels are downcutting on Kauai. The streams described in Hack (1965) cut through glacial till and bedrock, primarily sandstone and shale, while the Kauai channels are downcutting through basalt. Climate and precipitation rates are also incorporated in the coefficient but are more difficult to separate.

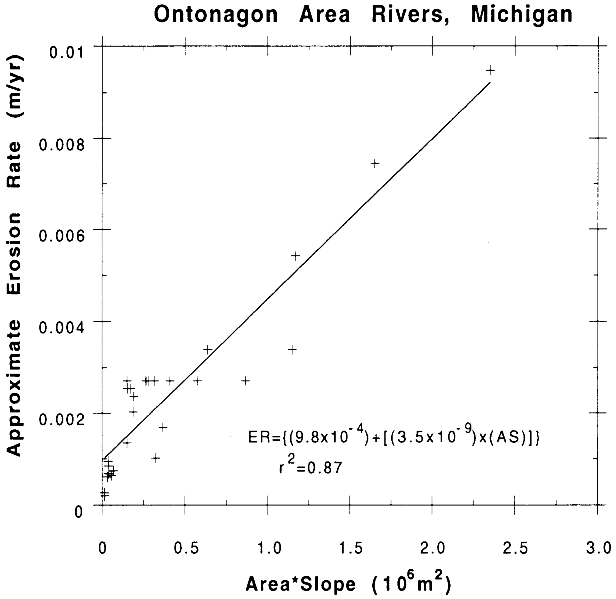

Figure 9. Calculated erosion rate as a function of drainage area and slope for rivers from the Ontonagon area, Michigan. Data are from Hack (1965, p. B19). One outlying point was excluded from the plot and regression (area of 2.9×10^6 and slope of 3.7×10^{-3}).

Recently, Young and McDougall (1993) similarly argued that stream power drives incision on channels carved into basalt in southeastern Australia. Although they do not present quantitative evidence in support of this conclusion, an incision rate proportional to an area-slope product is consistent with their observations that reaches with steep gradients and large drainage areas are deeply incised, compared to low gradient, small drainage area locations. A stream power rule qualitatively accounts for the varying rates of incision shown on the Australian profiles (Young and McDougall 1993).

The long profiles of the Napali Coast channels have prominent knickpoints. The notion of migrating channel knickpoints is not a new one (e.g., Penck 1924; Lewis 1945; Leopold et al. 1964; Holland and Pickup 1976; Pickup 1977; Begin et al. 1980; Foley 1980*a*; Miller 1991). In his study in Michigan, Hack (1965) found no evidence of migrating knickpoints. Young and McDougall (1993) documented the presence of bedrock knickpoints along channel profiles, but ascribed profile development to variations in stream power, not to headward propagation of knickpoints. However, inspection of their published profiles indicates to us that the greater incision rates experienced by steeper areas could also be interpreted as knickpoint propagation. We have hypothesized that knickpoints formed at tributary junctions in bedrock are propagating features and important incisional agents (Seidl and Dietrich 1992). Subsequently Wohl (1993) identified inner channel reaches on a bedrock river as migrating "knickzones" and noted the importance of these features in incision.

Knickpoint retreat is often studied experimentally (e.g., Brush and Wolman 1960; Leopold et al. 1964; Holland and Pickup 1976; Begin et al. 1980; Gardner 1983). However, the correspondence between flume studies of knickpoint behavior and waterfall retreat in basalt is unclear. The time scales and strength of the materials in the two cases are radically different and it seems likely that the process of erosion may similarly vary. The flume knickpoint lip preferentially may erode and flatten over time, as a direct consequence of the applied discharge, whereas steep bedrock knickpoints in rivers may erode principally by mechanical breakdown rather than by hydraulic processes. A single waterfall face made up of several basalt layers may erode primarily by exfoliation, cracking and weathering associated with stress release on the waterfall faces. Although cavitation at the base of waterfalls may aid in initial undercutting, river flow may have little or no effect on the retreat of the face. Comparison of channels in Kauai evolving under similar boundary conditions indicates that knickpoint migration rate and basin size are not clearly correlated. Channels with larger drainage areas generally do not have knickpoints closer to the basin divide than channels in smaller basins, perhaps underlining the importance of slope-dependent processes on knickpoint retreat. The rate of this knickpoint retreat can be estimated by determining the distance from the sea to the knickpoints along the Napali Coast profiles and then dividing this length by a maximum of 4 and a minimum of 2 m.y. As discussed in the modeling analysis, base level change has been effected by either a massive landslide or constant cliff retreat. The resultant knickpoint retreat rates range from approximately 0.5 to 2.0 mm/yr.

Modeling results support stream power-dependent erosion. Simple models predict several features characteristic of the Kauai channels, including the straight to weakly convex channel slopes. However, the modeling analysis indicates that stream power-dependent erosion cannot adequately account for apparent knickpoint behavior. If, as suggested above, knickpoint retreat is actually a mechanical process, rather than a discharge-dependent process, a second transport rule that postulates knickpoint retreat to be a function of slope could be necessary to model bedrock channel incision effectively. In a related study we concluded that it is inappropriate to use a single erosion law to explain the entire profile evolution because several erosion mechanisms, each with its own transport law, may operate in a single river channel (Seidl and Dietrich 1992). In figure 8*d* we show the resultant profile evolution assuming stream power-dependent erosion and an area exponent of 1.0, but with the slope exponent increased from 1.0 to 2.0. The predicted profiles closely reflect the pattern of knickpoint propagation we believe is shown on the Kauai profiles: the knickpoints migrate both "up distance" and "up elevation." We have no mechanistic basis on which to conclude that a transport law describing knickpoint propagation should have a slope exponent of 2.0, but it is interesting to note that this rule does generate propagating knickpoints.

Although we have reasoned that this stream power-dependent erosion law best applies to bedrock channels where sediment transport capacity exceeds supply and erosion is limited by erodability of the rock, the channels in Kauai are partly to completely boulder-mantled. The relatively thin mantle of boulders in Kauai and in many other channels in hilly and mountainous areas clearly indicates that the boulders do not prevent channel incision in the long term. Large rocks fall into the river canyon and there they will remain until they are buried, weathered, and broken down, or undercut by a propagating knickpoint. The lower reaches of the Kauai basins are characterized by a main channel gradient low enough for debris flows to be deposited. In Kauai, it appears that knickpoint propagation may be the dominant agent, as the boulders are very large, show little evidence of secondary transport once arriving in the channels, and persist for long periods of time in the valleys (Seidl et al. 1992; Seidl 1993). An understanding of the production and transport of boulders is necessary to understand profile development in Hawaii. We suggest that boulder production varies with hillslope gradient and length, and that production rate similarly varies with rock type. Boulders inhibit incision and, as Ahnert (1987) argued for sediment supply in general, as river canyons deepen there will be a tendency for boulder supply to overwhelm the channel. This may limit the bedrock incision rate to that set by the boulder breakdown rate. Boulders may also set the slope of about 0.1 typically found in Kauai rivers. Slopes much less will tend to aggrade and steepen, and a slope much steeper can transmit debris flows and erode.

Conclusions

Our analysis of the Hawaiian landscape raises issues about the form of longitudinal profiles, the importance of boundary conditions, and the possible significance of knickpoints. Field studies presented here reveal morphological similarities between different Hawaiian watersheds with similar age, rock, climate, and boundary conditions. These consistencies suggest that the same erosion processes are operating in different locales. We have shown that bedrock incision on some channel reaches correlates with a drainage area-slope product, a surrogate for stream power. Analyses of the straight and convex longitudinal profiles of Kauai streams suggest that base level history may affect the evolution of channel profiles. Stable base level results in the development of straight profiles, such as are observed in channels draining to the Mana Plain. Changes in base level may form knickpoints which propagate upstream, perhaps resulting in the steep reaches found on the Napali Coast channels. Knickpoint propagation may be a primary process of bedrock lowering along many channels and reflects base level history, as well as local tectonic events.

A simple stream power-dependent erosion law cannot fully account for the evolution of stream channel profiles on western Kauai. Longitudinal profile development is complicated by many factors, including sediment supply, storage effects, and weathering. We believe that comprehensively modeling profile evolution requires both a theory for boulder production, breakdown, and removal and a theory for knickpoint evolution. The advent of surface exposure age dating using cosmogenic isotopes may allow a quantitative investigation of the relative rates of incision by both the proposed processes, as well as assessment of the residence time of boulder-sized material in the basins (Seidl 1993). Models incorporating these processes should yield important insight into how landscapes respond to climatic fluctuations and uplift.

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