

Stream Profiles as a Proxy for Uplift in the San Bernardino Mountains

by

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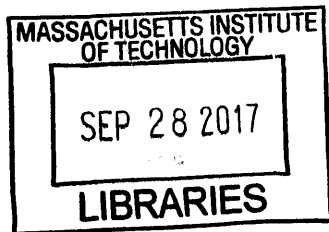
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ABSTRACT

Stream profile analysis provides new insight into the tectonic history of the San Bernardino Mountains of Southern California. The San Bernardino Mountains, along with the nearby San Gabriel Mountains, have been tectonically uplifted since the late Miocene due to transpression-related thrust faulting. Although regional uplift patterns are not as clear from this data as those of a stream profile analysis in the San Gabriel Mountains, the results observed indicate that this technique can extract useful tectonic data and provide a fast, inexpensive, and easy way to focus fieldwork in a region. For example, in the San Bernardino Mountains, stream profile interpretation from digital elevation models (DEMs) indicates the current/most recent uplift rates on the Yucaipa Ridge at the southern range front are only $\sim 0.5\text{-}0.6$ mm/yr, much lower than indicated by a published (U-Th)/He age-elevation transect. Also, a change in steepness index (k_{sn}) values between the north and south sides of the Santa Ana Thrust Fault suggests differential uplift across it as recently as the mid to late Quaternary. However, there are important limitations to the method that render interpretations non-unique. For example, the channel downstream of the dam at Big Bear Lake is much steeper than adjacent streams; a tectonic explanation is unlikely. One possibility is that large landslide- and debris-flow-derived boulders have armored the channel and caused the river to oversteepen.

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Introduction

The coupling of surface processes and landscape evolution to tectonics is a problem of great recent interest. One example of this is how climatic forcing influences the growth and decay of mountain belts. While the details of direct effects of erosional processes on orogen formation is not well understood (Whipple, 2004), it has been generally observed that the locations with the highest uplift and erosion rates have the steepest slope (e.g., Montgomery and Brandon, 2002). Therefore, it seems apparent that meaningful tectonic information can be extracted from topography. Hillslopes reach threshold gradients at relatively low rock uplift rates (e.g., Roering et al, 2001; Montgomery and Brandon, 2002) and thus retain no tectonic information at higher rock uplift rates. Bedrock channel gradients are thought to reflect tectonic conditions over a much wider range of rock uplift rates (e.g., Whipple, 2004). Therefore, I focus here on the use of the channel steepness index as an indicator of relative rock uplift rates.

The San Gabriel and San Bernardino Mountains are part of the Southern California Transverse Ranges heavily dissected by the greater San Andreas Fault system (Figure 1). Although currently geographically adjacent, they originated at different times and in different locations and have been brought together by the right lateral movement along the San Andreas Fault (Spotila et al, 2002). A bend in the otherwise strike-slip San Andreas Fault has created a transpressive margin in this region.

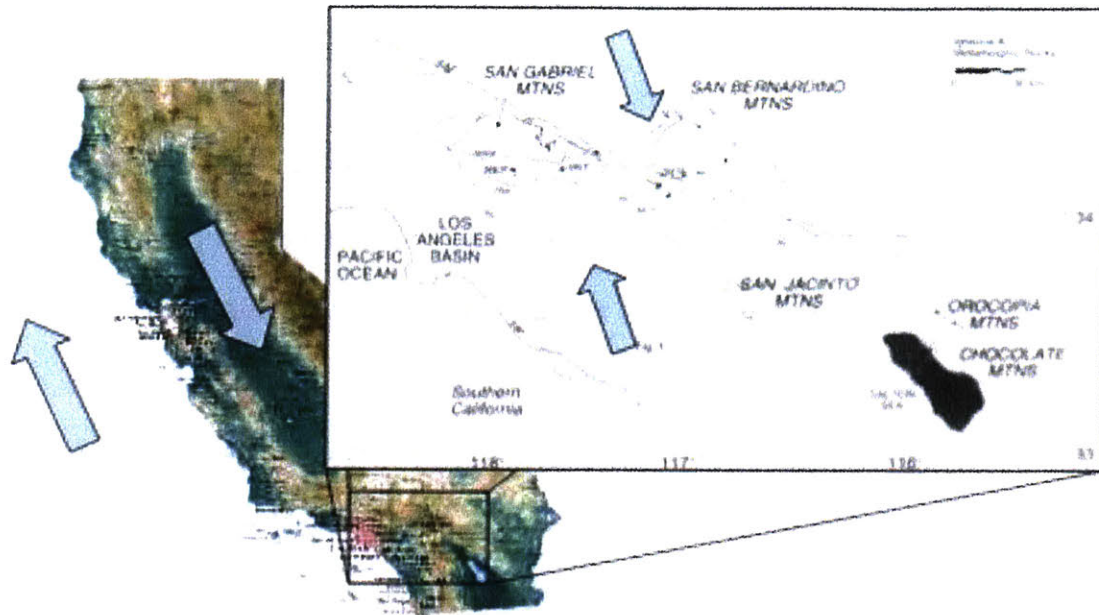


Figure 1. Map of the San Bernardino and San Gabriel Mountain Ranges in Southern California. Arrows show approximate relative plate motion of the Pacific and North American plates, separated by the San Andreas Fault (SAF). Zoom shows a simplified fault map of Southern California (after Blythe et al., 2002) through the bend in the SAF at transpressive margin where motion is oblique to the main fault.

Dewey et al. (1998) showed that in oblique boundaries strike-slip displacement cannot accommodate total relative plate motion, so the uplift of the San Bernardino is especially complex because it is likely due to thrust faulting on the North Frontal thrust system, Santa Ana thrust, and a series of faults at the southern range front, all relating to this transpression. The exact mechanics of this process is not well understood, and numerous models have been presented (e.g., Wilcox et al., 1973; Mount and Suppe, 1987).

The main morphological features of the San Bernardino Mountains include the Big Bear Plateau, a surface of old, deeply weathered granite. Some streams have begun to incise back into this plateau following uplift, but in many places it remains a remarkably continuous relict surface (Spotila et al, 2000). Also of note are the steep escarpments to the north and south of the plateau along the North Frontal and Santa Ana thrusts. Slopes

are much more gentle on the eastern and western margins. The range narrows and becomes higher to the south, where it is more heavily dissected by faults.

Meisling and Weldon (1998) proposed that the Santa Ana thrust has not been active recently, except locally, and mainly moved during the Miocene. Spotila et al. (1998) state that the uplift of the San Bernardino Mountains initiated after the Miocene epoch. Despite this, geomorphic indicators such as a high, steep escarpment indicate that the Santa Ana thrust did have an important role in uplifting the Big Bear Plateau (Spotila and Sieh, 2000), but the eastward disappearance of the escarpment could indicate the Santa Ana thrust is responsible for only a small portion of the uplift, focused locally along small sections of the fault (Spotila and Seih, 2000). Certainly, some of the uplift must be accounted for by the more southerly faults towards the main range front. Spotila and Sieh concluded in their 2000 paper that the North Frontal thrust is the primary structure in uplifting the San Bernardino Mountains and that it accounts for all but a few crustal slivers. These slivers are fault blocks that decrease in size and increase in complexity southward toward the San Andreas Fault. Young thermochronology ages from within these blocks indicate rapid uplift in this area (Spotila et al., 1998). My data provides new evidence that the Santa Ana thrust may have played a more active role in the uplift of the San Bernardino Mountains than previously thought and that the current uplift in the southern blocks is slower than the pulse recorded in the thermochronology data.

Method

I have attempted to gain further insight into the history and magnitude of the uplift of the San Bernardino Mountains using the long profiles of rivers that dissect the region. Spotila et al. (1998) define several tectonic blocks within the San Bernardino Mountains on the basis of geomorphology, major fault distribution, and thermochronology data. I examined and compared the channel profiles within these blocks and across the boundaries between them.

I analyzed channel profiles using 10-meter resolution digital elevation models (DEMs) which can be obtained from the U.S. Geological Survey (USGS) (<http://seamless.usgs.gov/> or <http://data.geocomm.com/dem/>). After downloading quads, I merged the data using ArcInfo from ESRI's ArcGIS program. Such remotely sensed digital data might contain imperfections due to cloud cover or extreme topography. To allow for this I filled the pits in the DEM (using the arc grid "fill" command). Once this was completed, I was able to generate a direction array and a flow accumulation array using built-in ArcInfo commands and the method developed by Snyder et al. (2000) and Kirby et al. (2003). Any computer script, however, that will follow a path of pixels downstream and record elevation, the length of the river, and the drainage area would suffice. I exported these new datasets into ascii format and converted the resultant text files into .mat files to be read into MATLAB.

Once I had the DEM data prepared, I used the profiler tool in ArcGIS with a reference concavity (θ_{ref}) of 0.45 and a cellsize of 10. The regional mean of observed θ values (in stream profiles with no known knickpoints, rock strength changes, or variable uplift) is often used as the reference concavity (Wobus et al., in press). A θ_{ref} of 0.45 falls within the typical range of 0.35-0.65 (Snyder et al., 2000; Kirby and Whipple, 2001;

Brocklehurst and Whipple, 2002; Kirby et al., 2003; Wobus et al., 2003) and accurately described the San Gabriel Mountains (Wobus et al., in press). After I selected my streams in ArcGIS, I used in-house Matlab scripts to analyze stream profiles as described by Wobus et al. (in press). By fitting the slope-area data to it, the reference concavity (θ_{ref}) allowed me to find normalized steepness indices. It is important to fit only the portion of the profile for which the empirical equation, $S = k_s A^{-\theta}$, accurately describes the slope-area relation, i.e. the section downstream of the critical drainage area (A_{cr}), which typically occurs around $A_{cr} \leq 10^6 \text{ m}^2$ (S is the channel slope, k_s the steepness index, A the upstream drainage area, and θ the concavity). This break in scaling probably represents the transition from debris-flow dominated colluvial channels to stream-flow dominated fluvial channels (e.g. Montgomery and Foufoula-Georgiou 1993; Stock and Dietrich, 2003). I saved figures in postscript form, and later, imported them into Adobe Illustrator for ease of comparison. A selection of the figures produced from this step is in Appendix A.

I imported these stream regressions and knickpoints back into ArcMAP. In order to see geomorphic indicators of uplift, I appended all the streams into one shapefile and colored channels by the normalized steepness index (k_{sn} , labeled as 'KsRefCon1') for a reference concavity index of -0.45. The streams are color-coded from gentle slopes in blues up to steep slopes in red in seven discrete categories chosen by natural breaks in the histogram of steepness index values.

I used the Jennings fault map (Jennings, 1977) of known Quaternary active faults for Southern California. Once overlaid onto my DEM and stream plots, this allowed me to see where faults correlate with changes in steepness that might indicate recent activity.

I imported the published thermochronology data for both the San Gabriel and San Bernardino Mountains (Spotila et al., 1998, Blythe et al., 2000; Spotila et al., 2001; Spotila et al., 2002; Wolf et al., 1998) as a point shapefile into ArcMAP in order to better compare those results with my own. I colored them by age in seven categories (see Figure 2).

Results

I collected just over 100 stream profiles to analyze from an initially broad geographic region that I selectively focused to specific areas as interesting patterns began to emerge (Figure 2).

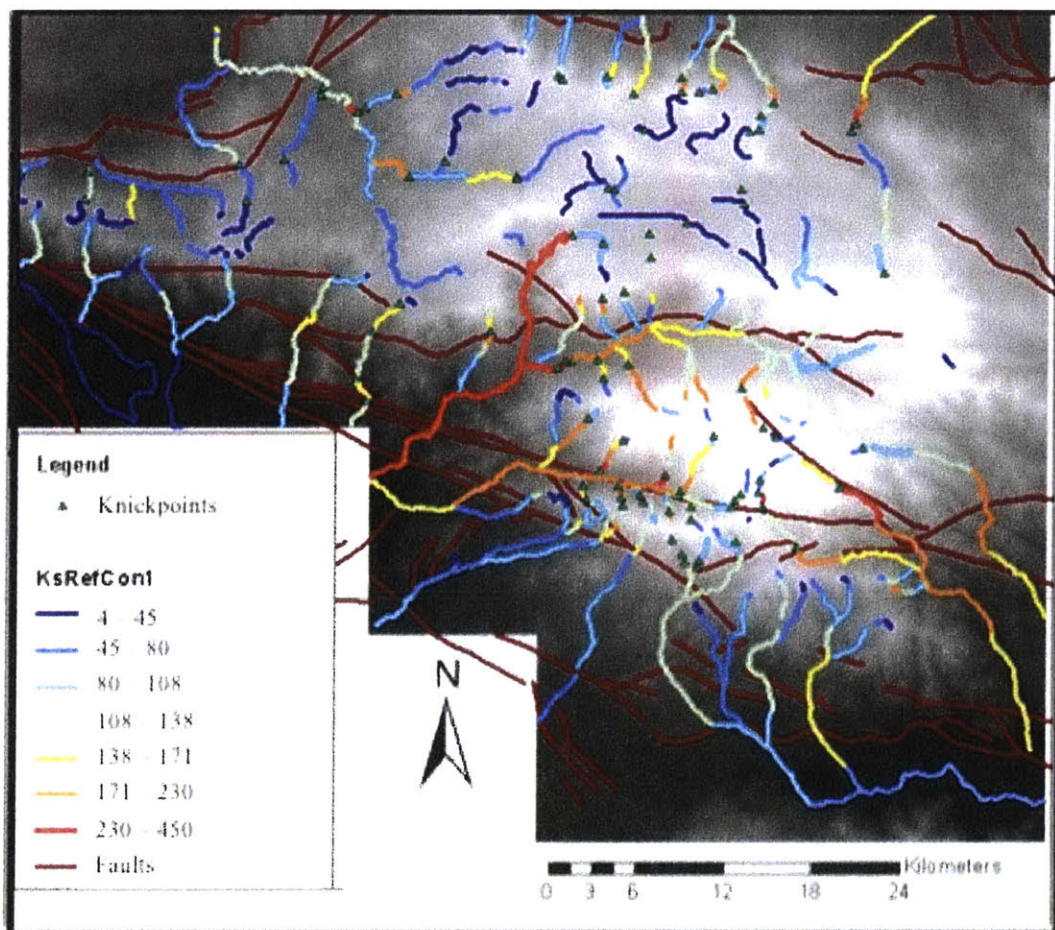


Figure2. Stream profiles collected in the San Bernardino Mountains, colored by steepness index (k_{sn}). Triangles show knickpoints, brown lines are faults digitized from Jennings (1977).

Unlike the results from the San Gabriel Mountains (Wobus et al., in print; see Figure 3), the data cannot be cleanly divided by region at this level of analysis, but in general the steepness values I found range from 3 (in the Big Bear lake) to over 400, with most falling between 65 and 180. In comparison, the analysis of stream profiles in the San Gabriel Mountains resulted in average k_{sn} values of 66 and 145-170 in low and high uplift rate zones, respectively (Wobus et al., in print). For the San Gabriel Mountains, Whipple et al. (in preparation) observed low uplift to be 0.1 mm/yr and high uplift to be 0.9 mm/yr.

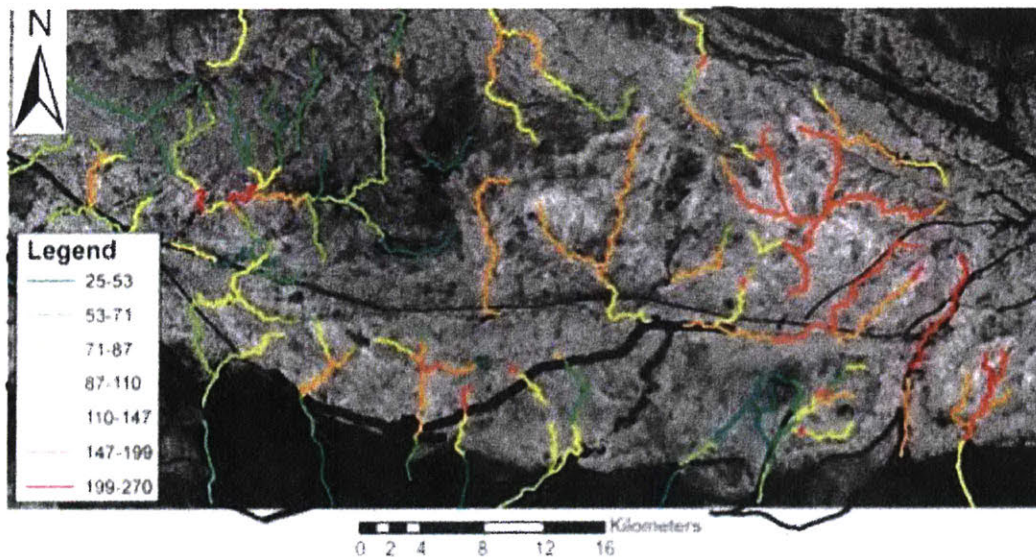


Figure3 Stream profiles colored by steepness index (k_{sn}) in the San Gabriel Mountains, California (Whipple, unpublished data). Regional variations in rock uplift are clear, with some local complications superimposed.

There are three particular areas of note revealed in this analysis. First, channel “ne26” downstream of where it empties from the dam at the southwestern edge of Big Bear Lake shows unusually high k_{sn} values, in the range of 315-370. The second area is the Yucaipa Ridge block as defined by Spotila et al. (1998). Steepness index values on

Yucaipa Ridge are moderate, around 85-120, which is not as steep as would be expected from the high erosion rates of 1.5-2mm/yr predicted by Spotila et al. (1998); based on data in the San Gabriel Mountains, such high erosion rates would be consistent with $k_{sn} > 200$ (Whipple et al., in preparation). Finally, complex along-stream patterns in k_{sn} values are observed on streams that cross the Santa Ana Thrust Fault and one of its southern splays. There are knickpoints that line up with the fault on some, but not all, streams. Broadly speaking, the k_{sn} values north of both splays are higher (127-151) than the k_{sn} values south of both splays (91-112), suggesting some recent differential rock uplift across this structure.

Analysis and Discussion

The observed patterns of stream steepness index in the San Gabriel Mountains is clear and well divided spatially into regions of higher and lower steepness (see Figure 3) with only minor local complications (Wobus et al., in press). These regions correlate well with known faults and independently estimated uplift rates for the range. This analysis of the San Bernardino Mountains proved to be not as straightforward. No large-scale spatial patterns in steepness were evident, and no simple correlation to the fault bounded blocks defined by Spotila et al. (1998) was observed. As discussed, the morphology in these two ranges is starkly different. Factors that were not examined in this study, but that might prove useful in a comparison of the two ranges, are climatic and lithologic variation between and within the San Gabriel Mountains and the San Bernardino Mountains, as well as a more robust examination of the current understanding of the tectonic history of the two ranges. Lithologic contrasts alone can result in differences in channel steepness

index comparable to those associated with large gradients in rock uplift rate (Snyder et al., 2000; Duvall et al., 2004; Stock and Dietrich, 2003; van der Beek and Bishop, 2003). In addition, further data collection and possibly the use of different dating techniques than have previously been published for this range, such as cosmogenic isotope dating, will help shed light on some of the poorly understood tectonic history of the San Bernardino Mountains.

Despite the complexity of the channel steepness data set as a whole, there are three regions where useful information can be extracted. Future work in these regions has a strong potential of adding to our understanding of both the strengths and weaknesses of the method used here and of the tectonic history of the field site. Channels with a high steepness index (k_{sn} value) tend to correlate with a high erosion rate (this relation is part of the strength of this method), but there can be local complications. For instance, the river that empties from the southwest corner of Big Bear Lake (ne26) has the highest k_{sn} values of my sampled streams (315-370), yet the morphology doesn't seem to fit that of a rapidly eroding channel. I propose that landslide and debris-flow boulders have armored the bed and lead to an oversteepening. A channel that is cutting very quickly into bedrock will likely form steep canyons with a sharp V shape at the base. On the DEM, most of the downstream section of this river has a wide canyon bottom that looks back-filled with sediment (Figure 4).

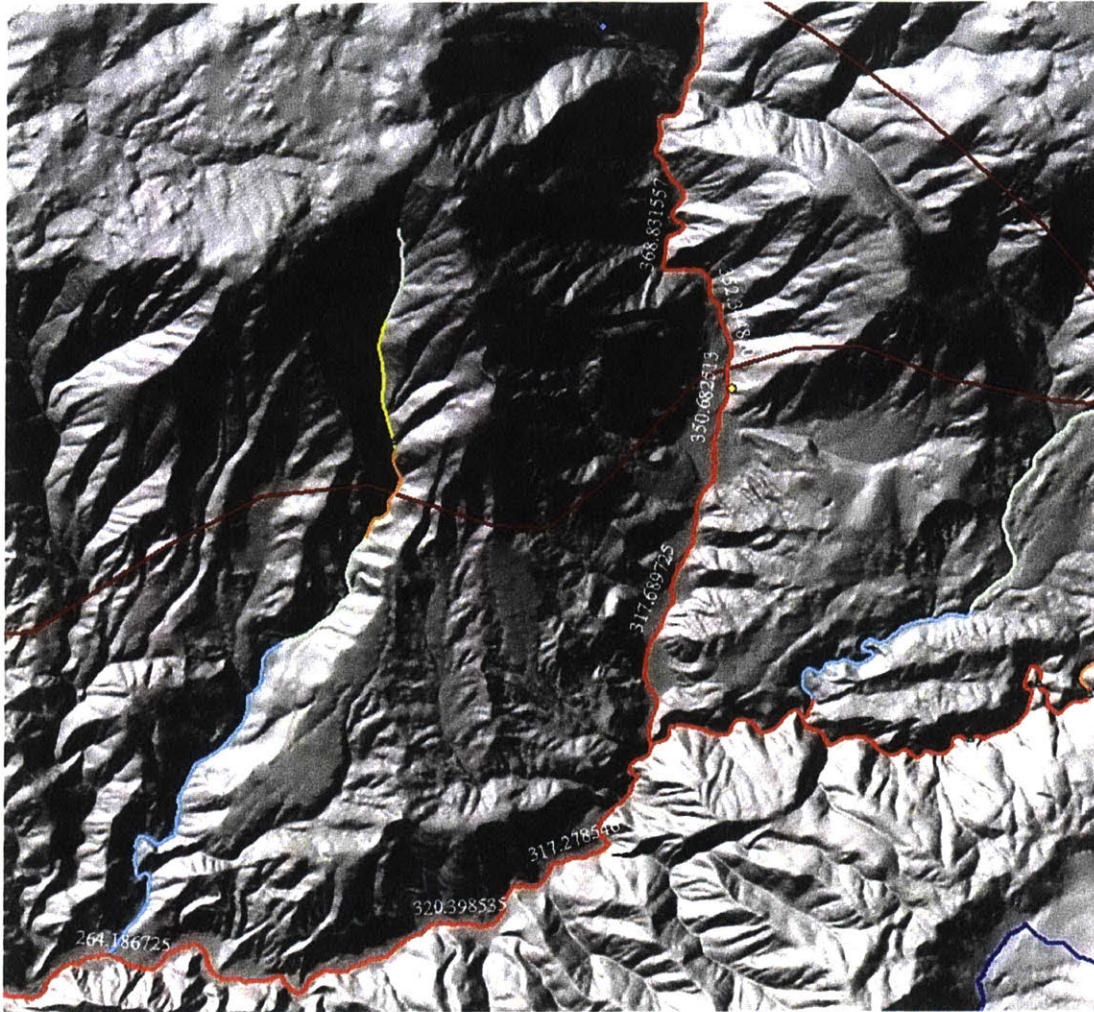


Figure4. Shaded hillslope image of channel “ne26” downstream of where it empties from Big Bear Lake. Note the wide, flat valley bottom indicative of alluvial fill. High (>300) k_{sn} values are shown over different stretches. Brown curved line that runs ~EW is the Santa Ana Thrust Fault.

Figure 5 also shows that the high k_{sn} values I see in this river are not necessarily an accurate representation of the steepness of that channel. The long profile immediately downstream of the lake appears to be linear, with almost no concavity, and so the reference concavity (0.45) could be a poor match for this drainage.

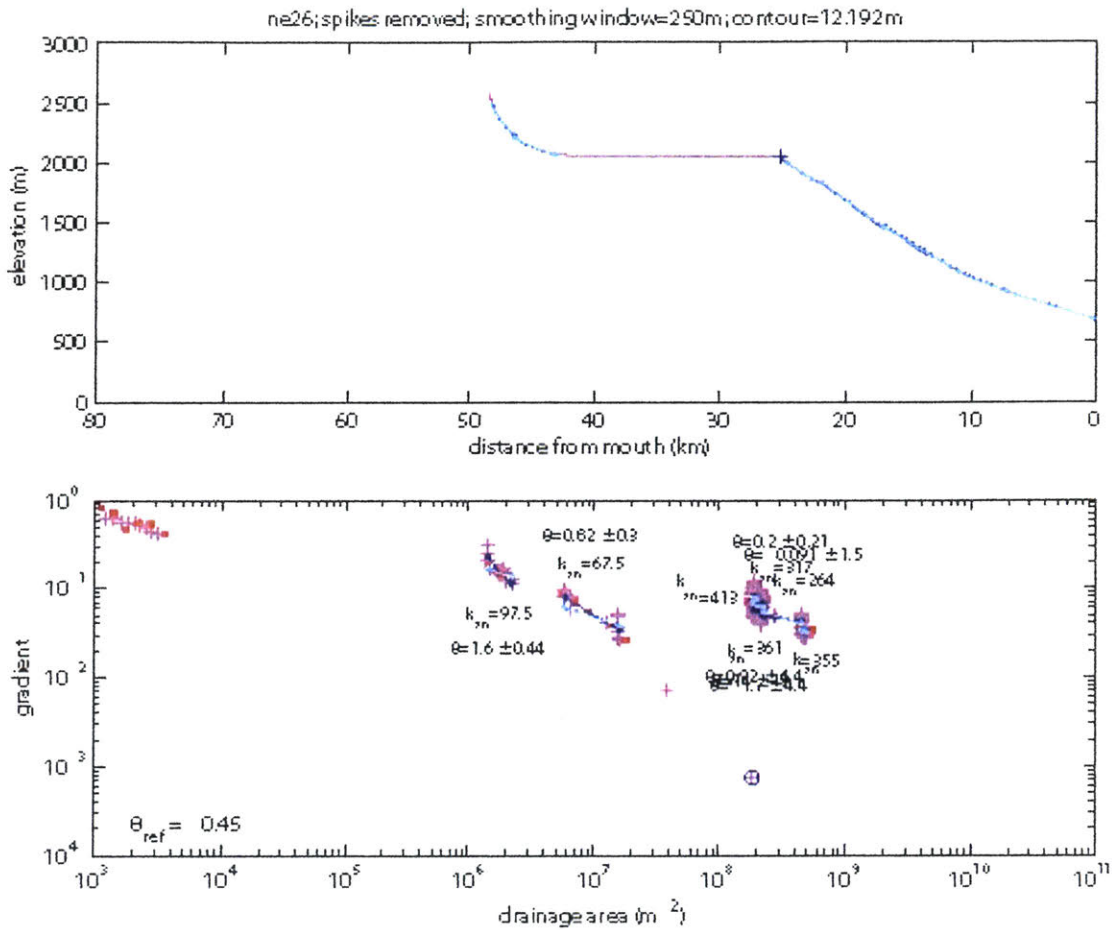


Figure 5. Long profile and slope – area data for channel “ne26.” Plateau in the profile is Big Bear Lake. The high k_{sn} values downstream can be seen in the slope – area plot.

Slope-area analysis (as opposed to a direct slope comparison) is useful because the downstream stretch of any given channel, with its significantly larger drainage area, should have a lower slope, all else being equal. Perhaps there are factors that cause this stream to have an effectively lower drainage area than the topography indicates. If the Big Bear Plateau is especially dry and contributes a lower flow volume relative to its area than is expected for this region, the stream could appear to be oversteepened.

Precipitation data from the National Department of Agriculture (see Figure 6) shows a

slightly lower average annual precipitation for the big bear plateau at 20-28 in/yr as opposed to 28-44 in/yr observed through the rest of the range.

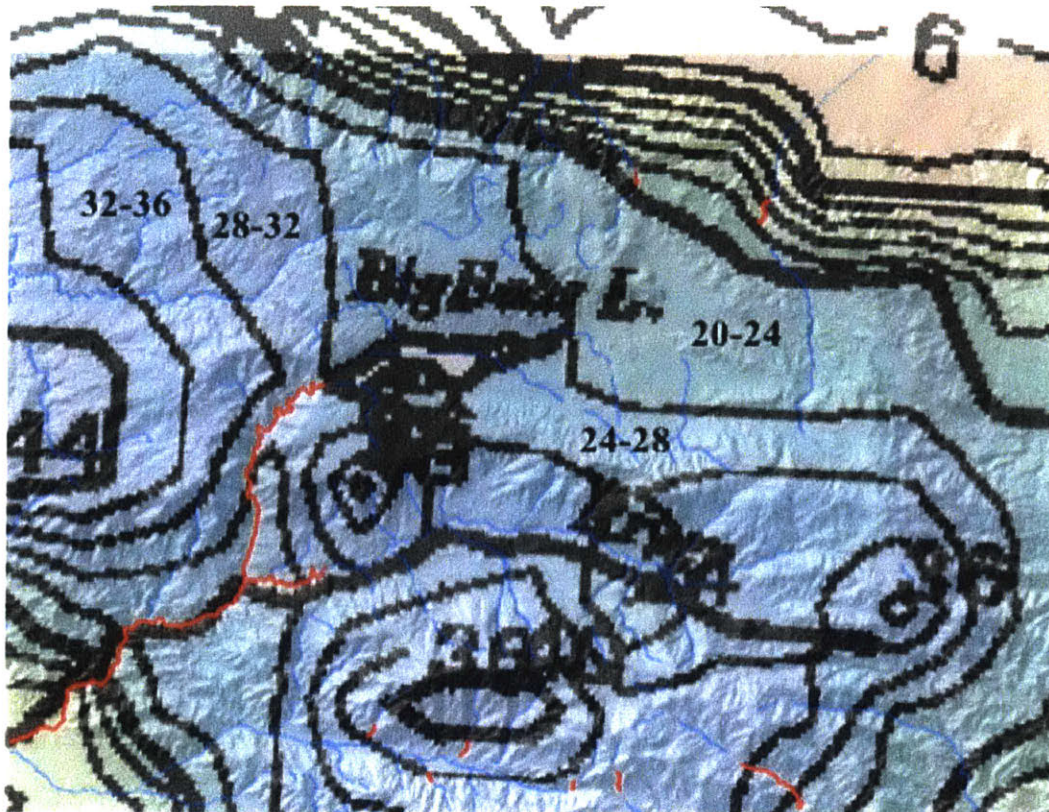


Figure6. Precipitation contours (in/yr) from National Department of Agriculture overlaid onto topography. Stream “ne26” is shown in red emptying from Big Bear Lake. The plateau is slightly drier than the rest of the range, but not significantly so.

When compared to a nearby stream drainage entirely below the plateau, it is apparent that at the same steepness the upstream drainage area is an order of magnitude lower (Figure 7). The precipitation difference cannot possibly make up that vast change in effective area and so may contribute slightly, but is not likely to have a substantial effect.

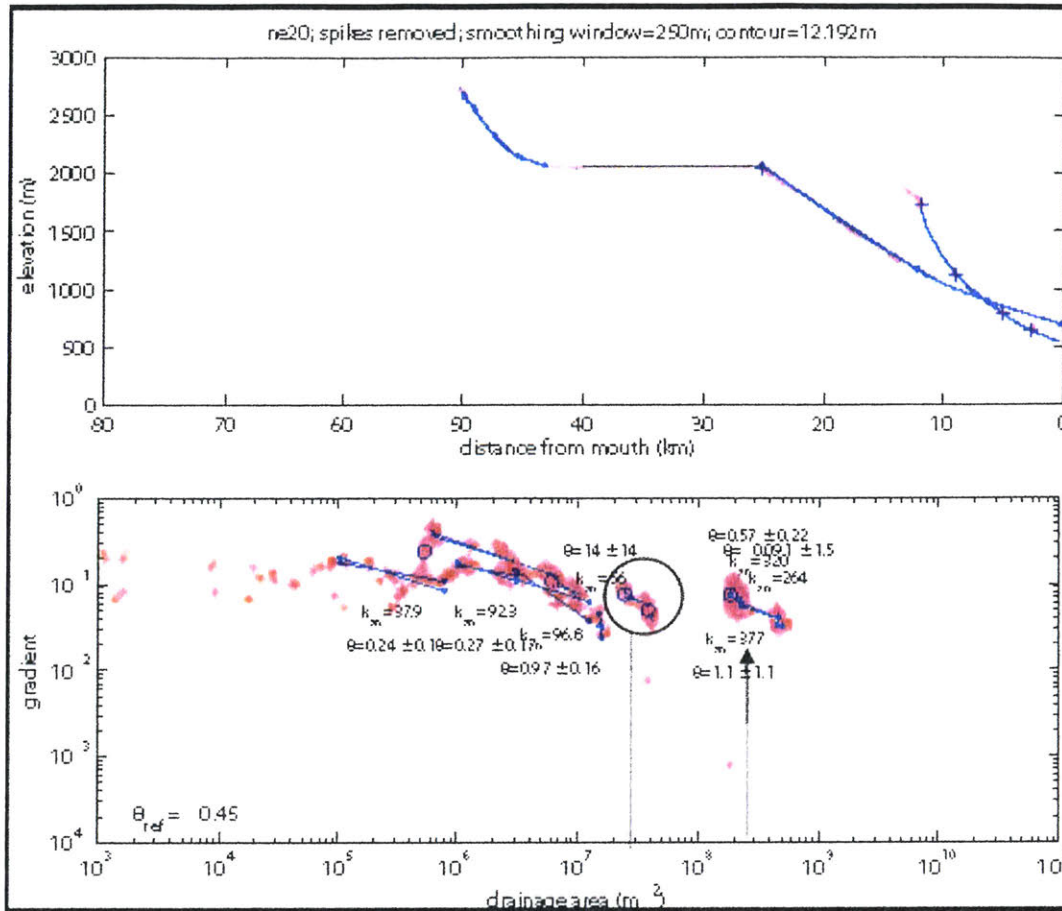


Figure 7. Channel “ne26” compared with a smaller, nearby channel. In the circle the smaller channel shows similar channel gradient to ne26, but at an upstream drainage area ~an order of magnitude smaller ($k_{sn} = 97$ as opposed to ~320).

Sediment flux can also have an effect on channel steepness. If the Big Bear Plateau is not eroding very much—which on average seems to be the case (Spotila et al., 2000)—then the stream could be sediment starved. This would lead to an inadequate supply of abrasive tools, inefficient erosion, and hence, a steep slope at only moderate rock uplift rates (e.g. Sklar and Dietrich, 2004; Whipple, 2004). However reasonable this expectation, a sediment-starved condition seems inconsistent with the observed valley fill described above. An alternative sedimentary effect, and arguably the most likely in this region, could be an armoring of the bed by boulders from landslides and debris flows, a phenomenon observed in the San Gabriel Mountains in areas of both high and low uplift

rates (Whipple, 2004). This would be consistent with the apparent presence of alluvial fill observed in the shaded relief map (Figure 5). The presence of large boulders could be responsible for inefficient erosion, and thus, a very steep channel, despite only moderate rock uplift rates. It is not yet fully known how debris-flows influence river profiles (Stock and Dietrich, 2003); if field observations confirm the presence of a large number of landslides in this drainage, it could be included in a future examination of this relation. Fieldwork will be necessary to determine to what extent these factors may be affecting this channel, but there is one further complication. Big Bear Lake is a reservoir, with a dam separating it from ne26. While the time scale of the dam (built in the 1880s) is much too short to have had any effect on the long profile, it is conceivable that it has affected measurable channel properties (grain-size in the bed, channel width, and percent alluvial cover, etc.). This effect might mean that field observations will not present a clear picture of why this channel has developed its anomalous profile.

The second region worth examining in further detail is the Yucaipa Ridge located on the southern front of the range. My moderately low steepness values for the Yucaipa Ridge block, as defined by Spotila et al. (1998), are unexpected given their thermochronological data indicating rapid uplift and erosion rates in that region. It is possible that the reference concavity is not an accurate description in this region, and observed steepness values are artificially low. Uplift as rapid as that proposed (1.5-2mm/yr or higher) could perhaps have caused this to be a landslide and debris flow dominated landscape. If that were the case, these channels would have low concavities and my reference concavity of 0.45 would not be valid. However, slope-area plots do not

support this – the reference concavity appears to be reasonable and thus the observation that k_{sn} values are no greater than 120-130 appears to be robust (Figure 8).

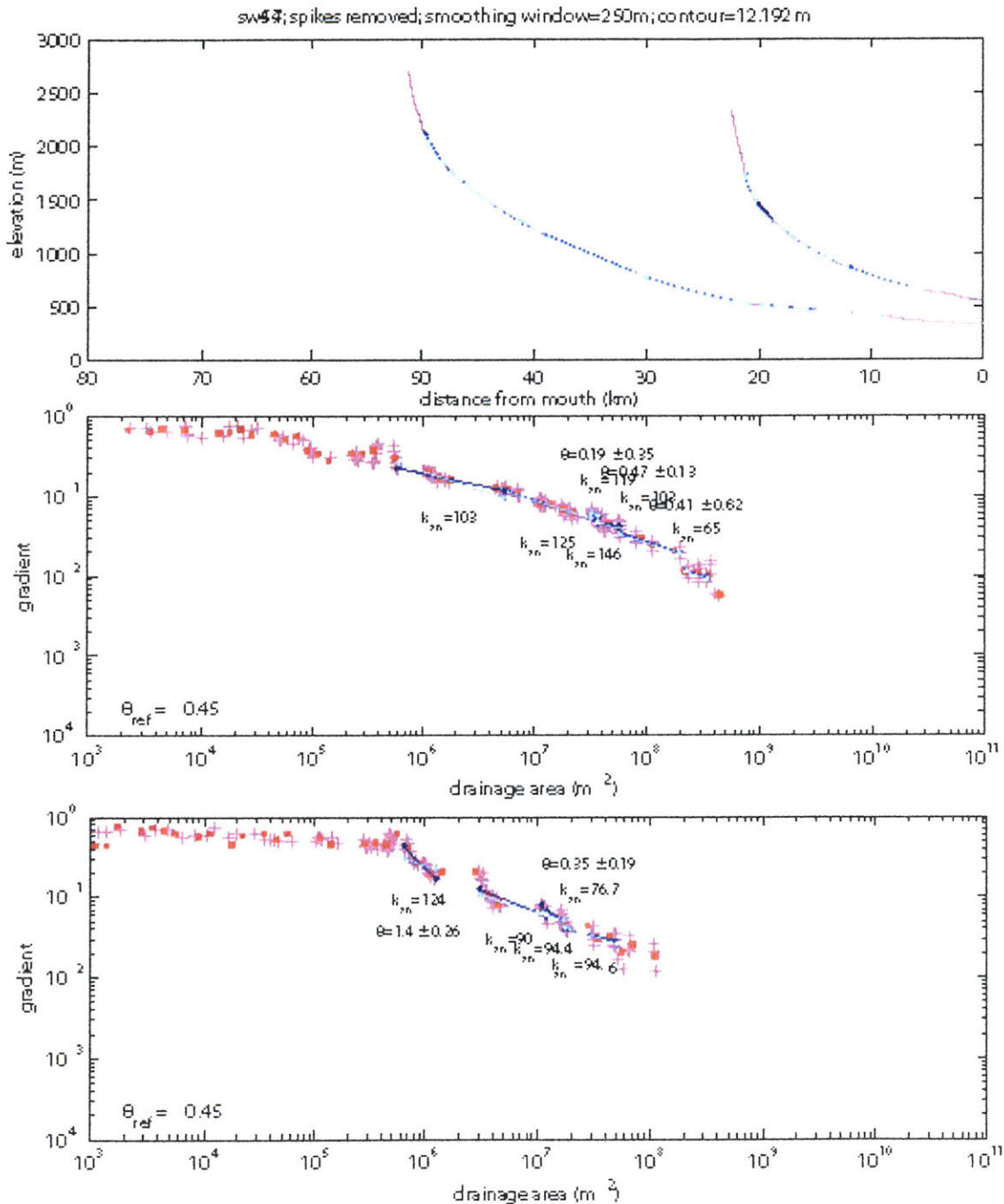


Figure 8. Two characteristic examples of stream profiles from the Yucaipa ridge. The break at about $A=10^6$ is apparent and indicates the transition from debris-flow to fluvial processes (e.g. Montgomery and Foufoula-Georgiou 1993; Stock and Dietrich, 2003). The steepness index values between 90-146 correlate with

moderate (~ 0.5 mm/yr) uplift rates based on data from the San Gabriel Mountains (Whipple et al., in preparation, see Figure 9).

In the San Gabriel Mountains, a preliminary quantitative correlation of erosion rate versus steepness value has been done using cosmogenic data for the region (Figure 9) (Whipple et al., in preparation).

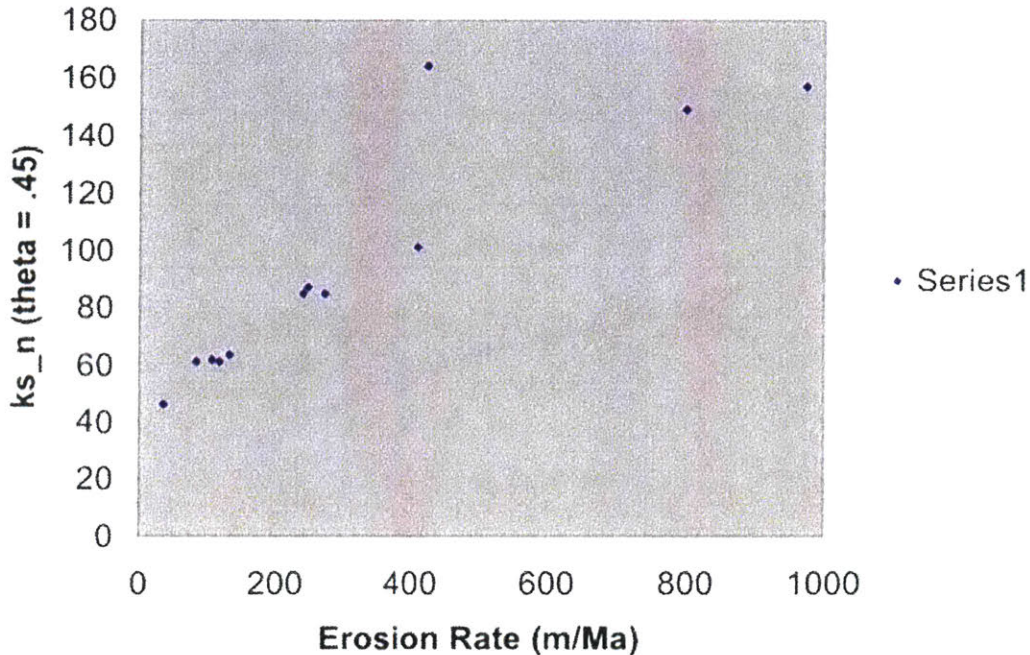


Figure9. Unpublished data from Whipple et al. show correlation in the San Gabriel Mountains (from cosmogenic data) of erosion rate and normalized steepness index (k_{sn}). If the San Bernardino Mountains act the same, Yucaipa Ridge steepness index values of ~ 120 - 130 correlate with an erosion (uplift) rate of 0.5 - 0.6 mm/yr.

If this method is to be valuable, the hope is that such quantitative information can be transferred between similar regions. The k_{sn} values observed on the Yucaipa Ridge correlate to an erosion (and therefore uplift) rate of ~ 0.5 mm/yr, significantly lower than those proposed based upon the thermochronology data. The contrast between observed k_{sn} values (~ 120) and those expected at erosion rates suggested by the thermochronology

data (>200) should be easily and reliably detected – uncertainty on k_{sn} values is typically well less than 10%.

It is possible that the geothermal gradient has been shifted towards the surface due to heating from friction associated with motion along the San Andreas fault (Spotila et al., 1998), although the fault lacks the expected heat-flow anomaly normally expected in high friction regimes (Turcotte and Schubert, 1983; Lachenbruch et al., 1985; Lachenbruch and Sass, 1988). It is, also, conceivable that subsequent heating related to faulting has reset the dates. However, even if the thermochronology data has been correctly understood, it is possible that this interpretation doesn't give the complete picture. The error bars on this data set are large (1.6 +/- 0.5 Ma), and Spotila et al. acknowledge in their 1998 paper that a much more complex cooling history than they proposed is allowed for in the data. They give a minimum uplift rate as 1.5mm/yr, but indicate it could be much higher. It is equally plausible that their data records a pulse of rapid uplift in the early to mid Quaternary, but that current rates are much slower. Their minimum rate may represent the average over the last 2Ma. In this scenario, only the slower uplift rates operating in the latest Quaternary are reflected in the channel profiles. The Yucaipa Ridge has a narrow width (<5km), with short channels that might have adjusted to the current tectonic setting relatively rapidly (on the few 100,000 year timescale). The DEM of the Yucaipa Ridge suggests soil mantled hilltops, which would be consistent with a reduced rate of rock uplift and which could potentially provide cosmogenic data that would help flesh out the uplift history of this fault block (Figure 10).

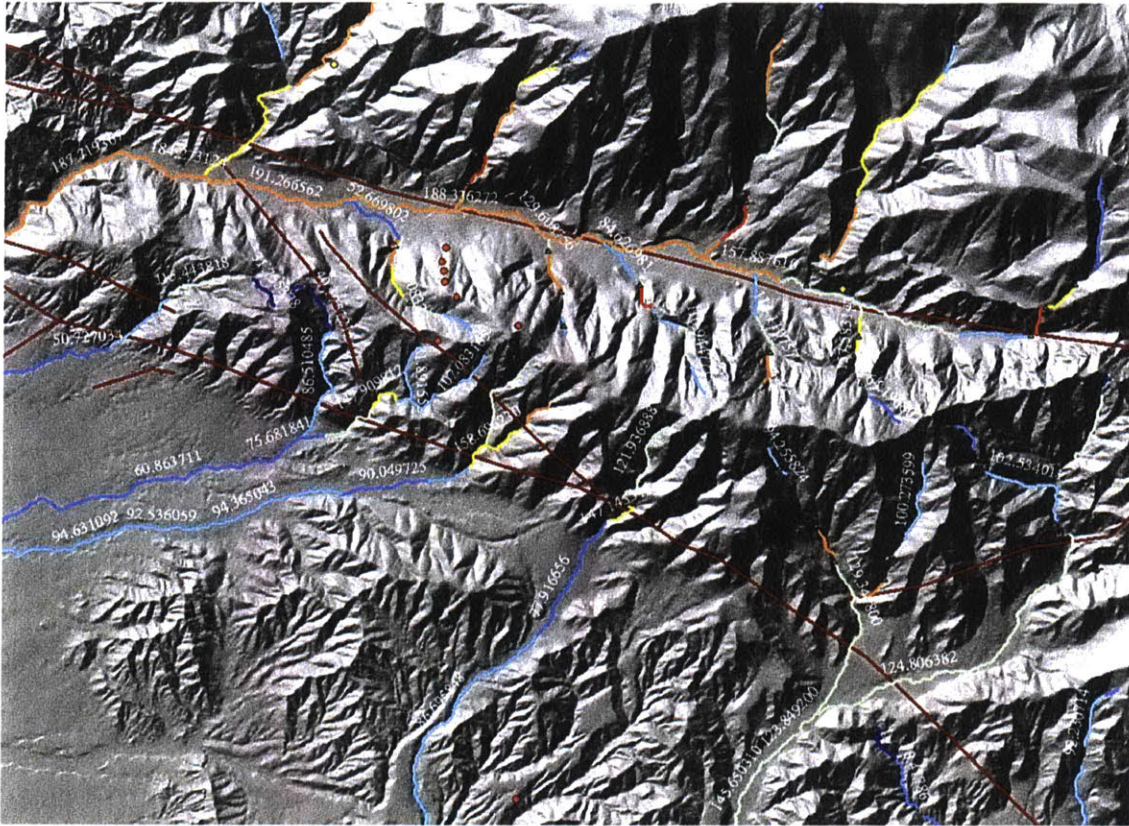


Figure10. Shaded relief map of Yucaipa Ridge fault block. Red dots indicate location thermochronology data in a vertical transect (Spotila et. al., 1998). White numbers are k_{sn} values. Rounding on ridge top may be a good location for cosmogenic data to further constrain uplift rates.

A future comparison of cosmogenic dates to my results (and possibly a more complete thermochronological study) would be useful not just in understanding the local geology, but it would, also, provide a helpful reference point for further development of stream profile analysis.

Finally, my stream profile data indicates that the Santa Ana Thrust fault may have been active more recently than the Miocene, and therefore, have played a role in the uplift and current morphology of the San Bernardino Mountains. It is difficult to interpret the complex k_{sn} values across the Santa Ana Thrust, and it would be useful to collect both field data and additional stream profiles for rivers that cross the fault in order to search for evidence of activity. This would also be a prime location to examine regional

lithology for a potential variation that happens to correspond with the fault and could be contributing to a false appearance of variable uplift. Generally, however, it appears that k_{sn} values are higher north of the fault than south of the fault for any given stream profile, though between profiles there is a large amount of variation (Figure 11). If these, in fact, do reflect the uplift, then it would indicate current or very recent activity along the thrust fault.

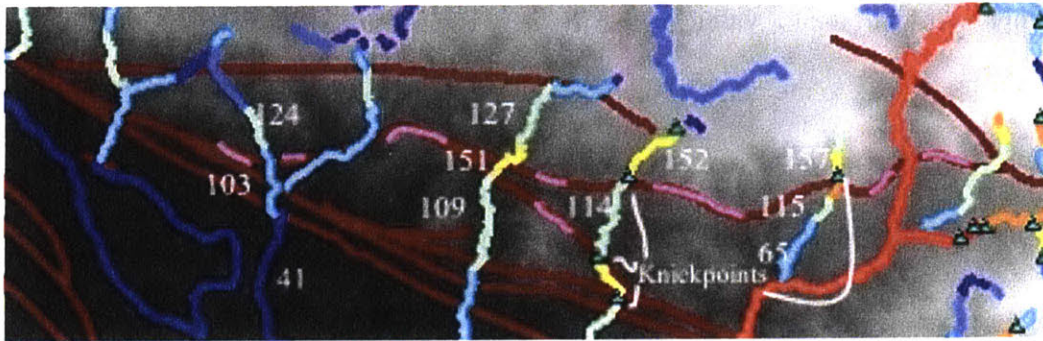


Figure 11. K_{sn} values on streams crossing the Santa Ana Thrust Fault (indicated in pink). The green triangles are knickpoints, some of which line up with the fault. Red drainage is channel “ne26.”

Conclusions and future work

Stream profile analysis is useful as a qualitative look at the tectonics of a region. As we develop a better understanding of the influence of erosional processes on tectonics and gather a larger data set to use as a baseline, it may become more quantitative. Certainly it is useful as a low cost and easy method for gaining enough insight into an area to efficiently focus fieldwork.

To fully understand the San Bernardino Mountains, it is clear that more data is needed. Field observations and laboratory techniques can provide further insight into this region, and in addition, will shed light onto the strengths and weaknesses of the technique employed here. Three regions in particular that would be good to look at are the Yucaipa

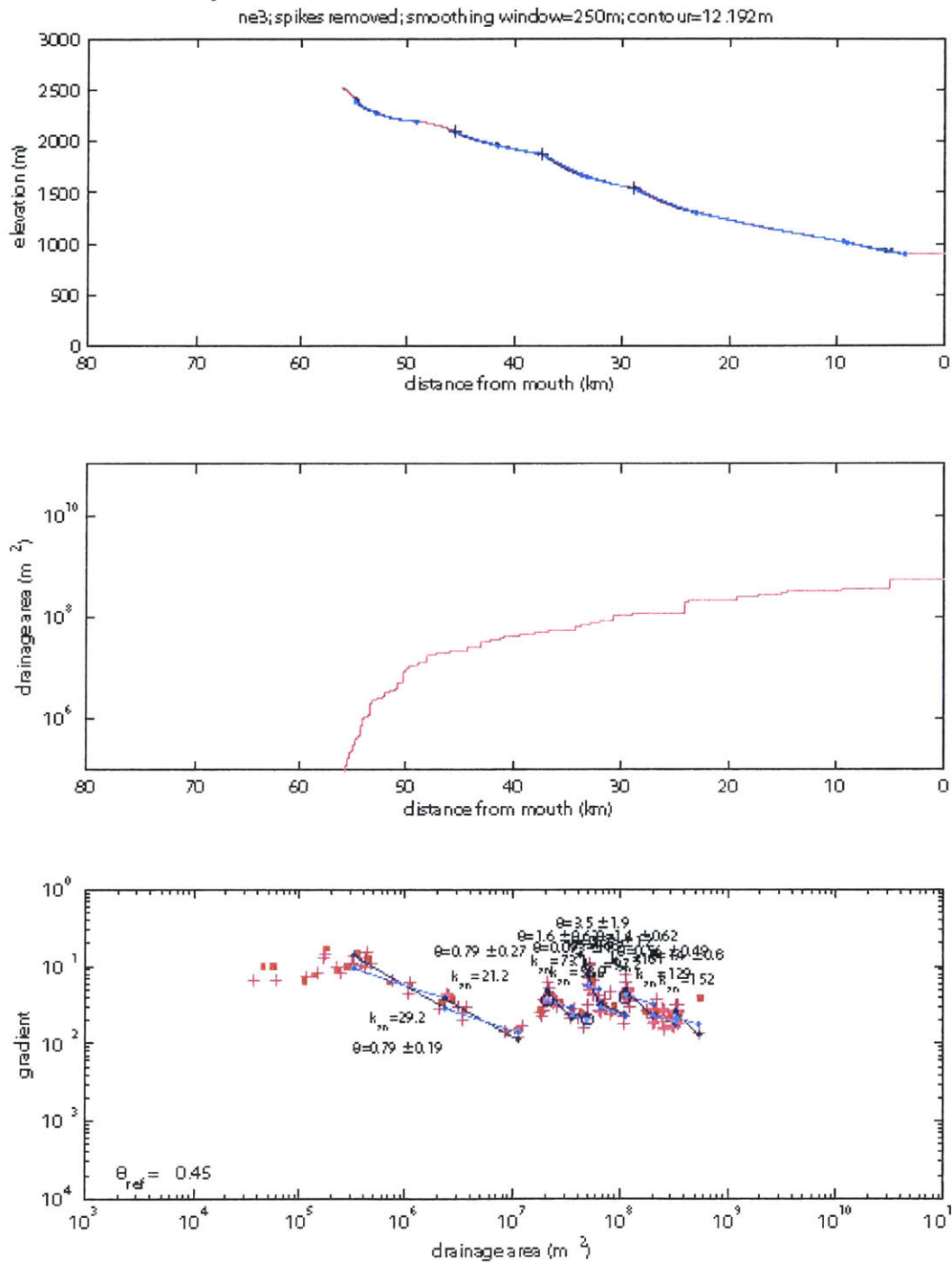
Ridge, the Santa Ana Thrust Fault, and the stream that empties from the southwest corner of Big Bear Lake (ne26).

The DEM of Yucaipa Ridge shows rounded hillsides along the peak that indicate a soil mantle that could provide good cosmogenic data to help constrain the current and historical uplift rates of this fault block. Steven Binnie, now at Edinburgh has collected some cosmogenic samples (unpublished) in the San Bernardino Mountains and a future comparison with the k_{sn} values found in this study could prove insightful. If the numbers show similarities to the correlation done for the San Gabriel Mountains, it will provide some of the groundwork for converting this technique into a more robust quantitative means of analysis.

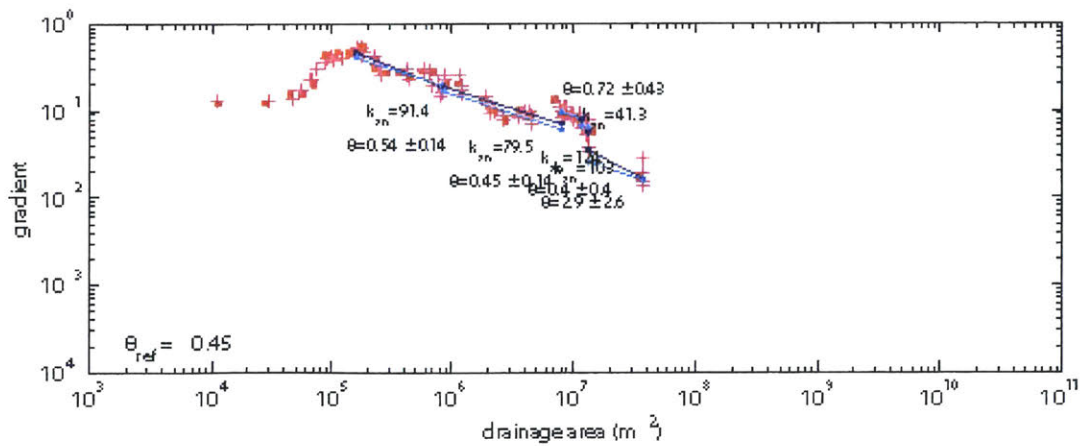
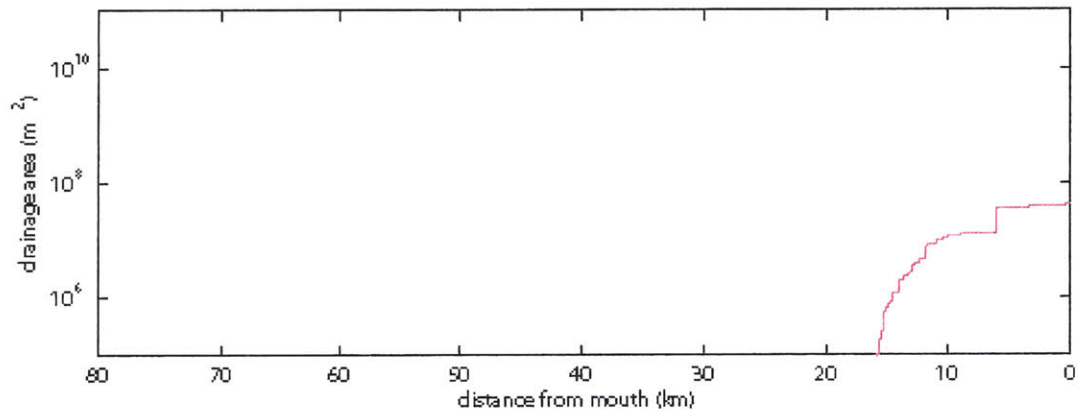
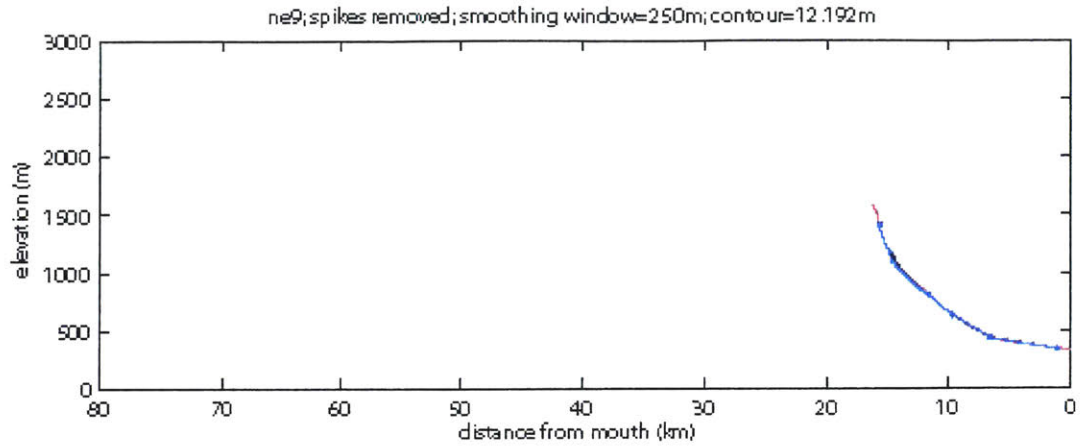
Field observations of the river channel draining Big Bear Lake would immediately provide insight into the nature of the processes driving the shape of this channel and its unusual profile. While it may not give all the answers, a closer examination of the channel will give more detailed information than can be seen from the remote sensing data. Despite its conveniences, remote sensing cannot replace field observation and leaves many questions that would quickly be answered by physical observation.

Appendix A – Selected stream profiles

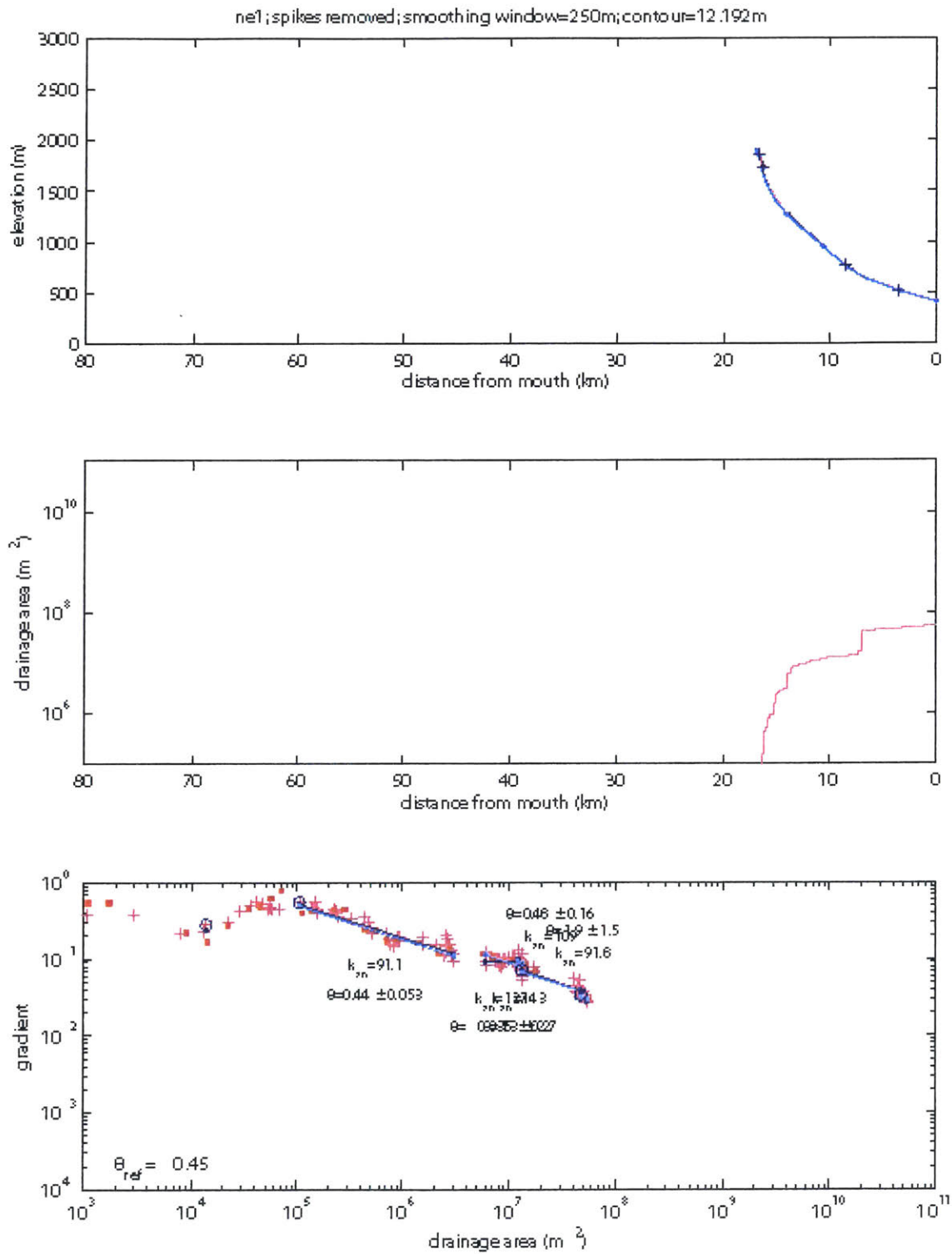
1. A long EW drainage on the northern section of the map shows a series of steps between knickpoints.



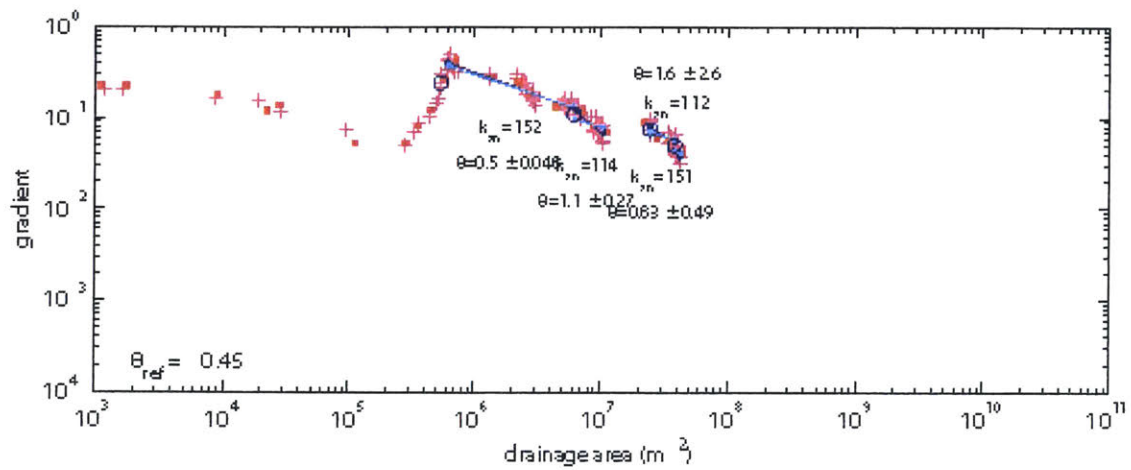
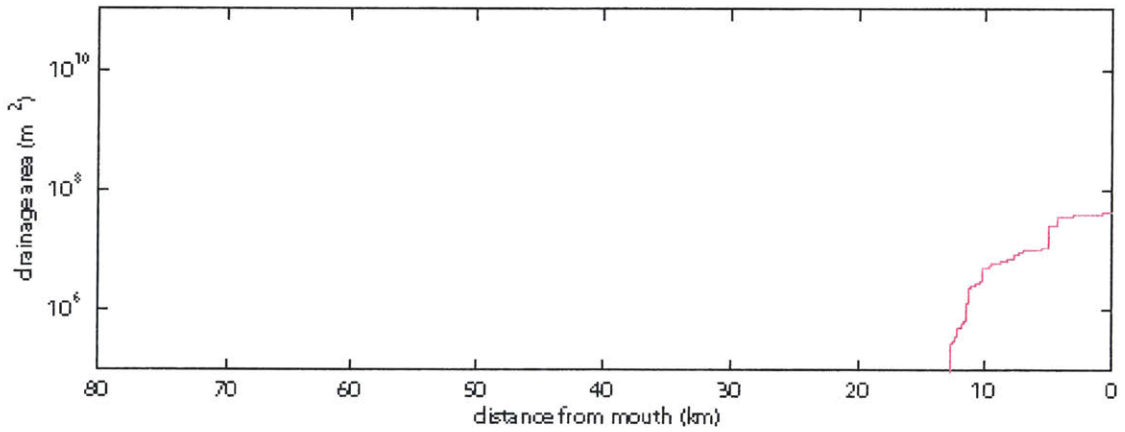
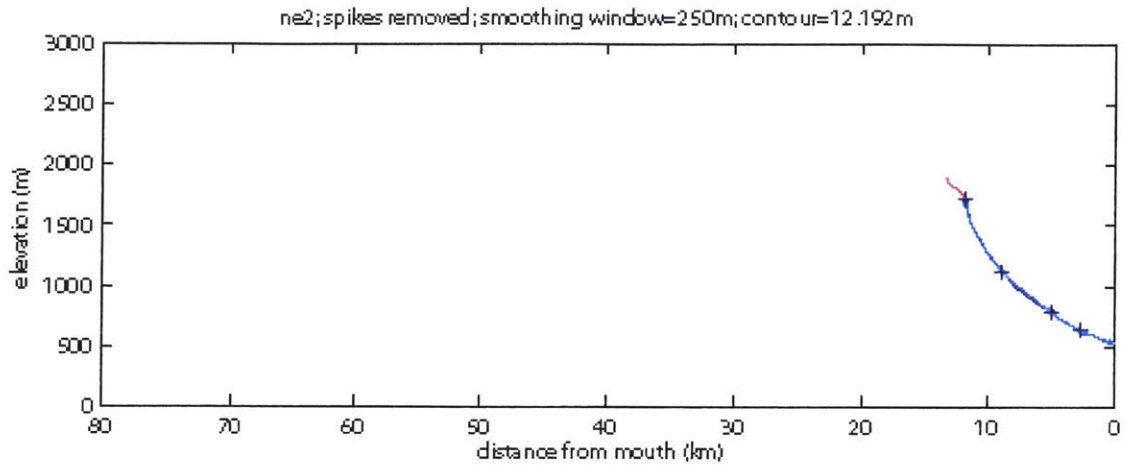
2. One of the streams that crosses the Santa Ana Thrust Fault



3. A stream that crosses the Santa Ana Thrust Fault. Knickpoints bound regions.

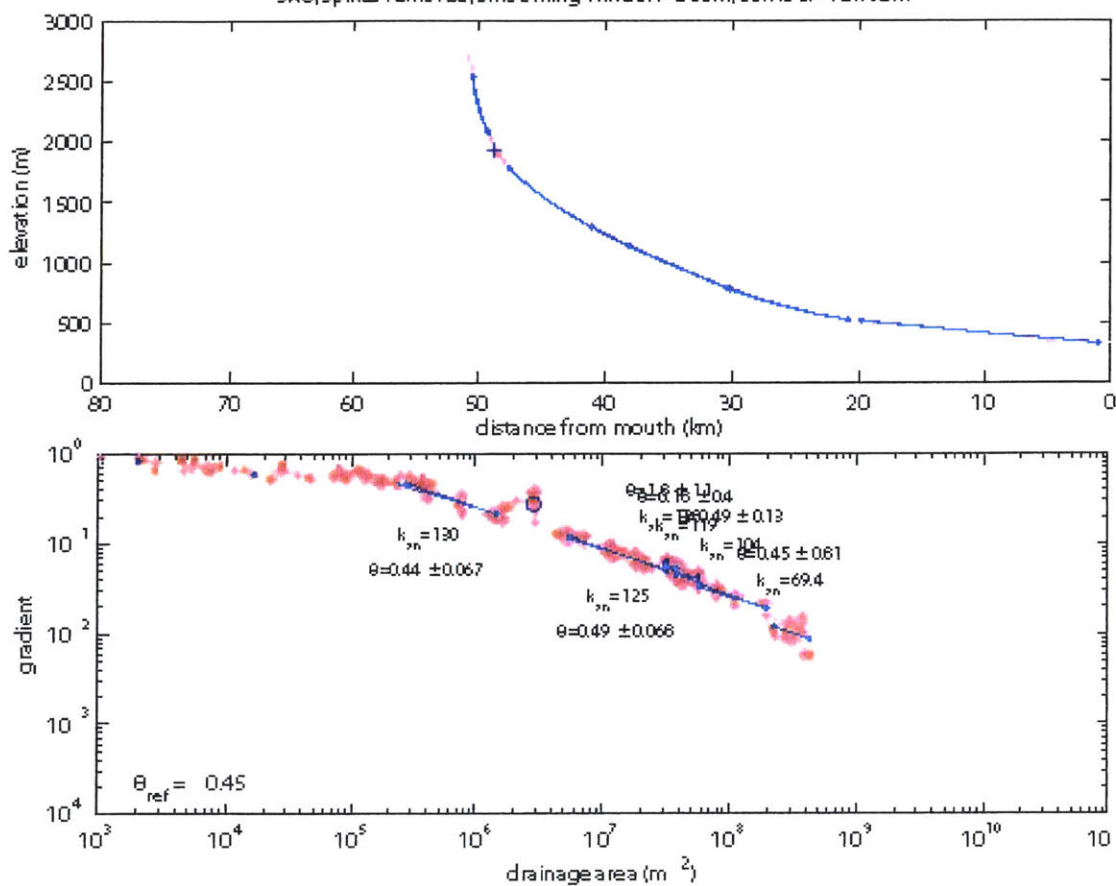


4. Stream that crosses both splays of the Santa Ana Thrust Fault (crossing points line up with knickpoints).



5. Example of smooth profile, from a south flowing stream that joins channel "ne26."

sw6; spikes removed; smoothing window=250m; contour=12.192m



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