A Study of Knickpoint Formation:
Geomorphic Analysis of San Simeon Creek

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Abstract

The highest point of orogeny in the Santa Lucia range occurs 50-60km from the nearest active faulting. This orogeny is believed to have occurred hear due to relatively weak Franciscan Mélange versus the granitic material at the fault boundary. This paper studies the development of a knickpoint in San Simeon creek to identify the role of relatively recent (graded time) tectonic activity in orogeny of the Santa Lucia range.

The 2003 earth quake is evidence of recent base level change with the occurrence of orogeny supporting the theory of continuous orogeny in recent and graded time scale. Although the knickpoint occurs in a resistant portion of the Franciscan Mélange, overall it is a relatively soft substrate suggests that Garcia and Mahan’s theory of Quaternary orogeny.

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Literature Review

KNICKPOINT PROPOGATION (INCISION WAVE) THEORY

A stream in equilibrium has a concave up longitudinal profile, this makes it possible for the stream to expend the least amount of energy while flowing toward base level, which is the ocean in most coastal areas. A disruption in the gentle curve usually characterized by a “convex reach” is known as a knickpoint. The initiation event of knickpoint formation can be any number of different events however it commonly ranges from a dramatic change in base level through isostatic rebound, tectonic uplift, a change in catchment area size possibly by a stream capture event, to a local change in rock type (Berlin & Anderson, 2007) (Frankel et al, 2007).

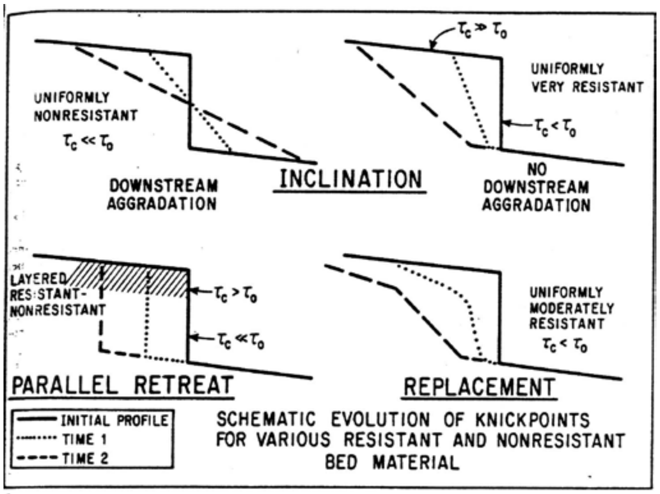


Figure 1. Illustration of the knickpoint migration theory developed by Thomas Gardner in 1983.

Knickpoint evolution occurs through the modes described by Gardner (1983) as parallel retreat (occurs where resistant rocks overlie weak rocks), inclination (occurs in nonresistant homogenous material or uniformly resistant material), and replacement (occurs in moderately resistant rock; Figure 1). Upstream propagation of base-level fall (by knickpoint migration or any other process) is also commonly referred to as an incision wave. Gardner (1983) developed his hypotheses through simulation using a flume and simulated sediment with a mixture of 70% sand, 19% silt-clay, and 11% kaolinite. The test flumes were all given the same initial shape and allowed to form a stable meander. The flumes were then exposed to different changes in base level and knickpoint migration progress was assessed at randomly chosen times throughout the experiment. .

BASE LEVEL CHANGE PHENOMENA AND KNICKPOINT DEVELOPMENT

Base level change can be resultant of isostatic rebound, tectonic uplift, change in sea level, or any combination of these. The change in base level causes the formation of a knickpoint, and available stream power increase at and slightly upstream of the knickpoint. This knickpoint in simplest terms is simply evidence of the stream adjusting its flow toward equilibrium and the path of least energy expenditure (Crosby & Whipple, 2006). Headward incision caused by base level change is in some instances evident as a knickpoint. Gardner's (1983) work on base level change identified the modes of knickpoint evolution; however it was further experimentation and observation that assessed the effect of base level change on stream power, channel equilibrium, and knickpoint migration. By applying the observed information into the "Celerity model" (Equation 1), Berlin and Anderson (2007) were able to accurately predict the location of the knickpoints already in place. This experiment tested the accuracy of the Celerity model and made significant progress towards understanding the evolution of knickpoints caused by base-level fall (Berlin & Anderson, 2007).

$E = KA^mS^n$
K: Dimensional resistance to erosion
A: Drainage area
S: Channel slope
m & n: Process dependent constant based off channel incision process

Equation 1. Stream Power Law (Celerity Model) (Berlin & Anderson, 2007)

Large-scale incision waves caused by base level fall, sometimes manifest as upstream-migrating knickpoints, have been documented in southern Spain, Using fluvial stratigraphy in combination longitudinal profile analysis evidence of knickpoint propagation was shown on large scales such as the 20km migration of the knickpoint zone on the Aguas/Feos river complex (Harvey and Wells, 1987), . This event was determined to be caused by tectonic stream capture, causing an increase in catchment area, thus triggering the incision wave (Harvey and Wells, 1987). Loget and Van Den Driessche (2009) evaluated knickpoint formation from the Messinian event base level fall of 1500m at the end of the Miocene era and compared it to current drainage configuration. The evaluation yielded results suggesting deep canyons formed by headward erosion due to the extreme event and is observable in the major valleys around the Mediterranean, despite the aggradation caused by an 80m sea level rise since the event (Loget & Van Den Driessche, 2009).

ROCK TYPE AND KNICKPOINT DEVELOPMENT

Resistance to erosion can also be the cause of a knickpoint formation and many studies have been conducted under that premise. Gardner (1983) established that hard, resistant material overlying nonresistant material also causes over steepening. It is the underlying material that fails as the stream abrades the bed and eventually the hard overlying surface loses its support and collapses; this is more specifically known as parallel retreat (Gardner, 1983). Knickpoints readily form in vertically bedded substrate of contrasting resistance to erosion (Frankel et al, 2007). Frankel et al (2007) studied two knickpoints in the Appalachian range demonstrating vertically bedded resistant material on Moores Creek and the Susquehanna River using a flume to simulate the conditions for observation. The heterogeneous substrate conditions were simulated by alternating clay and silt material. Upon applying a gently slope and allowing the stream to equalize, a sudden base level change was applied to simulate an event. Knickpoint formation occurred most prominently at the more resistant clay material forming a system of step pools. The mock stream demonstrated parallel retreat reaffirming Gardner’s (1983) knickpoint migration theory (Frankelet al, 2007). This is significant because rock type change intrusions can be found in many forms in addition to vertical beds (e.g. dike or sill intrusion).

Weissel and Seidl (1997) demonstrated rock type controlled knickpoint propagation rate in conjunction with fluvial processes by analyzing the Macleay River system. Strike and dip measurements were taken and compared to field photography to identify bedrock joint and fracture patterns. It was found the sub vertical jointing caused block and columnar toppling, signifying that the streambed material and structure plays a critical role in knickpoint migration and propagation (Weissel and Seidl, 1997).

CATCHMENT AREA AND KNICKPOINT FORMATION AND PROPAGATION RATE

The analysis and comparison of the Mediterranean area by Loget and Van Den Driessche (2009) mentioned previously yielded not only significant evidence of Messinian event base level fall but also highlighted a correlation between catchment basin area and knickpoint propagation rate. As catchment area increased, propagation rate increased accordingly in like material (Loget and Van Den Driessche, 2009). In addition to these results supporting a correlation between catchment area, Crosby & Whipple (2006) used a combination of aerial photography analysis and digital elevation model (DEM) to identify knickpoint location based on catchment basin size. The streams in the area were all believed to have been affected by the same base level change. Out of a total sample size of 235 streams, 75% of knickpoints were discovered at drainage basins between $1\times105\text{m}^2$ and $1\times106\text{m}^2$ (Crosby & Whipple, 2006). The increase in catchment basin area suggests a correlation between knickpoint propagation rates over time, which supports the Celerity Model developed by Berlin and Anderson (2007).

San Simeon Creek Study

1. Introduction

California has a complex network of faults ranging from micro faults to plate dividing faults such as the San Andreas Fault. As result, the complexity of the faulting has created a diverse landscape that is interesting for geomorphologists to study. Streams are an active element in a changing landscape and can often be used to understand the development of the landscape over graded and geologic timescales.

1.1 Tectonic and Geologic Setting

The central Coast Ranges are especially complex. For example, the highest point of the central Coast Range orogenic belt is 50-65 km from the major zone of active plate-boundary faulting at the San Andreas fault zone (McLaren et al, 2008). The range is located between the Oceanic fault and Nacimiento fault zone. Garcia and Mahan (2012) explain the phenomena through difference in geology between the plate boundary and the area of highest orogeny. The deformed zone is composed of Franciscan Mélange which relatively weak and is composed of an unconsolidated mixture of different rock types ranging in scale from cm to km in a mud matrix (Garcia and Mahan, 2011). Closer to the plate boundary, between the inactive Nacimiento Fault zone and the San Andreas fault zone, the Salinian terrane is composed of granitic material, as well as gneiss and schist (Page et al, 1998). The Franciscan Mélange complex is more susceptible to deformation and orogeny than the rocks of the Salinian terrane due to the vast difference in hardness.

Orogenesis of the Santa Lucia Range is believed to have occurred started around 6-8 Ma, according to a study based on thermocronometry data from rock samples in the northwestern portion of the range (Ducea et al, 2003). However, alternative studies in stratigraphic data indicate orogenesis occurring 3.5 Ma. Continuous versus episodic orogeny has yet to be determined with any certainty in the area. Page et al (1998) propose two main episodes of orogenesis separated by a period of tectonic acquiescence, the first starting at around 3.5 Ma, and the second ~400 ka. Page et al (1998) and argue that steady uplift as well as formation of the highest topography in the range has occurred since the most recent episode.

1.2 Recent Tectonic Movement

The 2003 San Simeon earthquake was caused by complex faulting and led to recent orogeny within the Santa Lucia Range. Recent InSAR imagery data shows the Oceanic/Nacimiento fault zone as the epicenter of the M_w 6.5 earthquake epicenter. McLaren et al. (2008) describe the earthquake as caused by a thrusting block in a reverse fault system in the Oceanic/Nacimiento fault zone. McLaren et al. (2008) measured the upward thrust during the event to have been ~72mm and describe the Santa Lucia Range as a “popup block”. The lifting of the Santa Lucia Range is result of convergence across the boundary between the Pacific Plate and the Sierran Microplate (McLaren et al, 2008; Garcia and Mahan, 2011). The convergence is accommodated by a network of and reverse faults (Page et al, 1998). The recent uplift event from the 2003 earthquake is a recent event of base level change caused by orogeny.

1.3 Analysis of Base Level Change Chronology

A knickpoint is an indicator of the stream correcting its flow to the path of least energy expenditure or equilibrium, which manifests as a visible break between two different base levels

(Crosby & Whipple, 2006). These features can be used as a tool for identifying significant landscape change events. The change in base level can be the result of many causes including tectonic uplift (orogeny), isostatic rebound, change in sea level, and stream capture events. Several forms of knickpoint formation can occur, each resulting due to differing conditions. Gardner (1983) coined the phrases inclination, parallel retreat, and replacement. Inclination occurs in two different forms, rotation and relaxation. Rotation refers to a stream equalizing in a universally nonresistant material by "rotating" along a central axis by depositing it's upstream material downstream. Relaxation knickpoint formation occurs in homogeneous, extremely resistant material. A relaxing knickpoint gradually lays back over time becoming less steep. Parallel retreat occurs in extremely resistant material overlying non-homogenous, non-resistant material. The knickpoint "retreats" upstream by eroding the weak underlying layer, thus causing the overlying resistant material to collapse. Estimating knickpoint progression of any of the different types of knickpoints can be difficult due to intrusions of rock with a different hardness than the existing rock. Beds of resistant rock can cause knickpoint progression to slow over geologic time as opposed to the usually much shorter graded time and must be accounted for when being used for studying base level change.

2. Methods

2.1 Area of Study

San Simeon Creek, the primary study site, is a perennial stream located in San Luis Obispo County, a few kilometers north of the town of Cambria. San Simeon Creek is within the

Pebblestone Shut-In and Cambria Quadrangle U.S. Geological Survey 1:24,000 scale topographic map quadrangles.

Analysis of the study site was done by creating a stream profile to illustrate changes in elevation over distance. Due to the small size of the stream and the accuracy variation of LIDAR data and physical maps, field surveying was decided to be the most accurate technique. A preliminary survey of the study site was performed to identify starting and stopping points for the surveying.

2.2 Field Methods

A Garmin Montana 650 Global Positioning System was used to make field notes and identify shooting points and fore shots made along the stream. Using an Abney level, level rod, and cloth tape, slope measurements in degrees (referred to below as (“shots”) were made at 50 meter intervals. Where 50 meter intervals were not possible, the distance between the rod and the level were recorded with accuracy down to 1 meter. The level rod was marked at eye level of the shooter with yellow tape to provide maximum angle accuracy possible. All measurements were taken from the center of the stream to preserve accuracy and consistency of the measurements.

The starting point was decided to be close at the relatively stable, alluviated lower portion of the stream. The endpoint was decided to be 300-500 meters upstream from the focus point (knickpoint). At each grade measurement point, a picture was taken for reference in the case that in the future results need to be verified. In addition to the site photos, each point was logged with its GPS coordinates, site notes, direction of shot, distance of shot, and angle of shot both in a field journal and on the Garmin unit itself. The survey took three total days in the field to log, therefore each endpoint was marked on the GPS to generate seamless data.

2.3 Analytical Methods

The field results were input into a digital spreadsheet for analysis and calculations. Each angle measured was plugged into the formula $\Delta \text{ Elevation}_{\text{calculated}} = \Delta \text{ Distance}_{\text{measured}} * \sin(\text{Angle}_{\text{measured}})$. The change in elevation was then added to the base elevation which was digitally identified using GIS software. A stream profile was then created (Figure 3.1) through a point line graph with change in elevation as the y-axis and the change in distance in the x-axis.

GIS software was used to create an accurate digital reference to the points in relation to existing georeferenced data provided by USGS and San Luis Obispo County public records. The geographic points were converted into a shape file from the GPS unit and overlain on a hillshade, a USGS geologic map shapefile, a USGS digitized fault line shapefile, and a digitized map of the stream network in the county for accurate analysis and visualization of the data (Figure 3.2).

3. Results

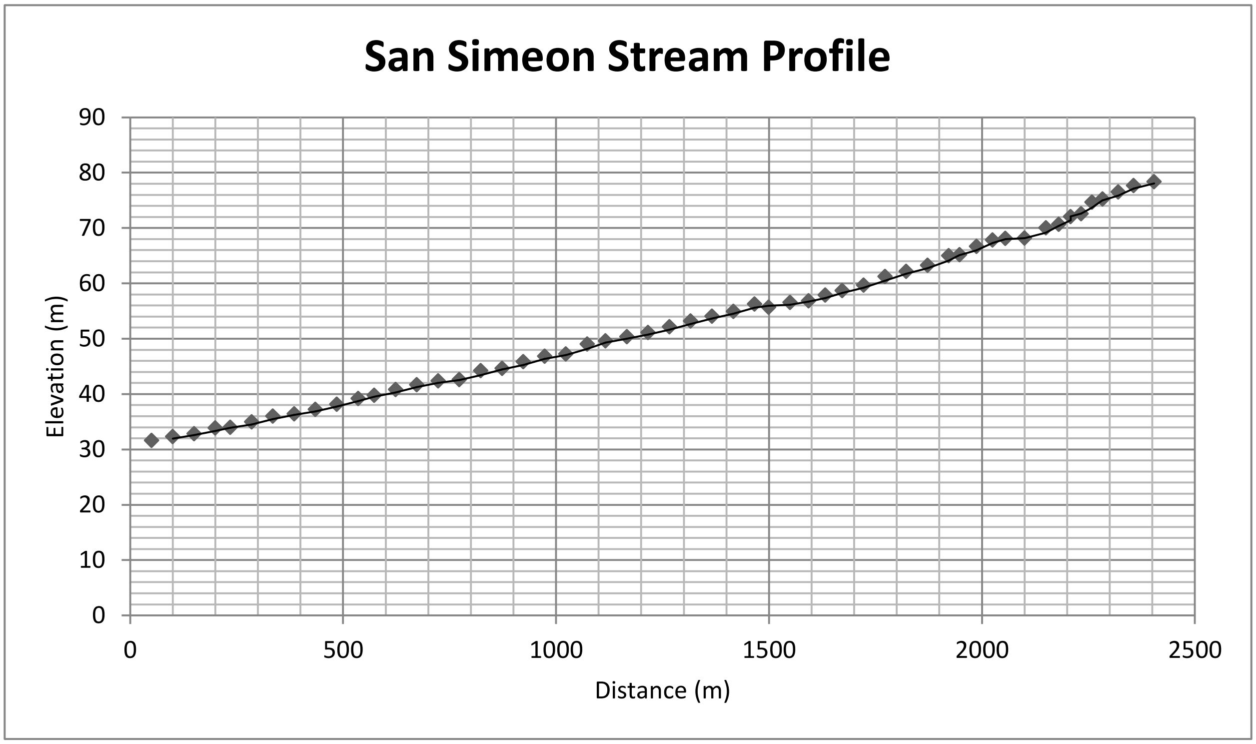
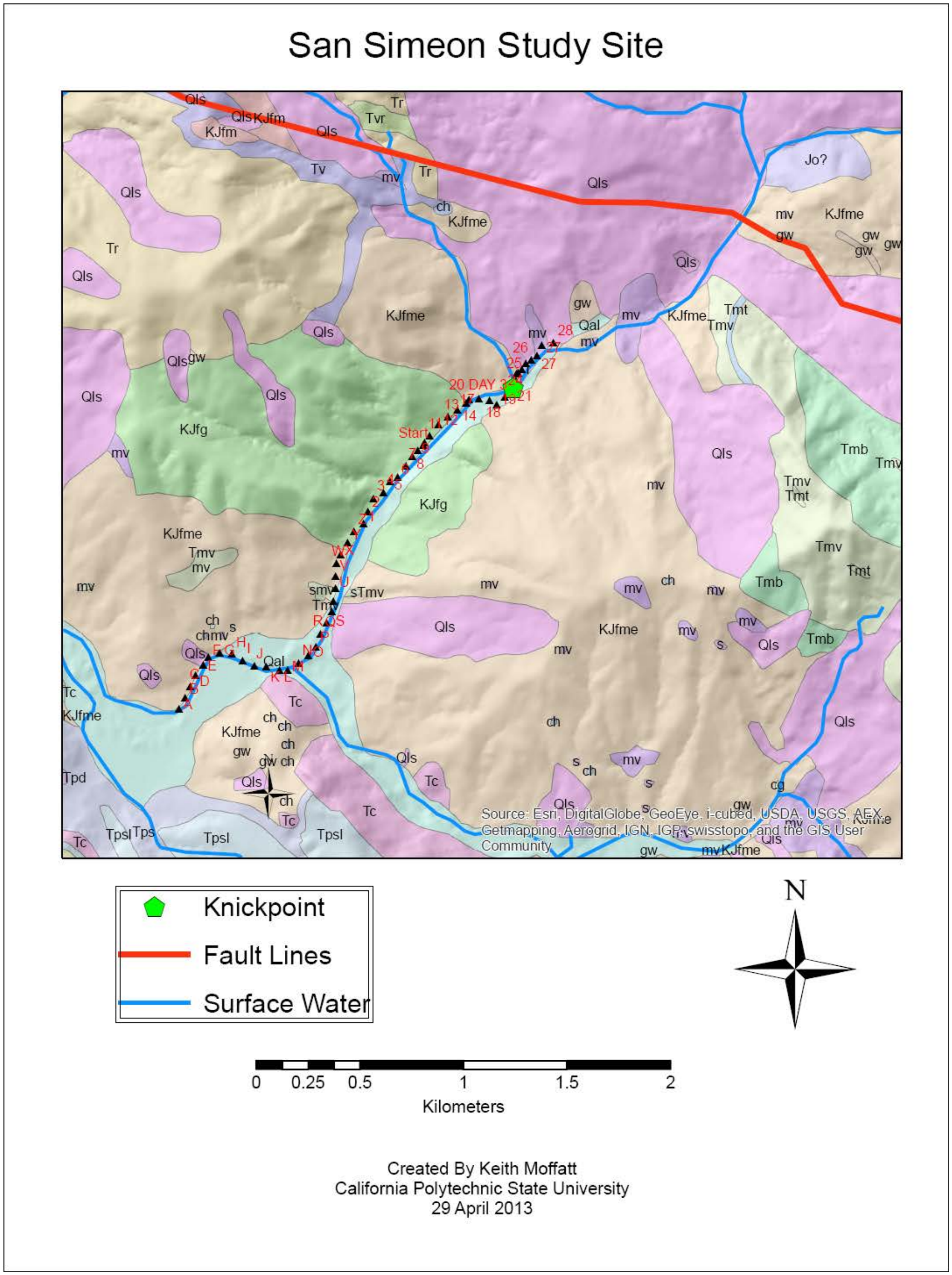


Figure-3.1, Profile exhibits change in elevation versus distance from ~30 meters elevation. A exists between 2,200 meters and 2,300 meters, and it reflects an abrupt change of elevation of the stream bed over a relatively short distance.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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Figure 3.2 The study area and surrounding the geologic structure provided by the USGS. Local geology consists of a range of rock types in a mud matrix forming Franciscan Mélange (Page et al, 1998).

Stream Profile Analysis

The lower section of the stream ranging from 0 m~2000 m is concave up, with a predictable upward elevation as distance upstream increases (Figure 3.1). The average stream grade at 50 m intervals is 1.06° below the knickpoint zone which for simplicity will be referred to as the lower stream profile. Between 2.2 km (2200 m) and 2.3 km (2300 m) an increase in average slope change over a shorter distance was noted and is distinctly different compared to the remaining stream profile. The fore shot from point 24-25 shows a 4.8% grade change which is a 22% increase in comparison to the lower stream profile.

The Upper stream profile average grade is 1.5%. While the sample size is smaller than the lower stream profile, the general trend of the upstream profile exhibits the characteristics of a stabilized stream segment graded to a local base level at the top of the knickpoint.

Geologic Survey Analysis

The streambed of San Simeon Creek is mantled by alluvium and large talus likely transported from the back slope of the surrounding canyon. The channel flows within Franciscan Mélange, which consists of with many different rock types having differing hardness. The knickpoint is formed in a small outcrop of resistant rock that may be serpentinite.

4. Discussion/Conclusion

The knickpoint identified in the field survey is formed in resistant rocks of the Franciscan Mélange. It cannot be unequivocally concluded that slip Oceanic fault has played a role in knickpoint formation. However, the relatively unconsolidated mud matrix is an ideal substrate for relatively fast knickpoint propagation caused by tectonically driven base-level fall.

Knickpoint formation along San Simeon creek suggests that base level change caused by tectonic activity has occurred in the Santa Lucia Range, which in turn suggests that Quaternary-time orogeny is occurring in the range. These findings support the model of Garcia and Mahan (2011), which proposes deformation in the nonresistant Franciscan Mélange due to the transference of strain by the much more resistant granitic material at the active plate boundary.

The scope of this study is not large enough to eliminate other possibilities to explain recent deformation of the Santa Lucia range. To solidify the theory, further study would be required. A stream longitudinal profile extending further upstream would be helpful in identifying any other possible knickpoints to gain a better perspective of deformation in the area. Studying several other streams in the range would be prudent for isolating the continuous recent uplift as the cause for knickpoint formation in the area. This study increases understanding of the recent uplift events of the Santa Lucia Range, and coupled with other studies, it can identify a more complete geologic history of the range.

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