

The Problem of Channel Erosion into Bedrock

M.A. Seidl & W.E. Dietrich

Summary

Although river incision into the bedrock of uplifted regions creates the dissected topography of landscapes, little is known about the process of channel erosion into bedrock. Here we present a testable framework for the study of fluvial incision into bedrock that combines theory with field observation. We quantify a simple erosion law by measuring drainage areas and slopes on both principal channels and tributaries. The data suggest that both a bedrock tributary and main stem will lower at the same rate at their confluence if the ratio of main stem to tributary drainage area equals the ratio of tributary to main stem channel slope at the junction. Erosion across several tributary junctions is therefore linearly related to stream power. Tributary slopes greater than about 0.2 deviate from this linear prediction, apparently because debris flows scour these steep tributaries. Further field study suggests that the common elevation of tributary and main stem may result from the upslope propagation of locally steep reaches generated at tributary mouths. This propagation continues only to the point on the channel where the channel slope is too steep to preserve the oversteepened reach, or knickpoint, and debris flow scour dominates channel erosion.

Our results suggest three general mechanisms by which bedrock channels erode:

(1) vertical wearing of the channel bed due to stream flow, by such processes as abrasion by transported particles and dissolution; (2) scour by periodic debris flows; and (3) knickpoint propagation. Consequently, application of a single erosion law to the entire bedrock channel network may be inappropriate.

1 Introduction

The use of computer models to examine landscape evolution, as pioneered by AHNERT (1973, 1976), has contributed greatly to lifting geomorphic studies to a more quantitative level and, in so doing, has led to the identification of two great

ISSN 0722-0723

ISBN 3-923381-32-8

©1992 by CATENA VERLAG

W-3302 Cremlingen-Destedt, Germany

3-923381-32-8/92/5011851/US\$ 2.00 + 0.25

deficiencies in field studies. The first is the inadequate description of real landscapes. Model validation should be based on quantitative comparisons between predicted and real landscape morphology, rather than on simple visual comparison and evaluation. Such corroboration, however, requires not only that distinctive attributes of real landscapes be identified and quantified, but also ideally that the initial conditions, time history of boundary conditions, and climatically-driven changes in erosion processes be ascertained. While some characteristics of landscapes, such as drainage density, do vary significantly with erosion process, others, including Horton's laws, do not (e.g. SHREVE 1966). Much work is still needed in identifying properties of real landscapes that can test theoretical predictions.

The other deficiency, and the one this paper addresses, is the paucity of field data available to define sediment transport relationships that are meaningful at geomorphic time scales. In part due to the stimulus generated by early efforts to model landscape development, there is a considerable literature on hillslope sediment transport processes, with perhaps the most advanced work being done on sheetwash-driven erosion (e.g. BRYAN 1987). WILLGOOSE (1989) has given a particularly thoughtful discussion of how to relate conventional event-based sediment transport equations to long-term transport laws.

Here we focus on the problem of the erosion law for channel incision into bedrock landscapes. WILLGOOSE et al.'s (1991) analysis, like that of many other modelers, treats the incision of channels as resulting from the net excess sediment transport ability over the supply from upslope. The sediment transport equation employed is argued to be of the form appropriate for alluvial channels. GILBERT (1877) reasoned that slope and discharge were the primary factors controlling channel incision and eventually this inference was formalized (e.g., by SMITH & BRETHERTON (1972), KIRKBY (1971) and most subsequent workers) to the transport law

$$q_s = KQ^m S^n \quad (1)$$

where q_s is the sediment transport rate, Q is the water discharge, S is the surface slope, and K , m , and n are constants.

Whereas CARSON & KIRKBY (1972) and WILLGOOSE (1989) demonstrate an equation of the form in (1) can be developed from alluvial sediment transport theories, the form of this equation is not known from non-alluvial bedrock channels. One of the few studies that addresses this problem is the innovative work by HOWARD & KERBY (1983). They reasoned that when a channel surface is bedrock, rather than covered by alluvium, the channel's transport ability exceeds supply. They showed that channel incision is limited primarily by the resistance of

the underlying bedrock to the boundary shear stress imposed by stream flows. These assumptions led to an erosion model, as compared to a sediment transport law, of a form essentially the same as (1). Because the dominant channel forming discharge is a function of drainage area, they argued that discharge, Q , could be replaced with contributing drainage area, A , which led to an erosion theory that can be written in the form

$$-\left(\frac{dz}{dt}\right) = K A^m S^n \quad (2)$$

where z is the distance above some arbitrary datum and t is time. HOWARD & KERBY (1983) analyzed the evolution of a small disturbed area in Virginia and used estimated rates of channel incision to assess the value of m and n in (2). Sediment supply is not specifically accounted for in (2) and certainly matters in providing tools, as well as limiting bedrock incision when it blankets the bed (e.g., AHNERT 1987).

Here we suggest an approach to test the Howard & Kerby hypothesis. The tendency first recognized by PLAYFAIR (1802) that tributary channels enter the main stem of a river at the level of the principal valley suggests another way to evaluate (2). If a tributary and its main stem are downcutting at the same rate, as required for each to be at the same level, and if all other factors, (geology, runoff rate, sediment supply per unit area, etc.) are approximately equal, and (2) holds, then

$$\begin{aligned} A_p^m S_p^n &= A_t^m S_t^n \\ \text{or } \left(\frac{A_p}{A_t}\right)^m &= \left(\frac{S_t}{S_p}\right)^n \end{aligned} \quad (3)$$

where p and t are subscripts which refer to the principal and tributary valleys, respectively. Equation (3) simply states the obvious trade-off between drainage area and slope to be expected if equation (2) holds: low gradient, large drainage area principal valleys are fed by steep gradient, small drainage area tributaries. In modelling it is most important to identify the ratio, m/n , (e.g. KIRKBY 1971, WILLGOOSE 1989). Note that (3) can be modified further to

$$\left(\frac{S_t}{S_p}\right) = \left(\frac{A_p}{A_t}\right)^{\frac{m}{n}} \quad (4).$$

Hence the ratio, m/n , can be evaluated by plotting the ratio of channel gradient

against the drainage area ratio for principal and tributary channels in an area of similar geology and climate.

In the following we report the results of a simple test of (4) using topographic maps from the Coast Ranges of Oregon, USA, which appear to support this technique, yielding a ratio of m/n equal to 1.0 for low gradient channels and greater than 1.0 for slopes steeper than 0.2 where debris flows dominate erosion. A more detailed field survey at the junction of a small tributary with the main stem in the Coast Ranges of California, USA, suggests that another process of bedrock incision, propagating knickpoints, may dominate channel lowering. Taken together these observations support the erosion law (2), but indicate that where slopes become steep or where propagating knickpoints occur, this law appears to be inadequate.

2 Coast Ranges of Oregon, USA

We selected several basins in southern coastal Oregon, USA, which contained the specific controls necessary to perform the analysis and calculated the ratio of main stem and tributary drainage areas to tributary and main stem slopes (fig. 1

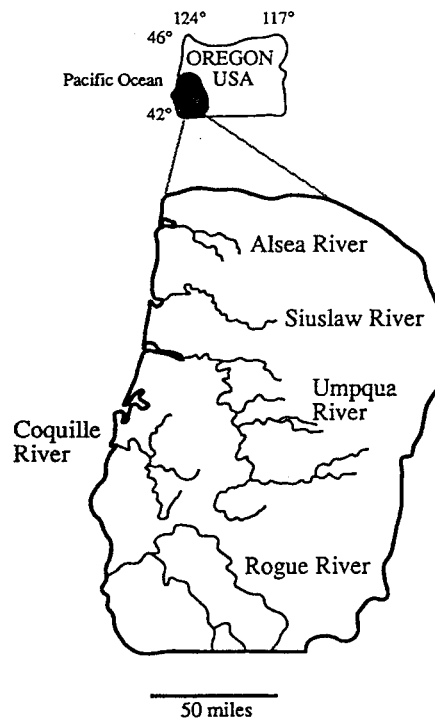


Fig. 1: Location map of the river basins of southern coastal Oregon, USA. The Alsea, Siuslaw, Umpqua, and Coquille basins were analyzed.

and table 1). The Alsea, Coquille, Siuslaw, and Umpqua river basins of southern coastal Oregon were analyzed because rivers in this area flow over uniform Cenozoic marine and estuarine sedimentary rocks (WALKER & KING 1969). (The Rogue river basin was not analyzed because the river flows over nonuniform volcanic rocks.) Channel beds in these basins are generally free of thick alluvial mantles and both main stem and tributary are known to be downcutting through the same lithology. In addition, the landscape is considered to be approximately in dynamic equilibrium, as measured sediment yields have been shown to approximate long term uplift rates (RENEAU 1988, RENEAU & DIETRICH 1991).

The southern coastal Oregon area is relatively wet and steep, receiving about 2500 mm/yr of rain and exhibiting hillslopes commonly greater than 30°. Until recent timber harvesting, the area was covered by a dense coniferous forest. The landscape exhibits no evidence of either glaciation or periglacial processes. The channels are bedrock dominated both because of the mechanically weak nature of the sandstone gravel shed to the channel and because of the relatively steep channel slopes. The average uplift rate of the area appears to be on the order of 0.1 m/ky (e.g. RENEAU 1988), although the details of the uplift history are not precisely known.

River Basin	Principal Channel	Tributary Channel	A_p/A_t	S_t/S_p	$(A_p/A_t)/(S_t/S_p)$	S_t	A_t (mi ²)
Siuslaw	Siuslaw River	Shoemaker Creek	1013.8	933.3	1.1	0.14	0.6
	Lake Creek	Unnamed	19.4	20.0	1.0	0.10	9.0
	Spencer Creek	Unnamed	53.3	6.7	8.0	0.40	0.006
	Cow Creek	Whitehorse Creek	7.8	5.3	1.5	0.02	10.0
	West Cow Creek	Unnamed	164.0	57.0	2.9	0.24	0.5
Umpqua	South Umpqua River	Slate Creek	774.1	60.7	12.7	0.20	0.6
	South Umpqua River	Salt Creek	210.8	80.5	2.6	0.27	2.1
	Elk Creek	Dixon Creek	18.3	21.3	0.9	0.20	3.0
	Cow Creek	Negro Creek	36.3	21.1	1.7	0.08	1.8
	South Umpqua River	Lookingglass Creek	9.6	11.3	0.8	0.005	158.0
	Steamboat Creek	Canton Creek	2.3	1.3	1.7	0.01	70.0
	Gassy Creek	Field Creek	4.7	3.0	1.6	0.03	1.7
	North Umpqua River	Unnamed	4519.0	818.4	5.5	0.40	0.8
	Elk Creek	Walker Creek	2.2	1.6	1.4	0.04	12.9
	Little River	Cavitt Creek	3.3	1.7	1.9	0.01	54.0
	North Umpqua River	Loafer Creek	12.9	7.5	1.7	0.12	15.5
	North Umpqua River	Nancy Creek	340.0	26.4	12.9	0.40	0.5
	Fish Creek	Camas Creek	14.4	9.2	1.6	0.13	4.8
Alsea	Alsea River	Scott Creek	22.3	15.8	1.4	0.04	15.0
	Alsea River	South Fork Alsea River	1.0	1.2	0.9	0.008	61.2
	Five Rivers	Elk Creek	91.2	52.8	1.7	0.20	1.3

Tab. 1: Summary of Oregon Coast Ranges data. A_p , A_t , S_p , and S_t refer to principal valley drainage area, tributary valley drainage area, principal channel slope, and tributary channel slope, respectively.

To avoid potential bias in site selection and to get a broad range of drainage areas, we chose junctions located in close proximity to United States Geological Survey (U.S.G.S.) gauging stations and inland of tidal influences. Channels identified on topographic maps as joining the channel across alluvial fans were not included in the analysis. The principal channel drainage areas used were reported in U.S.G.S. gauging station records (HUBBARD et al. 1989); tributary drainage areas were measured on U.S.G.S. 7.5' topographic maps. Local slopes for both main stems and tributaries for the 24 confluences analyzed were calculated from topographic maps at a scale of 1:24000. The vertical distance on topographic maps at a scale of 1:24000 is accurate to plus or minus 20 feet, while the horizontal distance is accurate to plus or minus 40 feet (U.S. DEPT. OF INTERIOR).

The results of the analysis are presented in table 1 and figs. 2 and 3. The calculated ratios between main stem and tributary drainage areas vary from 1 to 4519, and the slope ratios similarly vary over several orders of magnitude (table 1). The ratio of drainage areas to slopes plotted against tributary slope indicates the ratio generally falls between one and two when tributary slope is low (fig. 2). These data imply that erosion across these tributary confluences is linearly dependent upon stream power. Six junctions, however, have area-slope ratios of three to thirteen. The tributary slopes at these confluences are greater than or equal to 0.2. Field studies in this area of the Oregon Coast Range suggest that periodic scour by debris flows

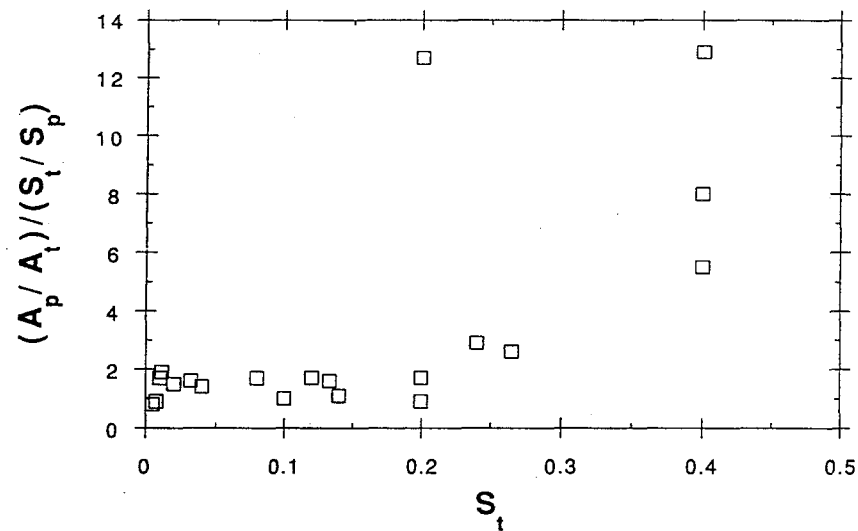


Fig. 2: Plot of the ratio between main stem drainage area (A_p) and tributary drainage area (A_t) divided by the ratio of tributary slope (S_t) to main stem slope (S_p) for 21 coastal Oregon basin confluences against tributary slope (S_t). The drainage area to slope ratio is approximately equal to one at low values of S_p , but when tributary slopes are greater than about 0.2, the ratio deviates from this value.

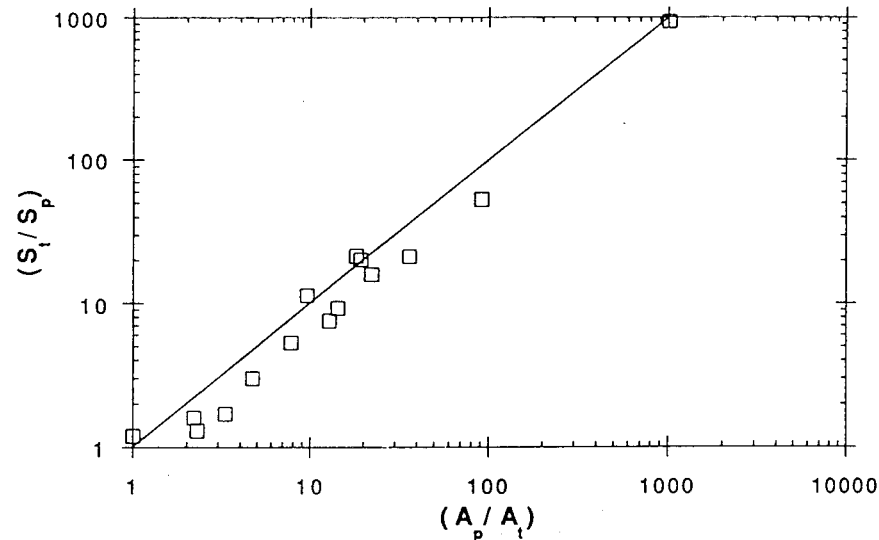


Fig. 3: Plot of the ratio between tributary slope (S_t) and main stem slope (S_p) against the ratio of principal valley drainage area (A_p) to tributary drainage area (A_t) for 16 coastal Oregon basin confluences. The data indicate a m/n value of essentially one and suggest that erosion is related linearly to stream power. The line drawn on the figure corresponds to a m/n value of 1.0. Errors in this analysis primarily arise from topographic map inaccuracy and result in vertical error bars which are approximately the same size as the figure symbols.

is the dominant erosional agent on steep, low order channels (e.g., DIETRICH 1975, PIERSON 1977, DIETRICH & DUNNE 1978, BENDA 1990). Consequently, we interpret fig. 2 as indicating a change in bedrock erosion process with change in gradient. At low gradients channel incision caused by abrasion and dissolution of the bedrock appears to vary linearly with stream power. On steep channels, where debris flow scour dominates, incision may vary more strongly with channel gradient than contributing area.

To evaluate the ratio m/n in (4) we re-plotted the fifteen data points from fig. 2 with area-slope ratios which clustered together. These data are presented in fig. 3 and indicate a m/n value in (4) of essentially 1.0. In effect, the area-slope product on the main stem is equal to that on the tributary. The m/n value of one corresponds to a simple stream power dependency for bedrock channel erosion and is similar to WILLGOOSE's (1989) choice of an m/n value of 0.86 for alluvial channels. Given the broad range of data and the uncertainty associated with using slope estimates from topographic maps, we interpret this result as support for a stream power hypothesis for bedrock channel incision when channel slopes are less than approximately 0.2.

The small number of data points for slopes equal to or greater than 0.2 and their higher variance make a similar m/n analysis less constrained. Nonetheless, a

regression forced to be of the form given by equation (4) for these steeper slopes would require m/n to be about 0.7; the exponent on the slope term is about 1.4 times that for the area term. Presumably in the case of debris flow scour, the area term would be a surrogate for the frequency and size of debris flow events, which would tend to increase with increasing drainage area (RENEAU & DIETRICH 1987). In general, steeper slopes should cause flows to have greater velocity and therefore exert a greater drag force on their beds. Debris flows do propagate downstream on to slopes less than 0.2, but they become progressively less erosive there (e.g., RENEAU & DIETRICH 1987) and in the Oregon Coast Range they typically terminate at the junction of second and higher order channels (BENDA 1990). Therefore, a downslope transition from debris flow scour dominated channel incision to stream flow dominated erosion at channel gradients of 0.2 seems reasonable. Our results, limited as they are by small sample size, suggest that equation (4) may be an appropriate equation to predict bedrock incision if the ratio m/n is allowed to vary with dominant erosion process as dictated by channel gradient.

3 Coast Ranges of California, USA

Although our Oregon results support a simple stream power dependency for incision across many tributary junctions, field inspection of Hawaiian bedrock channels suggests that another lowering process, which may be initiated either at tributary junctions or on the main stem, is also important and cannot be explained by this theory (SEIDL et al., in prep.). Many longitudinal profiles of Hawaiian channels exhibit distinct, locally steep reaches, composed of either single waterfalls or a series of bedrock steps. Such reaches, traditionally referred to as knickpoints (PENCK 1953), often are attributed to differential bedrock resistance (GILBERT 1877, WOLMAN 1955, MILLER 1991). However, inspection of these reaches reveals that the knickpoints apparently are not formed in more resistant rock types and led us to hypothesize that the upstream propagation of these knickpoints may be an important bedrock lowering process. The notion of migrating knickpoints in homogeneous bedrock is clearly not a new idea (e.g. PENCK 1953, LEOPOLD et al. 1964, PICKUP 1977, GARDNER 1983, MILLER 1991), but the relative importance of this process in causing channel incision is not well known. Here we report an empirical connection between bedrock incision, terraces, and knickpoints. We will examine a bedrock dominated channel, by which we mean a channel with a discernible bedrock bed and bedrock banks exposed along considerable parts of its length. Bedrock reaches may be thinly mantled by alluvium over much of their

extent but these mantled areas must be connected to reaches where the channel flows over bedrock and is contained by bedrock banks. This nomenclature is consistent with the relevant literature, as MILLER (1991) describes a particular bedrock stream with bedrock reaches several hundred meters in length interspersed with areas of alluvial banks and alluvial channel beds. WOHL (1992) similarly denotes channels as bedrock which have extensive areas of alluvium alternating with lengthy reaches of outcropping bedrock. This typical description of "bedrock channels" points to an unsolved problem: does the supply rate and size of the sparse, coarse alluvium found in these channels strongly influence rates of bedrock incision? We will not address this problem here, but will consider it in a subsequent paper (SEIDL et. al., in prep.).

We studied the longitudinal profile and terraces of a bedrock tributary, Elder Creek, to the South Fork of the Eel River in Mendocino County, Northern California (fig. 4). We chose this particular tributary because both main stem and tributary are bedrock dominated channels, have pronounced bedrock terraces, and are accessible. In addition, the morphology of Elder Creek is repeated on other tributaries to the Eel. The main tributaries to the Eel River currently spill across low bedrock steps thinly mantled with gravel as they join the river. A two meter high step occurs at the confluence of Elder Creek and the principal channel. In addition, most tributaries have steepened upper reaches along which straths are not preserved.

The Eel River runs nearly parallel to the Pacific coast for most of its length. The junction of Elder Creek with the South Fork of the Eel is located approximately 120 miles downstream of the mouth of the Eel (fig. 4). If inferred uplift rates from marine terraces (proposed by MERRITTS & VINCENT 1989) apply to the Eel River valley, the downstream reach of the river may be uplifting as much as ten times faster than the headwaters area on the South Fork of the Eel, where the study site is located. Uplift rates at the northernmost portion of the California coast are on the order of 4 m/ky whereas at the coast opposite our study site the rates are between 1.0 m/ky and 0.3 m/ky (MERRITTS & VINCENT 1989). It is unclear, however, if the uplift documented along the coast extends this far to the east.

The Eel River and Elder Creek flow over greywackes and shales of the Franciscan Complex of Mesozoic and Early Cenozoic age (JENNINGS 1977). The Elder Creek basin has a drainage area of 17 km², a maximum elevation of 1389 m, and a maximum relief of approximately 600 m (fig. 5). U.S.G.S. gauging station records indicate an average discharge for the last 21 years of 0.7 m³/sec, with an extreme discharge of 103.6 m³/sec estimated from floodmarks in a 1964 flow. Average bankfull discharge has been calculated at 14.7 m³/sec (TRUSH 1991). The longitudinal profile of the Elder channel is approximately eight kilometers in length. The lower four kilometers of channel are characterized by shorter patches of bare

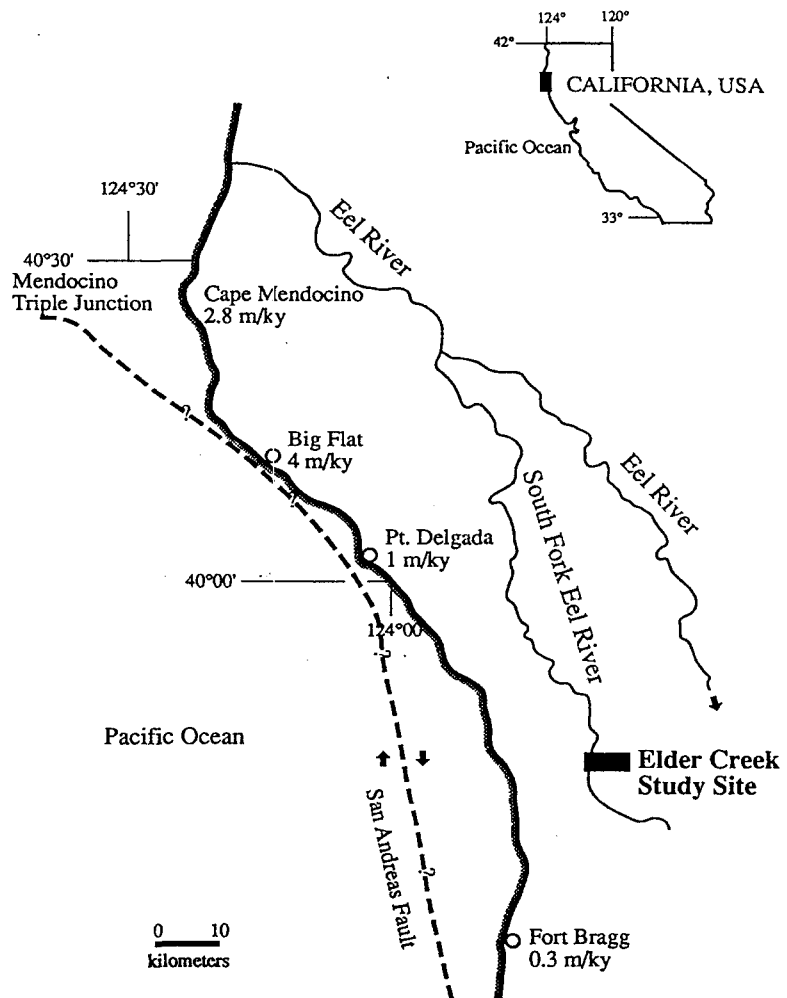


Fig. 4: Map illustrating the tectonics of the region around the Eel River, Northern California, USA (modified from JENNINGS 1977 and MERRITTS & VINCENT 1989). Numbers in m/ky refer to approximate coastal uplift rates discussed in MERRITTS & VINCENT (1989). The Elder Creek study site is shown on the figure. Elder Creek is a small bedrock tributary to the South Fork of the Eel River.

bedrock alternating with longer reaches of coarse gravel-, cobble-, and boulder-sized alluvium and by the presence of distinct bedrock terraces adjacent to the stream. The stream flows over bare bedrock for approximately 30% of its extent and is thinly veneered by coarse sediment for the corresponding 70% of its extent. The average surveyed gradient of the lower 4.2 kilometers of channel is 0.03. Upstream of this point the gradient steepens considerably, with an average slope, measured from topographic maps, along the upper four kilometers of 0.17 (fig. 6).

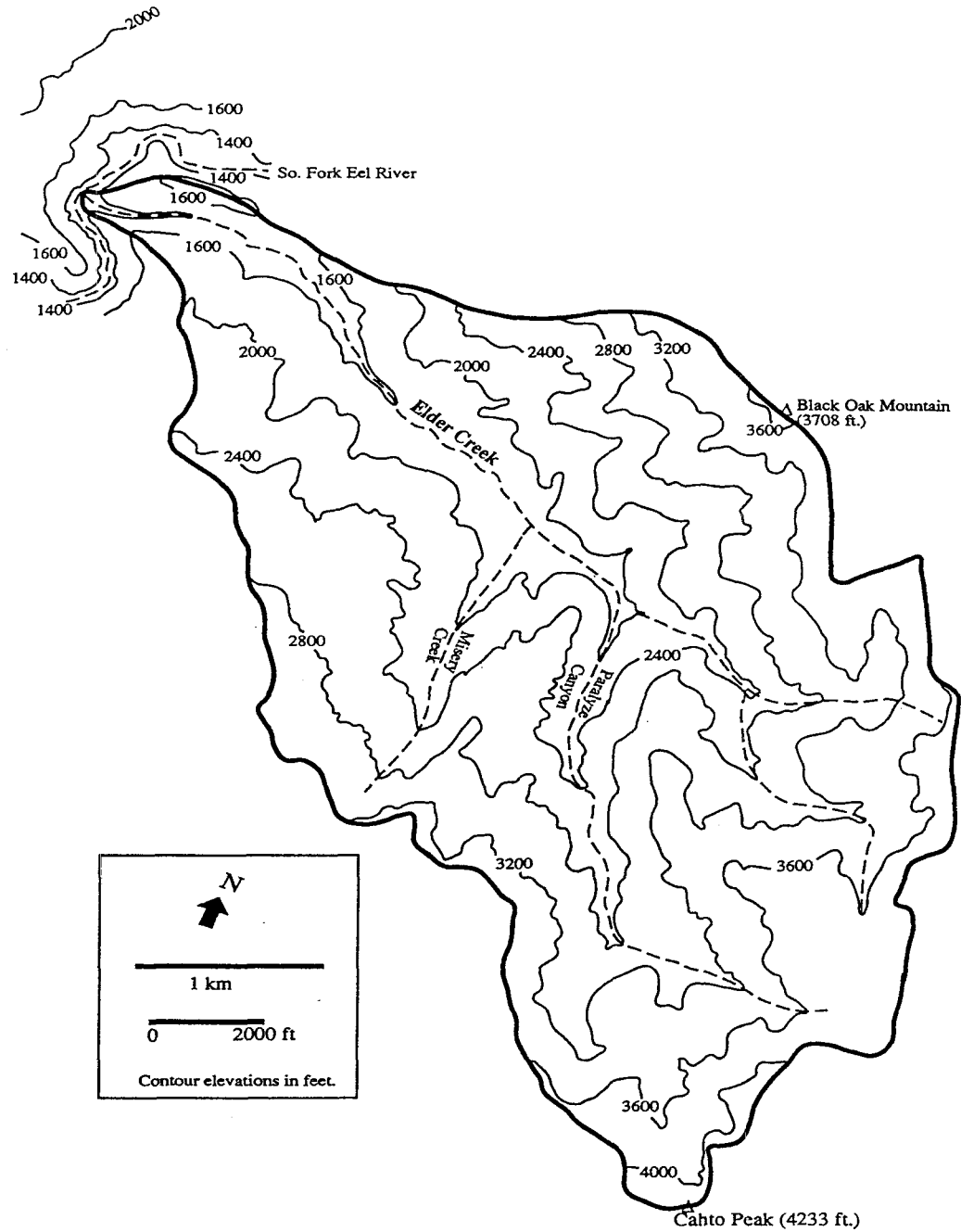


Fig. 5: Map of the Elder Creek catchment. The ground survey began at the confluence of Elder Creek with the South Fork of the Eel River and terminated just upstream of Misery Creek.

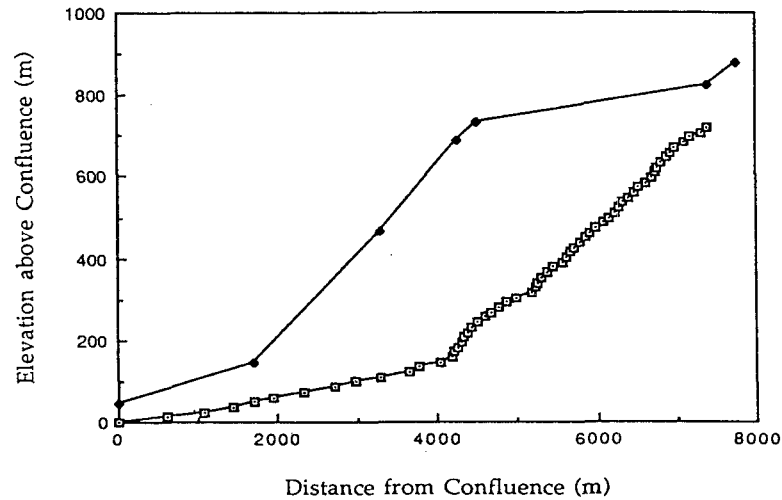


Fig. 6: Longitudinal profile of Elder Creek digitized from U.S.G.S. 7.5' topographic maps. The ridge above the channel is approximated by the curved line above the channel. The distance from the channel to the left bank ridge and the distance from the channel to the right bank ridge were measured and averaged from 7.5' topographic maps. The channel bed slope increases dramatically at a distance of approximately 4 kilometers; bedrock terraces do not occur upstream of this point.

The character of the channel also changes markedly in these upper reaches. Although one might expect the number and extent of bare bedrock patches to increase along the channel as the channel gradient increases, to the contrary, the bed material coarsens considerably and bare bedrock reaches are not visible in the upper four kilometers of channel. Large boulders several meters in diameter become increasingly common upstream, as well as smaller boulders and cobbles. This change in grain size correlates with a change in mode of delivery of material to the channel and in stepped-bed channel morphology: in high gradient streams, the occurrence of cascades and pools appears to coincide with areas of large-sized material delivered to the channel by landslides and debris flows, whereas riffle and rapid units appear to be found in areas characterized by finer sediment (GRANT et al. 1990). Bedrock terraces are no longer present in the upstream reaches of Elder Creek and hillslopes steepen as the canyon narrows.

The bedrock terraces of Elder Creek are discontinuous and the lower terrace levels terminate along steeper reaches of the channel. In order to document this pattern a detailed ground survey was required. Channel bed elevations on Elder Creek were surveyed every 5 to 10 meters using a hand level and stadia rod. The longitudinal profile of the stream was surveyed for a total of 4.2 kilometers, until the channel slope increased and bedrock terraces were no longer preserved (fig. 6). Cross-sections were made perpendicular to the channel every 50 to 100 meters and

averaged 80 meters in length (figs. 7 and 8). In all, 46 locations were surveyed. Cross-section locations were documented in meters upstream of the confluence of Elder with the South Fork of the Eel River and an arbitrary elevation of 0 meters was assigned to the junction. Many of these bedrock terraces are covered by thin alluvial deposits averaging one to two meters in thickness (fig. 9); in places, however, the alluvium is locally as thick as four to five meters. Debris flow deposits and alluvial terraces also occur along the channel. The occurrence of these alluvial deposits and debris flow deposits increases in the upstream direction as the number of large tributaries entering the Creek increases and many of these deposits are located at these tributary junctions. Differentiation between bedrock terraces, alluvial deposits, and debris flow deposits was greatly simplified by the excellent terrace exposures along the stream. All terraces were field-checked after the surveying had been completed to ascertain the bedrock, alluvial, or debris flow nature of the features. Bedrock terraces occurring along the South Fork of the Eel River also were surveyed using a hand level and stadia rod.

Three flights of bedrock terraces, or straths, are preserved along Elder Creek: terrace levels T1, T2, and T3 (fig. 10). These terraces are continuous and lie roughly parallel to the channel. Two noticeably oversteepened reaches, or knickpoints, also punctuate the slope of the channel bed, one at a distance of 2.3 kilometers and one at 3.0 kilometers upslope of the confluence. The knickpoint occurring at 2.3 kilometers is formed in shale, is approximately 7 meters in height, and displays a large plunge pool at its base. The knickpoint occurring at a distance of 3 kilometers is a series of smaller bedrock steps formed in greywacke. Neither knickpoint occurs at a site where the local bedrock can be interpreted as obviously more resistant to erosion.

As illustrated in figs. 10 and 11, the upper surfaces of the two knickpoints connect to the downstream bedrock terraces. In fact, the upstream limits of terrace levels 1 and 2 terminate in channel knickpoints. Terrace level 3 ends at the point in the channel where the bed slope increases markedly. As there is a long reach after 3 kilometers distance lacking terraces, the extension of terrace level 3 to 4 kilometers distance must be considered speculative.

We propose that fig. 10 and related field observations could be interpreted to indicate that the strath terraces mapped on Elder Creek formed by progressive migration of knickpoints that originated at the mouth of the Creek. LEOPOLD et al. (1964) predicted that knickpoints would migrate if the ratio between height of the knickpoint face and flow depth is greater than one and if stream flow is competent to transport material downstream of the base of the waterfall. On Elder Creek both these conditions are satisfied. In our interpretation terrace surfaces are time transgressive, with T1 and T2 still being formed, although T3 has terminated

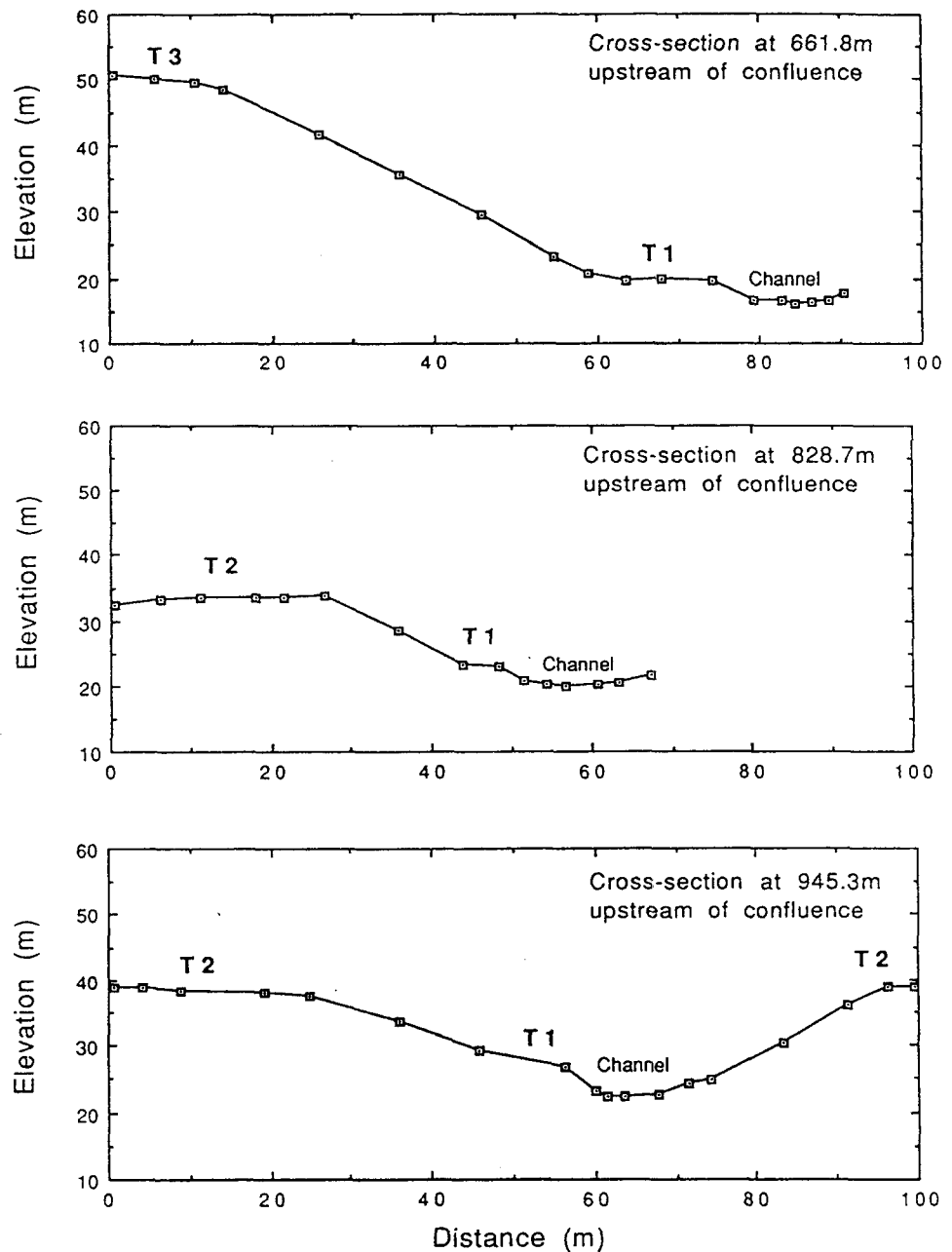


Fig. 7: Cross-sections surveyed along Elder Creek documenting bedrock terraces T1, T2, and T3. On all cross-sections 0 meters distance corresponds to the left bank. The cross-sections are arranged with the farthest downstream terrace at the top of the figure; the distances in meters written in the right corner of each cross-section corresponds to its distance upstream of the Elder-South Fork of the Eel confluence. Note that the three cross-sections are shown at the same scale and have been vertically exaggerated.

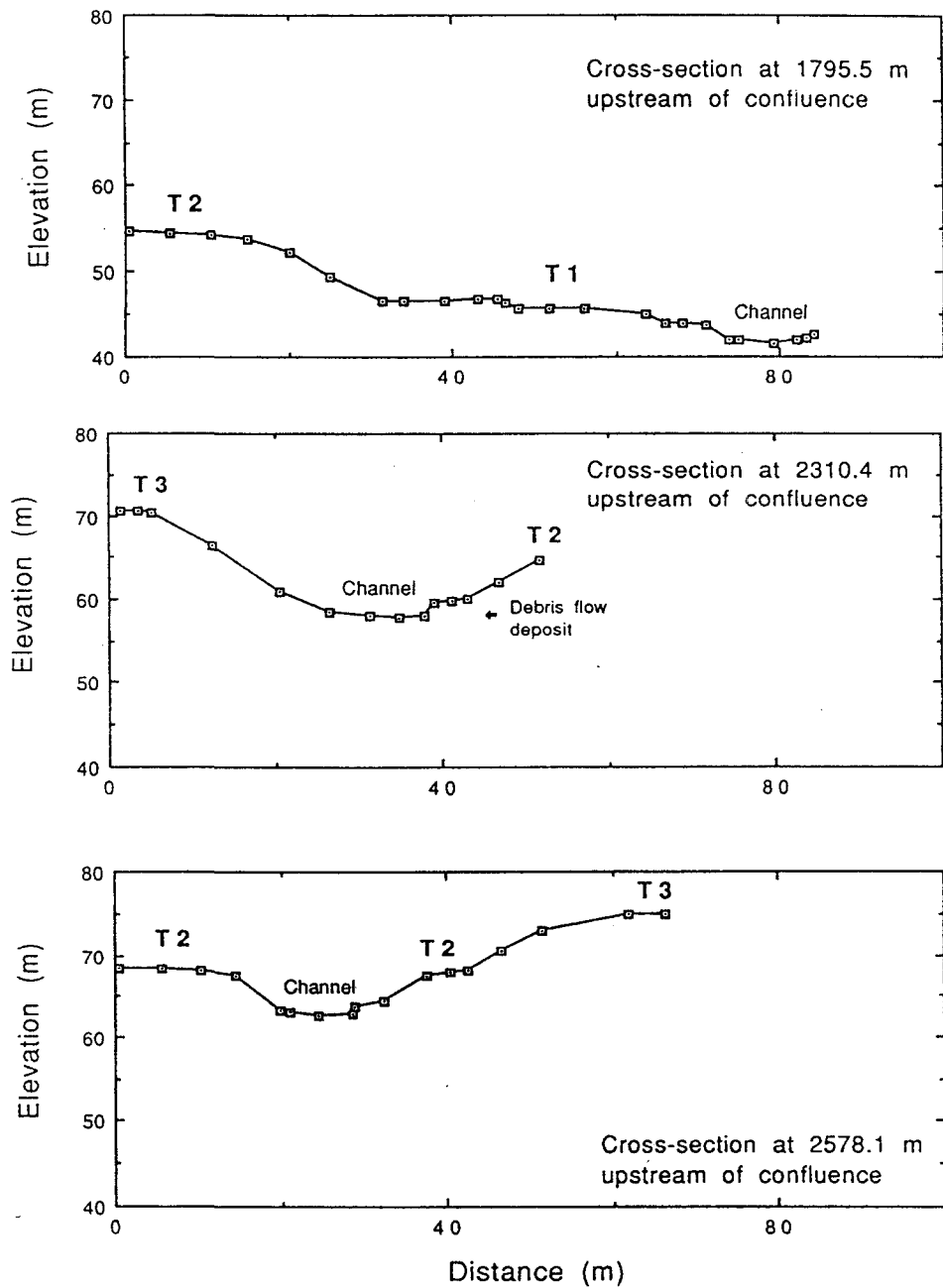


Fig. 8: Cross-sections surveyed along Elder Creek documenting bedrock terraces T1, T2, and T3. On all cross-sections 0 meters distance corresponds to the left bank. The cross-sections are arranged with the farthest downstream terrace at the top of the figure; the distances in meters written in the right corner of each cross-section corresponds to its distance upstream of the Elder-South Fork of the Eel confluence. Note that the three cross-sections are shown at the same scale and have been vertically exaggerated.

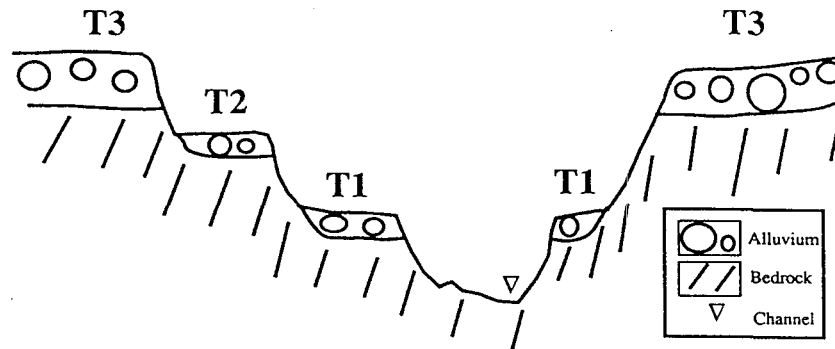


Fig. 9: Schematic drawing of Elder Creek terraces showing the channel and three flights of bedrock terraces, T1, T2, and T3, capped by exaggeratedly thick alluvial deposits.

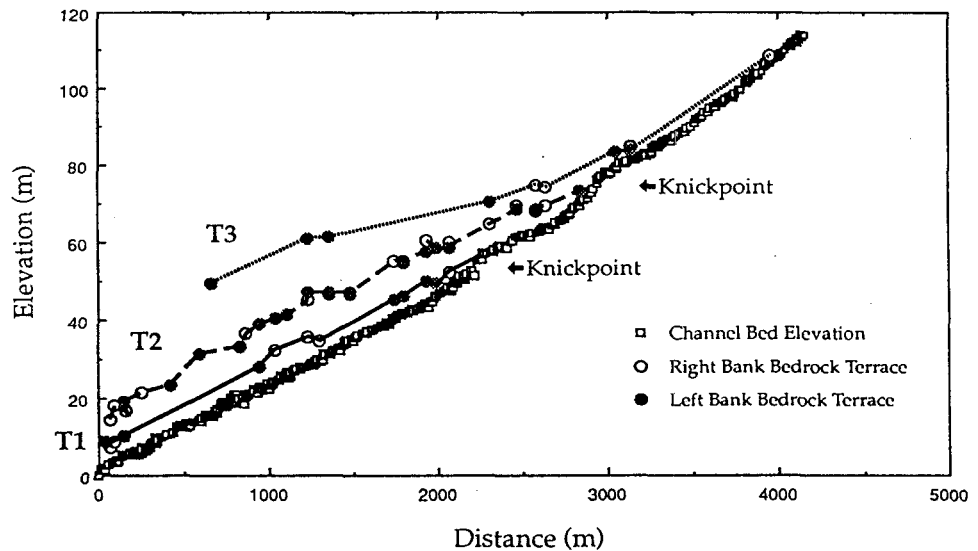


Fig. 10: Elder Creek surveyed longitudinal profile and bedrock terrace elevations. 0 meters distance corresponds to the confluence of Elder and the South Fork of the Eel River. Terrace levels T1 and T2 end abruptly at channel knickpoint locations. Terrace level T3 terminates where the channel bed slope increases markedly. The lines connecting terrace locations are not perfectly straight because of the thin alluvial caps of 1-3 meters thickness on the straths.

against the abrupt slope increase from 0.03 to 0.30 (figs. 10 and 12). This suggests that steps will propagate only when the gradient of the channel bed is low relative to the knickpoint gradient. The upper reaches of the Elder drainage basin are characterized by very steep, extremely bouldery stretches. Most of the debris flow deposits occur just downslope of these upper reaches, and both the large sediment relative to the channel size and the steep channel slope indicate that debris flow

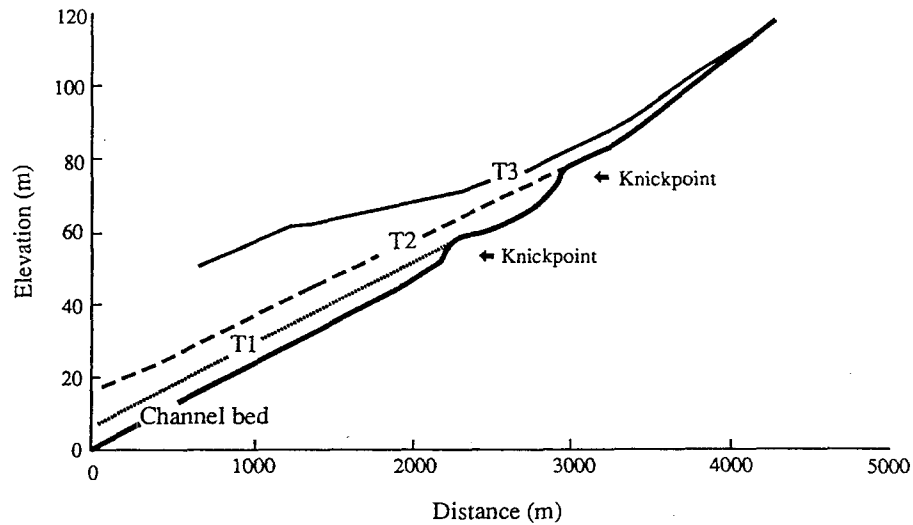


Fig. 11: Figure illustrating general trends shown in fig. 10.

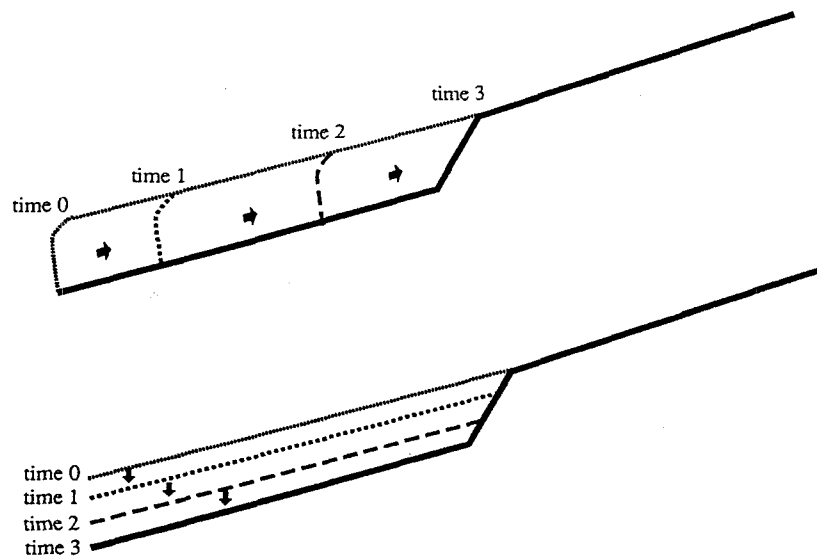


Fig. 12: Schematic drawing showing the evolution of the longitudinal profile assuming two incision scenarios.

Top: knickpoint propagation is the principal incision process; the progression of a knickpoint along a channel profile results in the formation of a terrace parallel to the stream.

Bottom: vertical incision caused by processes other than knickpoint propagation, including abrasion; the knickpoint forms as a result of differential rates of vertical erosion. Details of the relationships shown are not intended to match the specific terrace levels observed in Elder Creek.

processes dominate the erosion here.

Knickpoint propagation is not the only process capable of producing the sequence of strath terraces documented on Elder Creek. Differential lowering upstream and downstream of the knickpoint due to a change in bedrock resistance or faulting across the knickpoint could result in the observed pattern of knickpoints connected to downstream bedrock terraces (fig. 12). However, this more traditional interpretation necessitates an abrupt change in lithology or structure across a knickpoint. We could not identify either control on Elder Creek knickpoint formation. Neither channel knickpoints nor the bedrock step which occurs at the confluence of Elder Creek with the South Fork of the Eel appear to be perched on more resistant rock or along fault traces. The common occurrence of this bedrock step at other tributary junctions in this area suggests knickpoints are currently being formed on these channels. Bedrock terraces preserved along Elder Creek may be correlated with straths occurring on the South Fork of the Eel River (fig. 13). This correlation suggests that periodic incision along the South Fork, perhaps also due to knickpoint migration, causes bedrock steps to form along its tributary junctions, much as occurs today along Elder and other tributaries. These steps could then propagate upstream as knickpoints of approximately constant height until damped out by steep tributary slopes. It is difficult to judge at what point these steps will begin to propagate upstream, as we do not understand what, if any, critical height must be attained by the step, nor how that height is maintained as the knickpoint propagates upstream.

This reasoning stands in contrast to the work of MILLER (1991) and GARDNER (1983). MILLER (1991) concluded that knickpoints are formed when channel orientation changes relative to strata dip. He analyzed many small knickpoints, each the thickness of several beds on the order of 50 to 200 cm in height. His study documented the importance of geologic controls on knickpoint formation. Because knickpoints are linked with dipping strata, headward knickpoint propagation is restricted by channel gradient and geologic structures. MILLER (1991) found that tributaries to the Ohio River have variable numbers of knickpoints along their profiles, although they are tied to the same base level; he consequently did not see a connection between a base level change and formation and migration of a single knickpoint. Nonetheless, even when knickpoints form due to variable resistance in the underlying bedrock, they still are known to propagate through the resistance and once the resistance is passed, should lead to a more rapid incision pulse travelling some distance upslope.

GARDNER's (1983) experiments, conducted in homogeneous material, indicated that knickpoint propagation does not occur. Instead, vertical knickpoint faces were shown to be rapidly removed and replaced by a uniform gradient across the

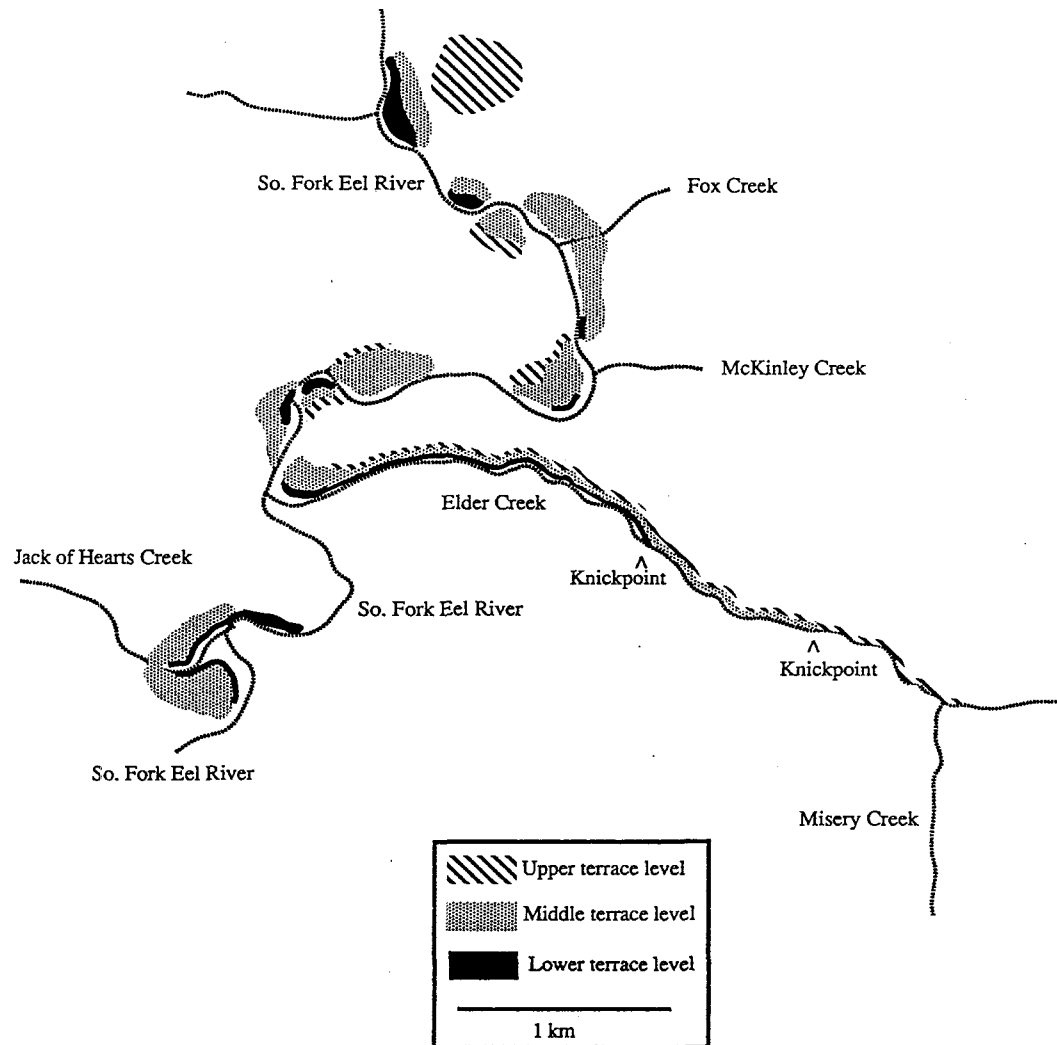


Fig. 13: Map of bedrock terraces present along the South Fork of the Eel River and several of its tributaries. The terrace locations were determined from topographic maps, field reconnaissance, and surveyed cross-sections. The upper, middle, and lower terraces detailed along Elder Creek correspond to T3, T2, and T1 of figures 10 and 11. Note that the Elder terraces are drawn as continuous to delineate their general trends, as interpreted from fig. 11.

longitudinal profile. In contrast, SCHUMM et al. (1987) have argued from field studies that knickpoints formed by base level drop may propagate a great distance up drainage networks. Clearly more work must be done to understand the mechanics of knickpoint propagation and to document its occurrence in bedrock channels in other locales.

4 Discussion and conclusions

Our results suggest that equation 2 with m/n equal to 1.0 can be used to predict erosion in non-alluvial channels less steep than about 0.2, at least in coastal Oregon. The linear dependency on stream power that the lower gradient reaches exhibit is consistent with the general assumption that rivers downcut through bedrock by a suite of processes which can be expected to vary with stream flow induced boundary shear stress, or stream power (BULL 1979, VANDERPOOL 1982, HOWARD & KERBY 1983, SEIDL et al. 1989). On steeper tributary slopes, however, the analysis suggests that erosion is by debris flow scour, which, if it can be modelled using equation (2), requires a m/n ratio less than 1.0, perhaps closer to 0.7, indicating a larger slope dependency.

The linkage between main stem downcutting and tributary incision via propagating knickpoints illustrates how topographic adjustments that originate on the main stem might spread to the rest of the basin. Such knickpoints may originate on a main stem as a result of sea-level change, shoreline migration, tectonic uplift or differential incision against more resistant bedrock. Even if the main stem is downcutting progressively without knickpoint propagation, bedrock steps may tend to form at tributary junctions and propagate upstream along the tributary. Tectonic and eustatic variations which affect the base level of the main stem and originate at the lowest part of the channel network and spreads upslope may inherently generate periodic downcutting along its tributaries. This hypothesis for bedrock channel incision is similar to one originally proposed for alluvial channels (SCHUMM & HADLEY 1957). The upslope spread of this base level change may not terminate at the drainage heads, but rather on the steep portions of tributaries. This implies that landscapes above this steep point would gain in height relative to the lower valley, but could in some circumstances remain unmodified. This limit, if common, could be important in understanding the relationships between tectonics, climate, and landscape uplift and erosion. Knickpoint initiation also may result from an inherent tendency in some rivers for the main stem to incise relative to its tributaries, sending pulses of incision up tributaries as knickpoints.

The observation that tributary erosion may occur by knickpoint propagation points to a need for mechanistic models. A simple stream power erosion law will not propagate a knickpoint that maintains the same height as it migrates upstream. Numerical results indicate that knickpoints grow larger with time and, consequently, knickpoint propagation does not generate a downstream channel slope parallel to the channel gradient upstream of the knickpoint, as observed on Elder Creek (SEIDL et al., in prep.). In addition, neither abrasion nor other flow-induced erosion associated with stream power nor incision by knickpoint propagation will explain

erosion on channel slopes steeper than about 0.2; instead debris flow scour appears to be the major agent of erosion. A single erosion theory, therefore, may not apply to the entire bedrock channel network. It appears that models of landscape evolution which assume a single transport law throughout a drainage basin need to be modified to predict the incision caused by knickpoint propagation and debris flow scour.

Our results also point to the possibility of correlating tectonics and climate change with differences in erosional and depositional episodes. The stream power approach can be interpreted to suggest how rates of channel incision might vary with climatic change. The exponent m and the coefficient K in (2) are particularly sensitive to climatic variations. Changes in the magnitude and pattern of precipitation could affect the discharge-drainage area relationship or the drainage area-basin length relationship, which would have direct consequences on the value of m . Similarly, the several factors inherent in K , including sediment load and bedrock resistance, might be affected significantly by changes in climate. Warmer temperatures could enhance chemical weathering of a channel bed and facilitate abrasion by transported particles, as long as coarse, resistant particles are eroded into the channel from the hillslopes. If increased storminess could be shown to imply increased runoff, this erosion model would support the link between climate change and accelerated erosion proposed by MOLNAR & ENGLAND (1990).

Our hypothesis that there are three different general mechanisms responsible for incision of channels into bedrock, each requiring a different "erosion law," is motivated by simple field data. More data need to be collected and modelling studies need to be done to test the proposed erosion laws. Local rates of erosion can now be estimated using recently developed surface exposure dating techniques based on cosmogenic isotopes (see for references and discussion LAL 1991, LAL 1988, LAL & PETERS 1967). This new technique should be particularly useful in testing for knickpoint propagation. Finally, from the point of view of both modelling and field observations, more work is needed on the problem of assessing when sediment supply and grain size of bed material become controlling factors in rates of bedrock channel incision.

Acknowledgement

We thank N. Shubin, J. Seidl, and S. Anderson for enthusiastic field support, and N. Shubin and J. Kirchner for discussions and reviews of the manuscript. This research was partially funded by the National Science Foundation, the Lawrence Livermore National Laboratory Institute for Geophysics and Planetary Physics, the

Geological Society of America, and the University of California Natural Reserve System.

References

- AHNERT, F. (1973):** COSLOP2-a comprehensive model program for simulating slope profile development. Geocom Programs 8, London, 24p.
- AHNERT, F. (1976):** Brief description of a comprehensive three-dimensional process-response model of landform development. Zeitschrift für Geomorphologie N.F. Supplement Band 25, 29-49.
- AHNERT, F. (1987):** Process-response models of denudation at different spatial scales. Catena Supplement 10, 31-50.
- BENDA, L. (1990):** The influence of debris flows on channels and valley floors in the Oregon Coast Range, U.S.A. Earth Surface Processes and Landforms 15, 457-466.
- BRYAN, R.B. (1987):** Processes and significance of rill development. In: BRYAN, R.B. (Ed.) Rill Erosion Processes and Significance, Catena Supplement 8, 1-15.
- BULL, W.B. (1979):** Threshold of critical power in streams. Geological Society of America Bulletin 90, 453-464.
- CARSON, M.A. & KIRKBY, M.J. (1972):** Hillslope Form and Process. Cambridge University Press, Cambridge.
- DIETRICH, W.E. (1975):** Sediment production in a mountainous basaltic terrain in central coastal Oregon. Unpublished M.S. thesis, University of Washington, Seattle, Washington.
- DIETRICH, W.E. & DUNNE, T. (1978):** Sediment budget for a small catchment in mountainous terrain. Zeitschrift für Geomorphologie N.F. Supplement Band 29, 191-206.
- GARDNER, T.W. (1983):** Experimental study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material. Geological Society of America Bulletin, 94, p. 664-672.
- GILBERT, G.K. (1877):** Report on the Geology of the Henry Mountains. U.S. Government Printing Office, Washington D.C.
- GRANT, G.E., SWANSON, F.J. & WOLMAN, M.G. (1990):** Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geological Society of America Bulletin 102, 340-352.
- HOWARD, A.D. & KERBY, G. (1983):** Channel changes in badlands. Geological Society of America Bulletin 94, 739-752.
- HUBBARD, L.E., HERRETT, T.A., KRAUS, R.L. & MOFFATT, R.L. (1989):** U.S. Geological Survey Water-Data Report OR-89-2.

- JENNINGS, C.W. (1977):** Geologic Map of California. California Division of Mines and Geology.
- KIRKBY, M.J. (1971):** Hillslope process-response models based on the continuity equation. In: BRUNSDEN, D. (Ed.), Slopes: Form and Process, Institute of British Geographers, Sp. Publ. 3, 15-30.
- LAL, D. (1988):** In situ produced cosmogenic isotopes in terrestrial rocks. Annual Reviews in Earth and Planetary Science Letters, 16, 355-388.
- LAL, D. (1991):** Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. Earth and Planetary Science Letters, 104, 424-439.
- LAL, D. & PETERS, B. (1967):** Cosmic-ray-produced radioactivity on the earth. In: FLUGGE, S. (Ed.), Handbuch der Physik XLVI/2, Springer-Verlag, Berlin, 551-612.
- LEOPOLD, L.B., WOLMAN, M.G. & MILLER, J.P. (1964):** Fluvial Processes in Geomorphology. Freeman, San Francisco.
- MERRITTS, D. & VINCENT, K.R. (1989):** Geomorphic response of coastal streams to low, intermediate, and high rates of uplift, Mendocino triple junction region, northern California. Geological Society of America Bulletin 101, 1373-1388.
- MILLER, J.R. (1991):** The influence of bedrock geology on knickpoint development and channel-bed degradation along downcutting streams in south-central Indiana. Journal of Geology 99, 591-605.
- MOLNAR, P. & ENGLAND, P. (1990):** Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg? Nature 346, 29-34.
- PENCK, W. (1953):** (trans. by CZECH, H. & BOSWELL, K.C.) Morphological Analysis of Land Forms. MacMilland, Great Britain.
- PICKUP, G., (1977):** Simulation modeling of river channel erosion. In GREGORY, K.J. (Ed.), River Channel Changes, John Wiley & Sons, New York, 47-60.
- PIERSON, T. (1977):** Factors controlling debris-flow initiation on forested hillslopes in the Oregon Coast Range. Unpublished Ph.D. thesis, University of Washington.
- PLAYFAIR, J. (1802):** Illustrations of the Huttonian Theory of the Earth. Dover, London.
- RENEAU, S.L. (1988):** Depositional and erosional history of hollows: Application to landslide location and frequency, long-term erosion rates, and the effects of climatic change. Unpublished Ph.D. thesis, University of California at Berkeley.
- RENEAU, S.L. & DIETRICH, W.E. (1987):** The importance of hollows in debris flow studies; Examples from Marin County, California. Geological Society of America Reviews in Engineering Geology, 7, 165-180.
- RENEAU, S.L. & DIETRICH, W.E. (1991):** Erosion rates in the Southern Oregon Coast Range: Evidence for an equilibrium between hillslope erosion and sediment yield. Earth Surface Processes

and Landforms 16, 307-322.

SCHUMM, S.A. & HADLEY, R.F. (1957): Arroyos and the semiarid cycle of erosion. *American Journal of Science* 255, 161-174.

SCHUMM, S.A., MOSLEY, M.P. & WEAVER, W.E. (1987): *Experimental Fluvial Geomorphology*. John Wiley & Sons, New York, 413p.

SEIDL, M.A., DIETRICH, W.E. & KIRCHNER, J.W.: Longitudinal profile development: An analysis of Hawaiian channels (in prep.).

SEIDL, M.A., LOEWENHERZ, D.S. & DIETRICH, W.E. (1989): Form and process in fluvial erosion of bedrock. *Eos* 70, 1125.

SHREVE, R.L. (1966): Statistical law of stream numbers. *Journal of Geology*, 74, 17-37.

SMITH, T.R. & BRETHERTON, F.P (1972): Stability and the conservation of mass in drainage basin evolution. *Water Resources Research*, 8, 1506-1529.

TRUSH, W.J. (1991): The influence of channel morphology and hydrology on spawning populations of steelhead trout in South Fork Eel River tributaries. Unpublished Ph.D. thesis, University of California at Berkeley.

U.S. DEPT. OF THE INTERIOR: U.S. Geological Survey ESIC National Mapping Program.

VANDERPOOL, N.L. (1982): ERODE-A computer model of drainage basin development under changing baselevel conditions. In: CRAIG, R.G. & CRAFT, J.L.(Eds.), *Applied Geomorphology*, Allen & Unwin, London, 214-224.

WALKER, G.W. & KING, P.B. (1969): U.S. Geological Survey Geologic Map I-595.

WILLGOOSE, G. R. (1989): A physically based channel network and catchment evolution model. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts.

WILLGOOSE, G., BRAS, R.L. & RODRIGUEZ-ITURBE, I. (1991): Results from a new model of river basin evolution. *Earth Surface Processes and Landforms* 16, 237-254.

WOHL, E.E. (1992): Gradient irregularity in the Herbert Gorge of Northeastern Australia. *Earth Surface Processes and Landforms* 17, 69-84.

WOLMAN, M.G. (1955): The natural channel of Brandywine Creek, PA. U.S. Geological Survey Professional Paper 271, 1-56.

Address of authors:

Michele A. Seidl

W.E. Dietrich

Department of Geology and Geophysics

University of California at Berkeley

Berkeley, CA 94720

U.S.A.