Chapter 6
Geologic controls and channel profiles, eastern Santa Cruz Island, California

AARON KING[A]* AND BRIDGET TRACY[B]
[A]CIVIL & ENVIROMENTAL ENGINEERING
[B]HDROLOGICAL SCIENCES GRADUATE GROUP
UNIVERSITY OF CALIFORNIA, DAVIS, CA 95616
*AMKING@UCDAVIS.EDU

Abstract
Longitudinal profiles of stream channels give clues to patterns of landscape development. We explored the application of equilibrium theory of longitudinal profile development in the context of the young landscape of eastern Santa Cruz Island. We created a geologic and topographic dataset of the eastern portion of the island to analyze the influence of lithology and accumulated watershed area on longitudinal profiles. We examined these factors to explain the long profiles that were observed using theory. A test of the significance of the difference in slopes between the two dominant bedrock types across all channels resulted in a p-value of 0.038. This level of significance did not hold when the channels were parsed by Strahler order. No strong correlation was found between watershed area and slope. Most of the streams on eastern Santa Cruz Island are unable to adjust quickly enough to establish or maintain equilibrium with uplift and base level fluctuations.

Introduction
Tectonic uplift and changing sea levels combine to produce terraces, ridges and cliffs on Santa Cruz Island (SCI) (see Chapter 4). These features are dissected by ephemeral stream channels that only flow during large winter storm flood flows. The island is made up of two major rock types, the Santa Cruz Island Volcanics (SCIv), an erosionally-resistant basalt, and the Monterey Formation shale (MF), a more erodible rock type prone to slope failure. We used a Digital Elevation Model (DEM) and a spatially referenced version of the Weaver et al (1964) geologic map of SCI to examine the longitudinal (long) profiles of eastern SCI in the context of modern geomorphic theory of long profile evolution. Based on field reconnaissance, we expected the difference in erodibility between these two rock types to be an important control on stream channel geomorphology and the long profile of channels. We found that although this effect was evident in some streams, and statistical significance was established, the effect of lithology was not a dominant factor in most channel profiles. Rather, long profile shape on these streams

reflects constant adjustment due to rapid changes in uplift and base level, never establishing an equilibrium condition.

Background

The most generally recognized theory of stream profile evolution states that for any given channel, there exists a theoretical equilibrium long profile such that work expenditure by the stream is minimized (stream efficiency is maximized) for the rate of uplift, erodibility, flow and sediment supply (Knighton, 1998; Leopold, 1994; Mount, 1995). This equilibrium profile is generally characterized as a concave-upward power function of horizontal distance from base level. A stream reach has attained its equilibrium profile when stream power is equal to the work required to maintain the channel slope at that reach.

Uplift and base level changes

Base level for SCI stream networks is sea level, which varies relative to the bedrock channel system due to climatic and tectonic forcing. Uplift of SCI is occurring at approximately 0.7 – 1.5 mm/year (see Chapter 4). Snyder *et al.* (2002) modeled long profile responses of bedrock channels flowing to the sea to uplift rates of 0.5 and 4.0 mm/year. Their study found that offshore uplift rate and bathymetry were the most important factors determining the response of stream profiles to base level decline (Figure 6.1). In cases where offshore uplift matches onshore uplift and the offshore bathymetry is flat, as in the case of an emerging marine terrace, the stream is lengthened seaward and cuts a channel in the terrace. Deposition may occur at the mouth of such a channel as the stream gradient decreases below that required to transport the sediment supplied by upstream reaches. In the case of offshore uplift less than onshore, or steep offshore bathymetry the stream-mouth reach is steepened and a knickpoint may develop and propagate upstream (van Heijst and Postma, 2001). In all cases, the features that are induced by base level changes can migrate, attenuate and often superimpose on older features formed by earlier base level changes.

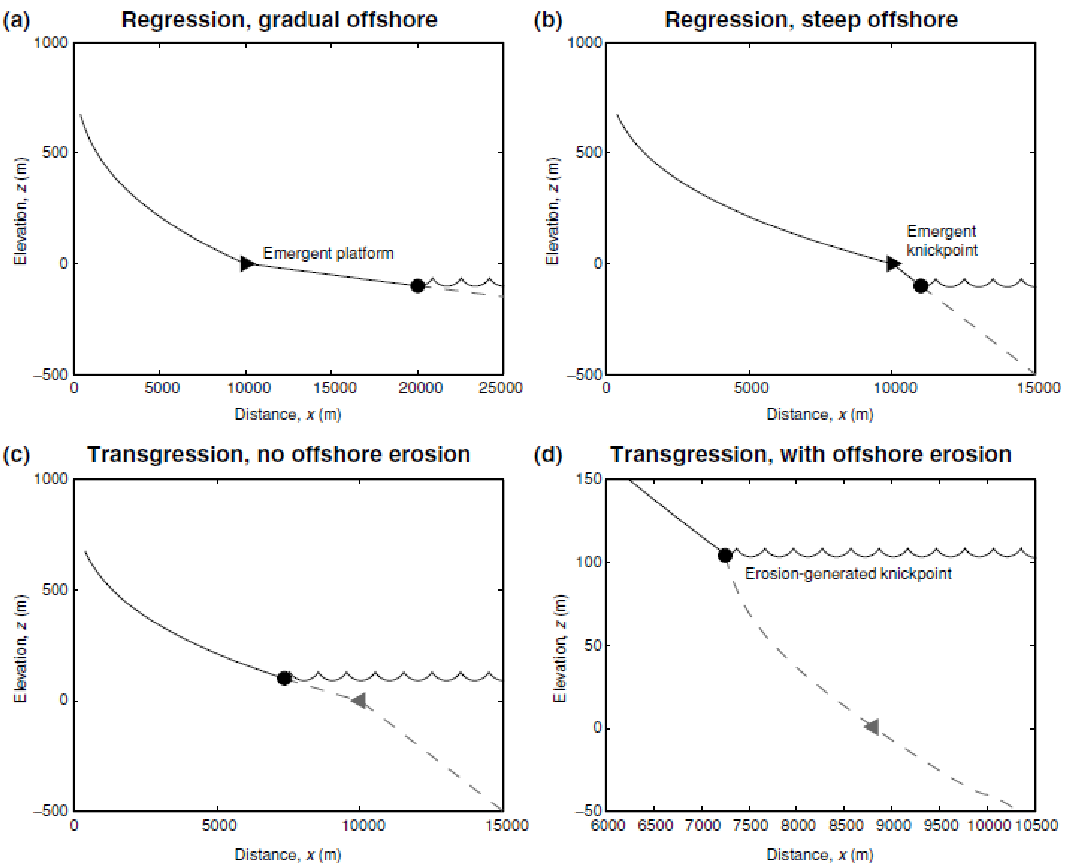

Figure 6.1. Idealized scenarios of base level decline **[a, b]** and rise **[c, d]** relative to the channel bed. The triangle represents initial sea level, the circle represents the sea level at some future point. From (Snyder *et al.*, 2002).

Uplift also directly influences slope and elevation of upper channel reaches, and, importantly, is both temporally and spatially dynamic. One result of uplift is increased local topographic relief. Similar to the results of base level decline, stream reaches with high topographic relief produce steep channels (Duvall et al., 2004; Wohl, 1999). As slope increases, stream power increases, producing a negative feedback on rising bed slope that pushes the stream profile towards equilibrium, although, in channels with uplift rate higher than incision rate, such as the majority of channels on SCI, equilibrium will not be attained.

Bedrock type as control on long profile shape

Higher stream power is required to erode more resistant rock, and thus, channels in more resistant rock are relatively slower to transform to a low gradient, low energy shape than channels in less-resistant rock, all else being equal. Duval *et al.* (2004) compared profiles of streams flowing through bedrock of differing resistance and found that more resistant rocks produced steeper channels, agreeing with model results from Moglen and Bras (1995). Due to its higher density and hardness we expect incision rates in the SCIv to be slower than in the MF. We therefore expect the two geologic units to produce different equilibrium long profiles (Figure 6.2) and to approach these equlibria at different rates. We also expect long profiles in the SCIv to retain steepness throughout their length compared to those in the MF, which should attain lower slopes and flattened lower reaches more quickly.

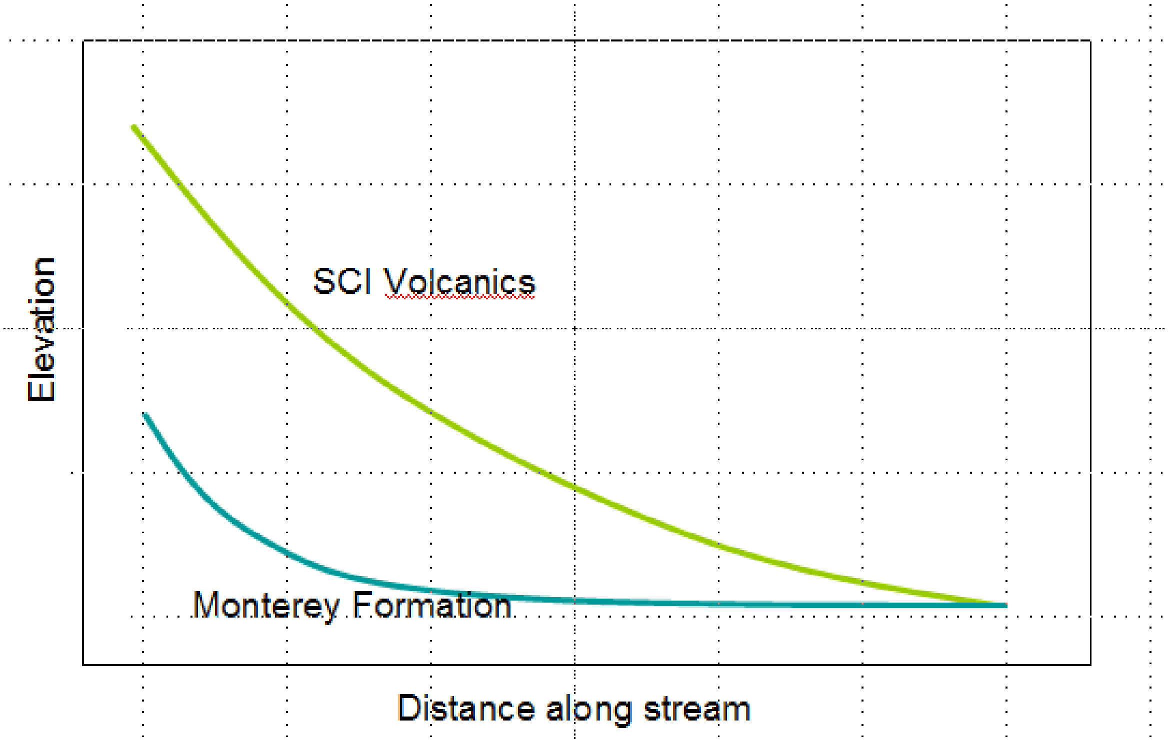

Figure 6.2. Postulated steady-state profiles for the two bedrock types. Assumes identical initial conditions. If the two channels were allowed to incise naturally, given identical flow, they should approach different equilibrium profiles. The harder rock would maintain steepness along more of its length than the softer rock channel.

Methods

We developed a set of line features in ARCGIS to represent channels based on a 10-meter Digital Elevation Model (DEM) from the USGS. We defined channels based on a 25 hectare (ha) contributing area. We chose this watershed size because it produced channel lengths similar to those found on USGS quadrangle maps of the Island. Duvall et al (2004) showed that a 30m resolution DEM was sufficient for extracting long profiles in small catchments, so our higher-resolution dataset should also suffice.

We scanned a geologic map of SCI presented in Weaver et al (1964) at high resolution, georeferenced it at a scale of 1:5000 with a total RMS error below 10 meters and digitized the polygons of the map (Figure 6.3) for use in our analysis of the influence of rock type on channel profiles.

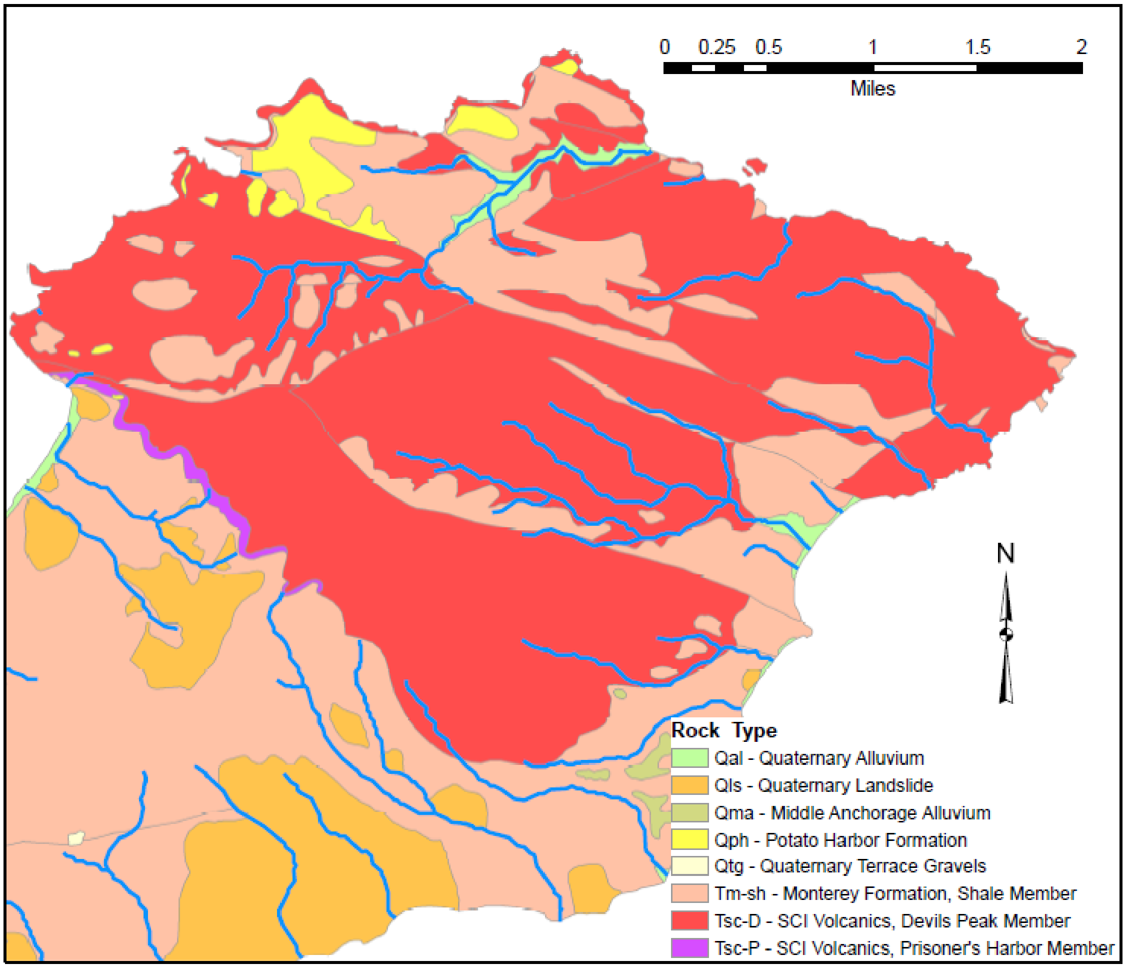

Figure 6.3. Study area includes the Eastern portion of Santa Cruz Island. Geologic unit boundaries are adapted from (Weaver, 1964).

We define a geologic reach (georeach) as that part of a stream channel that lies between headwaters, tributaries, or base level (the ocean) and flows in no more than one bedrock type. This is slightly different from the normal definition of a reach, which does not consider bedrock type, typically. We attributed each georeach with its length, length-weighted means of profile curvature and slope based on the same 10 meter DEM as that used in the development of the streams, rock type, Strahler order and the mean and maximum flow-contributing area. Since higher order streams can be expected, all else being equal, to have lower slopes and curvature(Leopold, 1994), we examined the ordinal distribution of the georeaches by bedrock type to determine if any bias might be introduced.

In addition to the wider-scale quantitative analysis, we chose four streams for further inspection and qualitative analysis (Figure 6.4). We recorded the DEM elevation and geologic unit at 5-meter intervals along these streams. We identified the 5-meter interval closest to each fault that the stream crossed or confluence that entered the channel. We also identified the portions of each channel that passed along a fault or geologic contact. We plotted each of the four long profiles along with the geologic and confluence information. We analyze these stream profiles below based on these GIS data in the context of the theory of long profile development.

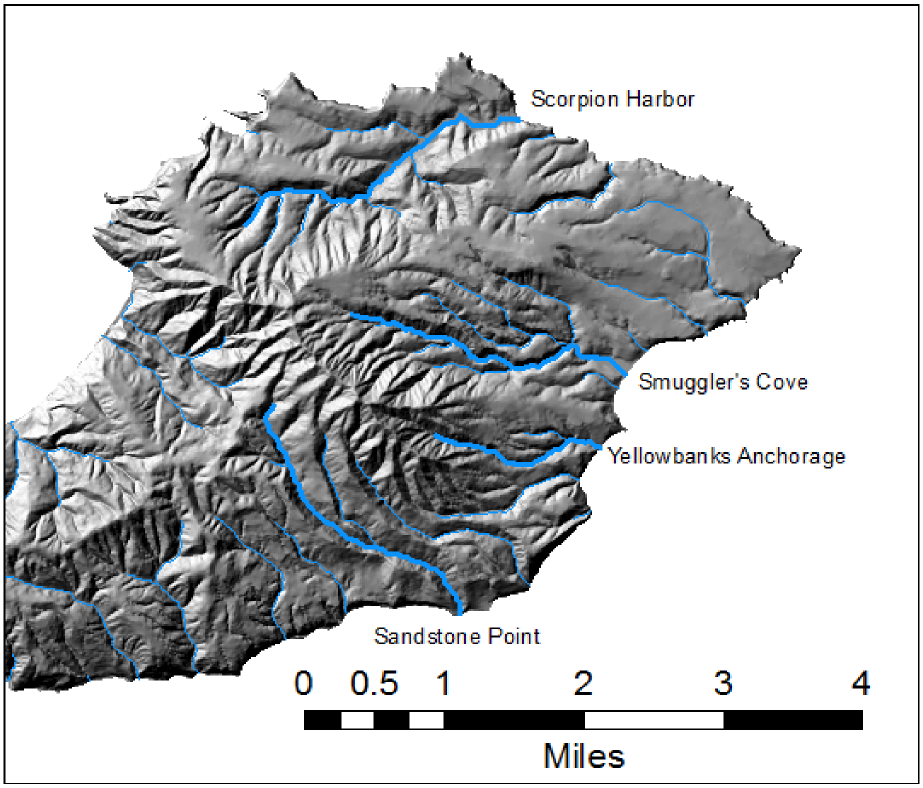

Figure 6.4. Four streams chosen for further analysis. The coastal feature to which each stream flows was used to name the stream.

Results: Reach-averaged analysis

There were 53 georeaches in the SCIv bedrock, and 46 in the MF bedrock within the study area. The average of length-weighted mean slopes in the SCIv was 28 percent, in MF that average was 24 percent. The 87 first-order georeaches in the study area averaged 26 percent slope, the 31 second-order georeaches averaged 21 percent, and the 3 third-order georeaches averaged 11 percent slope (Table 6.1). The numbers of georeaches in the two bedrock types were similarly distributed across stream orders (Table 6.1).

Table 6.1: **Summary of results of GIS analysis**

		Reach Order			Reach Bedrock				All	
		1	2	3	MF	SClv	Qal	Qls	Reach	
Mean of Length-Weighted Means of:	slope	27	21	11	24	28	12	33	25	percent
	curvature	3.0	3.6	1.6	3.0	3.6	1.1	4.0	3	(m/m)/m
	flow acc-umulatio	37	155	375	63	68	165	64	75	ha
	Count	87	31	3	46	53	12	10	121	Reaches
			Count by Order	1	35	38	6	8	87	
				2	11	13	5	2	31	
				3	0	2	1	0	3	

A 1-tailed, unequal variance, T-test of the average length-weighted mean slopes of all MF vs all SCIv georeaches resulted in a p-value of 0.038, which suggests that the means are significantly different. However, when the mean slopes were tested across same-order streams only, the p-value was 0.055 for 1st-order reaches, and 0.088 for 2nd order reaches. The higher p-values for ordinal groupings indicates that the range of values of slopes do not decrease proportionally with the number of sampled slopes. In fact, the T-test of mean slopes between 1st and 2nd order georeaches resulted in a p-value of 0.091, indicating no significant difference between these means. The variation in slope within a stream order is on the same scale as that across bedrock types, and greater than the variation between orders. We interpret these results to mean that lithology does play a significant but not dominant role in determining slope. This should be taken as evidence that the landscape is young, and few, if any, of the channels have reached equilibrium. As the channels approach equilibrium, lithology should become a more important control on slope (Duvall *et al.*, 2004).

In general, long profile slopes in the study area are high. This is likely due to the combination of rapid uplift and intermittent flows, and the fact that these are very small watersheds. Although colluvial inputs to the channels are generally high due to ubiquitous mass-wasting of hillslopes (see Chapter 7) in the study area, this is unlikely to be a driver of long-profile shape (but see the discussion of figure 6.5, below) because the channels are generally not transport limited.

Correlations between flow accumulation (watershed area, A) and slope (S) by georeach, whether all georeaches were taken together, or parsed by bedrock type and/or order, were low (Table 6.2a).

Table 6.2: R-squared Correlation Coefficients (a) and Slope Coefficients (b) Between Contributing Area (A) and Slope (S), for all reaches, MF, and SCIv, by order.

a

	Correlation Coefficients		
	All Orders	Mean A	Max A
Mean S	All Rock Types	0.145	0.123
	MF	0.059	0.042
	SCIv	0.060	0.027
	1st Order	Mean A	Max A
Mean S	All Rock Types	0.092	0.031
	MF	0.145	0.025
	SCIv	0.077	0.004
	2nd Order	Mean A	Max A
Mean S	All Rock Types	0.145	0.123
	MF	0.085	0.132
	SCIv	0.268	0.048

b

	Slope Coefficients		
	All Orders	Mean A	Max A
Mean S	All Rock Types	-0.0006	-0.0004
	MF	-0.0005	-0.0003
	SCIv	-0.0004	-0.0002
	1st Order	Mean A	Max A
Mean S	All Rock Types	-0.0023	-0.0003
	MF	-0.0023	-0.0004
	SCIv	-0.0034	-0.0001
	2nd Order	Mean A	Max A
Mean S	All Rock Types	-0.0006	-0.0004
	MF	-0.0005	-0.0005
	SCIv	-0.0004	-0.0001

Further, trend analysis (Table 6.2b) shows that the slopes, while tending to decrease slightly with increasing watershed area, are statistically invariant across order and watershed area. For example, the best correlation was found between mean watershed area and slope in 2nd order georeaches with SCIv bedrock, however, the slope of the relationship between area and slope was of very low magnitude (-0.0004). These data indicate that these channels are far from equilibrium. If the channel were generally at or near equilibrium profiles, there would be much greater correlation between slope and the watershed area, and greater variation in slope between georeaches with different watershed areas.

In cases where valley slope is generally parallel to the fault between shale and basalt members, the stream channel often followed the fault. This may have confounded the method of analysis developed in this paper. Since the channel might wander back and forth across the contact between the two bedrocks over lengthy segments, it was difficult to associate slope or other parameters with a particular rock type in those segments. Furthermore, it is possible that breccia at the fault would erode more easily, causing knickpoints, zones of transport limitation, or other geomorphic anomalies that would be difficult to detect with the current analysis.

Focus streams

Sandstone Creek exhibited a near-linear profile (Figure 6.5). Slope for most of the stream is approximately 7%. Except for a short reach of SCIv at the headwaters, this stream flowed in MF for its entire length.

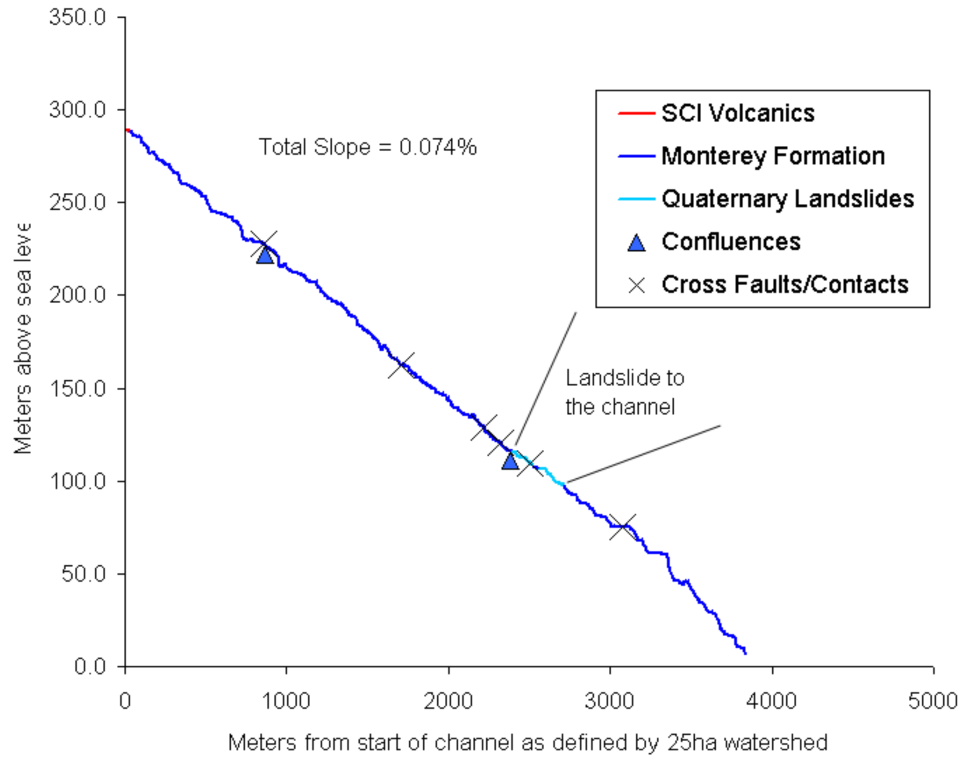

Figure 6.5: Sandstone Creek long profile.

A large landslide feature abuts the channel about two thirds of the distance from the headwaters to the mouth of the stream. The slope does not change appreciably above or within the landslide. There is a decrease in slope below the landslide contact, followed further downstream by increased slope.

The bulge in the profile of Sandstone Creek below the landslide contact indicated in Figure 6.5 is likely to be fluvially transported material that entered the channel when the landslide occurred and is now attenuating and migrating downstream. This plug of sediment creates a local decrease in slope upstream and a local increase downstream. This feature itself is a non-equilibrium feature, while the overall profile seems to be currently in disequilibrium.

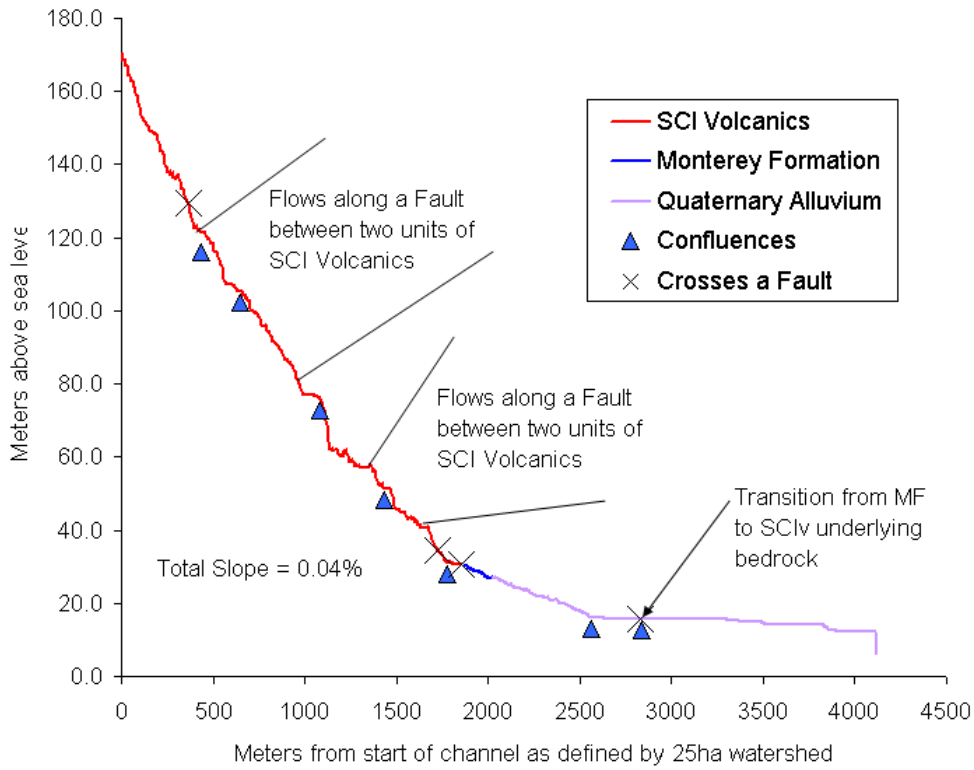

Figure 6.6. Scorpion Creek long profile.

Scorpion Creek exhibited the most concave-up long profile of the four streams (Figure 6.6). The upper reaches of the stream flow through SCIv and the long profile appears to be strongly influenced by confluences in this region. All of these tributaries also flow through SCIv exclusively. Each confluence is preceded by a typical upstream reduction in slope and a downstream increase. Two segments of the upper stream flow along faults between different units of SCIv. The stream transitions from SCIv to MF low in the watershed, and channel slope changes from approximately 8% to approximately 1% at the bedrock transition. There is also a small tributary confluence at that location.

There are several indications that Scorpion Creek may be at or near its equilibrium profile. Although the upper reaches are very steep, that fact is consistent both with the expectations we have for the harder bedrock of those reaches and rapid uplift rates. There are no obvious breaks in the slope indicating migrating knickpoints. Only the effects of confluences interrupt the relatively smooth concave profile within each bedrock type.

The bedrock transition at about 1900 meters on the x-axis corresponds with a pronounced change in channel slope. A small tributary does enter the main channel near the same location, but, since the other confluences do not mark major transitions in slope, it is likely that lithology is the driver here. The channel changes from a confined bedrock channel to a semi-unconfined alluvial channel at this fault. Substantial deposition and highly unsorted gravel and boulder size classes indicate that the stream is transport-limited below the fault.

The lowest reach of the stream is divided almost in half by another orthogonal fault that marks the transition from MF back to SCIv bedrock. This lower SCIv underlying the alluvium may be acting as a grade control, limiting the slope of this last reach.

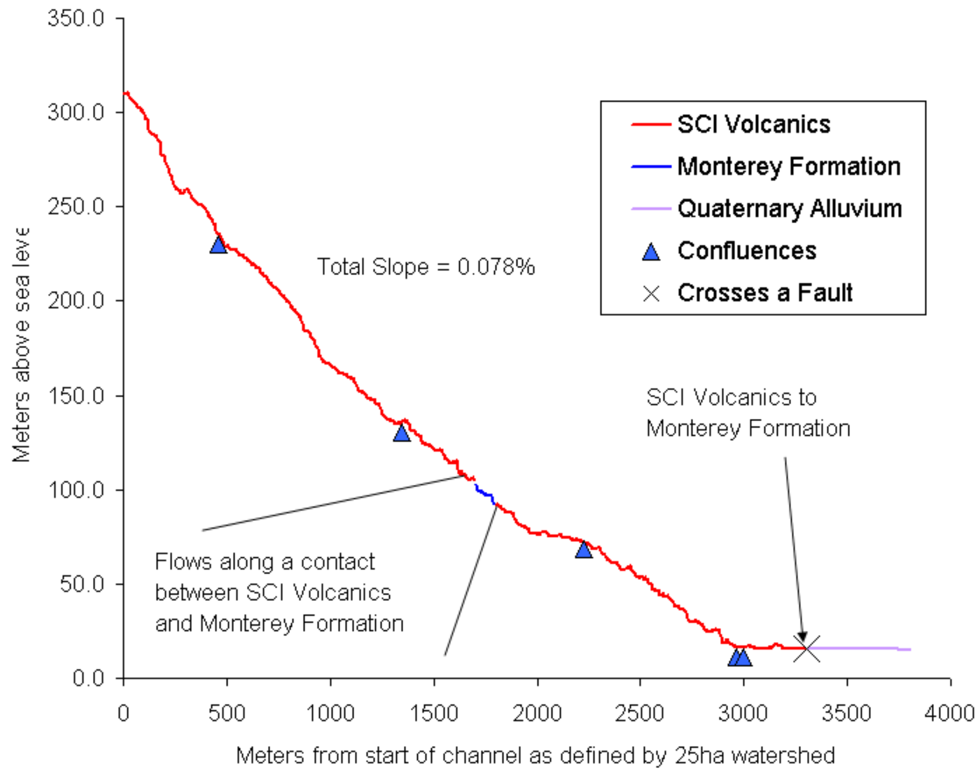

Figure 6.7. Smuggler's Creek long profile.

Smuggler’s Creek also displays a concave-up profile (Figure 6.7). The channel passes through SCIv bedrock except for a short reach that flows along a fault between MF and SCIv. The two most upstream confluences each mark a section of the channel with reduced slope, that is followed by a steepened section. These convex-up features are not in evidence at the lowest confluence.

The 3rd confluence exhibits a large discontinuity in slope. This may be due to the fault just upstream, or the feature may be a downstream-migrating remnant of a sudden influx of material either through mass-wasting or gully erosion.

The lowest reach of the stream flows over Quaternary alluvium underlain by MF bedrock. No profile feature appears at the fault between the two bedrocks. The slope and alluvial depositional nature of this final reach is a typical response of the stream profile to onshore uplift accompanying offshore uplift. The stream is extending out over the rising wave-cut marine terrace, and will continue to do so until uplift circumstances change or the terrace end is reached.

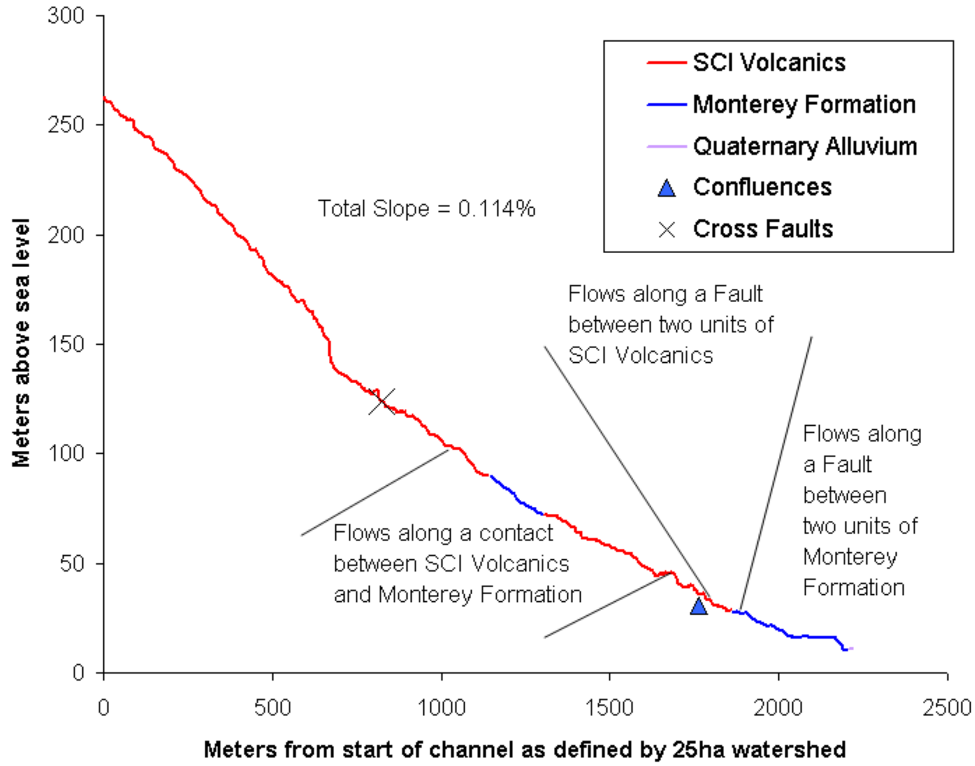

Figure 6.8. Long profile for Yellowbanks Creek.

Yellowbanks Creek is the shortest of the four streams profiled, at about ½ the length of the other three streams (Figure 6.8). The profile is concave up and much steeper than the other three streams.

There is a prominent knickpoint at the mouth of the stream that represents the nonequilibrium response of the stream to sea-cliff retreat. There is a short reach of Quaternary alluvium below the knickpoint that likely is derived from the cliff material.

The channel follows contact surfaces for much of its lower portion, and crosses a fault near the middle of its length. There is a very steep feature above the uppermost fault that interrupts the profile form, with a steeper slope above and a more shallow slope below the feature. This feature appears to be an old knickpoint that has migrated upstream and attenuated as it went. This is another example of nonequilibrium, as the feature form is not steady and progresses away from its original state.

The upper knickpoint also provides evidence of the disequilibrium state of the entire channel. The slope above the migrating knickpoint is steeper than that below it. Therefore, the channel is not returning to the state it was in prior to the passage of this knickpoint. Instead, the channel slope is reset, noticeably lower in elevation and gradient, presumably closer to the equilibrium slope.

Conclusion

Although the difference in slope between the two dominant bedrock types was statistically significant, in most cases where a transition occurred from one rock type to another, there was little or no discernable slope change. Lithology was not generally the dominant driver of slope in a georeach. Several other factors played important roles in the overall development of long profiles.

Confluences, sea-cliff erosion, landsliding and faulting, and rapid uplift all have observable effects on channel slopes in the study area. Confluence effects on long profiles were observed in the four focus streams as upstream reductions and downstream increases in slope. Sea-cliff erosion appeared to have initiated a knickpoint in at least one of the focus streams. A landslide contact on one stream channel was associated with a topographic feature that may be an attenuated slug of colluvially-derived material migrating downstream from the contact. All streams and reaches exhibited steep slopes that were in large part driven by the high regional uplift rate relative to base level.

In general, the eastern portion of Santa Cruz Island is dissected by streams with profiles far out of equilibrium. Causes of this include small watershed size, rapid uplift and limited duration competent flows. Scorpion Creek is the only example of a stream that may be achieving an equilibrium between incision and uplift. This stream is the largest on the eastern Island, and this fact likely explains the stream's ability to incise at a rate comparable to the uplift it experiences. In the case of Scorpion Creek, the transition from SCIv to MF did correspond with a marked change in slope, implying that such a slope transition, or lack thereof, may be diagnostic of the equilibrium state of the stream.

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